MASTER THESIS

ADAPTIVE STORAGE LOCATION ASSIGNMENT IN A HETEROGENEOUS FLEET UNIT-LOAD WAREHOUSE

A DISCRETE EVENT SIMULATION STUDY

P.H. LANGEVELD

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Adaptive storage location assignment in a heterogeneous fleet unit-load warehouse

A discrete event simulation study

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Author
P.H. Langeveld (Pim)

UNIVERSITY OF TWENTE.

University of Twente
Industrial Engineering and Management
PO Box 217, 7500 AE Enschede
tel. +31(0)534899111

Academic supervisors
First supervisor: dr. L. Xie (Lin)
Second supervisor: dr. B. Alves Beirigo (Breno)

Bolk Business Improvement B.V.
Zuidelijke Havenweg 2
7554 PR, Hengelo

Company supervisors
S. Huuskes (Stijn)
N. Tijink (Niek)

MANAGEMENT SUMMARY

This thesis was conducted at Bolk Business Improvement (BBI) to provide Green Valley Cocoa Logistics (GVCL) with a method to efficiently and effectively use an Automated Guided Vehicle (AGV) fleet in combination with manual operators to handle the material handling in very narrow aisles (VNAs).

Introduction

Currently, there is no storage policy chosen to implement in the warehouse, and there is no strategy for allocating tasks to AGVs or manual operators. The ideal situation is that all information available is used to make the best decision possible for each activity in the warehouse. The research goal is defined as:

> “To develop a storage location assignment policy and retrieval policy, considering task division between automatic and manual handling, that reduces the material handling and intersecting flow, under the given restrictions in the new GVCL warehouse.”

The resources of GVCL come with a set of restrictions which impact the storage location assignment decision:

- An AGV can not pick up a pallet that was manually placed
- Pallets stored above each other must be the same pallet type
- Pallets unloaded with the Automatic Truck Loading- and Unloading System (ATLS) can only be stored with AGVs
- AGVs require working zones which prohibit manual operators from entering the working zone
- Resources only work in their specialized area

Therefore, this research focuses on finding the best storage assignment policy for incoming pallets, that best deals with these constraints. The main research questions is:

> “How can GVCL assign a storage location to incoming pallets to ensure timely completion of all storage and picking tasks, considering the shared workspace between AGVs and human workers in the new warehouse?”

Approach

To answer the research question, we conduct a context analysis to gain insight into the product flows. Based on the context analysis and a literature review, we formulate a new two-stage storage

policy approach, which we evaluate by performing a discrete event simulation study (DES). The first stage heuristic we call the *Occupation Based Resource Assignment* determines the occupation ratio per VNA, and assigns each VNA to a class (full, empty, or mix) based on the occupation ratio. Next, the heuristic assigns the empty and mix VNAs as a working zone for the AGVs, which will fill these aisles with incoming pallets. The full aisles are the working zone of the manual operators, which will primarily perform pick tasks. The second stage heuristic, which we call the *Split Lot Workload Assignment*, assigns pallets of inbound truckloads to an exact storage space in the warehouse, by assessing if pallets with a shared lot number must be stored in the same VNA or not, depending on the lot size. We compare these policies to a rule-of-thumb policy, the *Baseline*, which divides each compartment into two working zones: the left half for manual operations and the right half for AGVs, and assigns incoming pallets to the aisle where pallets with the same lot number are stored, or the nearest open location.

Findings

Using the proposed policies, compared to the Baseline policy, can reduce the average store time per pallet by 12.43%, pick time by 16.14% and reduce the average dock-to-stock time can be reduced by 11.58%, but causes an increase in the shipping time of 8.798%. The occupation based resource assignment policy emphasises the aisles with the most open spaces for storage tasks and selects the aisles with the most pallets to focus the outbound activity. The shipping time increases because the policy does not adjust to days with a lower workload, and assigns most pick tasks to manual operators. Pick time on individual pallets is decreased, but the total time to complete an order therefore increases. The policy increases the fraction of pallets stored with AGVs by 95.51%, while reducing the fraction of AGV pallet picks by 15.84%. This difference is the result of the occupation based resource assignment policy directly connecting the inbound activity to AGVs and outbound activity to manual operators. The Analytical Hierarchy Process (AHP) is used to assess if the proposed storage policy indeed outperforms the Baseline based on the importance of the KPIs for GVCL.

Conclusion

In conclusion, the research goal was reached by developing a two-stage storage assignment heuristic that considers the heterogeneous fleet. We answer the research question by recommending the occupation based resource assignment as the first stage and split lot workload assignment as the second stage storage policy. The proposed policy achieves order picker efficiency and warehouse effectiveness but requires flexibility: picking manually stored pallets in an aisle assigned to AGVs occurs in 1.95% of the pallet picks.

Recommendations

We recommend management of GVCL to implement the proposed 2-stage heuristics to efficiently and effectively operate the heterogeneous picker fleet in the unit load warehouse. Using the occupation based resource assignment policy to assign 9 aisles per compartment to manual equipment, to allow for manual picking activity. The other 6 aisles in the compartment are assigned to AGVs. The AGVs are used to primarily handle storage tasks. This allows for an average of 92.60% of the inbound pallets to be stored with AGVs, and 40.04 % of the outbound pallets to be picked with AGVs, compared to 47,36% and 47.58% under the baseline policy. The reduction in outbound pallets picked is caused by the decision to prioritise assigning the inbound workflow to AGVs. Theoretically, because more pallets are placed with AGVs, more pallets can potentially be picked with AGVs. The simulation results have also shown that an average dock-to-stock time of 24.9 minutes and an average shipping time of 38.83 minutes is possible. We recommend GVCL to use these times for planning the inbound and outbound order arrivals accordingly. Knowing the required time to complete orders, they can set a maximum allowed time for inbound and outbound orders to arrive, as well as plan when to release the picking lists for outbound orders. We recommend BBI to develop middleware that interacts with the WMS and data interface of Client X to implement the two-stage heuristic.

PREFACE

Hengelo, November 2024

Dear reader,

In front of you is my Master's thesis titled 'Adaptive storage location assignment in a heterogeneous fleet unit-load warehouse: a discrete event simulation study', written to conclude the track Industrial Engineering and Management at the University of Twente. This research was conducted at Bolk Business Improvement (BBI) in Hengelo.

First of all, I am grateful for the opportunity that BBI provided me with. With this research project, I got the chance to be part of the impressive Green Valley Cocoa Logistics project. Niek and Hein, thank you for the opportunity to do this assignment at BBI, and for providing me with the freedom for creativity. I would also like to thank Stijn for the supervision and help throughout the project. Finally, I would like to thank Sander for helping me with data collection and explanation of the processes of external parties connected to GVCL.

Secondly, during the execution of the research, I had the pleasure of being supervised by dr Lin Xie. I would like to thank you for guiding me during the graduation project and for challenging me along the way. I would also like to thank dr Breno Alves Beirigo for providing me with valuable feedback and helping me improve the thesis.

Finally, I had a great time as a student at the University of Twente, thanks to all my friends, family and roommates for making this possible. Last but not least, Kelly thank you for always being by my side.

I hope you enjoy reading my thesis!

Pim Langeveld

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GLOSSARY AND ACRONYMS

Glossary

Client X Manufacturer of cocoa products, the client for which GVCL provides logistic services. 1

FleetControl Software that controls all the AGVs. Receives input from WMS. 3, 13

Former warehouse Previous third-party logistics provider for Client X, used fully automated warehouse. 4, 9

Operator Person working in the GVCL warehouse, responsible for storing and picking unit-loads. 1

Acronyms

AGV Automated Guided Vehicle. 2

AHP Analytical Hierarchy Process. 36, 46

AS/RS automatic storage/retrieval system. 32

ATLS Automatic Truck Loading- and Unloading System. 4

BBI Bolk Business Improvement. 1

DES Discrete Event Simulation. 37

GVCL Green Valley Cocoa Logistics. 1

KPI Key Performance Indicator. 25

LHV Longer Heavier Vehicle. 19

VNA Very Narrow Aisle. 1, 2

WMS Warehouse Management System. 3, 4, 13

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1 INTRODUCTION

In this report, I present my research for Green Valley Cocoa Logistics. The study focuses on the internal logistics in a new warehouse, specifically the storage assignment and pallet retrieval selection in compartments equipped with a fleet of manual and automatic forklifts and reach trucks.

In this chapter, we introduce the background and approach of the research. We present the background in Section 1.1 by introducing the company and their client. Section 1.2 shows the research motivation. The problem description is discussed in Section 1.3. Next, we show the research questions and approach in Section 1.4. The scope of this research is presented in Section 1.5. We finally discuss the research approach in Section 1.6.

1.1 Background

This research project is carried out at Bolk Business Improvement (BBI) in Hengelo, the Netherlands. BBI is a part of Bolk Transport and specialises in improving logistic and production processes using experience from practice and smart data processing. BBI is responsible for designing the internal logistics of a new warehouse for Green Valley Cocoa Logistics (GVCL), a joint venture between TMA, Gam Bakker and Bolk Transport. The purpose of this joint venture is to serve as the logistics service provider for Client X. GVCL will distribute cocoa powder for Client X, produced in Western Africa and the Netherlands. The GVCL warehouse is built on a TMA plot in the port of Amsterdam. At the start of this research project, the design phase of the GVCL warehouse was completed, and the construction began. Before the warehouse becomes operational in September 2024, all the operational activities must be defined.

1.1.1 Brief introduction to warehousing concepts

The main activities in a warehouse consist of *receiving* goods from suppliers, placing them into *storage*, *picking* items from storage, and *shipping* items to customers. Receiving consists of unloading the delivery vehicle, inspecting the goods, and registering what was received. The storage activity is the process of placing goods into a storage location. The picking process consists of selecting items from storage locations based on customer order lists and moving the product from storage to the shipping area. Shipping is preparing the picked items for shipping, for example by (re)packaging the product, labelling items, and inspecting the goods.

The processes involving moving goods in a warehouse can be performed by order pickers, referred to as an Operator. Some tasks require equipment, such as forklifts. To optimally use warehouse space, racks increase the usage of the vertical space. To further increase available storage space, racks can be organised in Very Narrow Aisles (VNAs), requiring special equipment that fits in those aisles. To reduce the dependency on manual operators, automated equipment

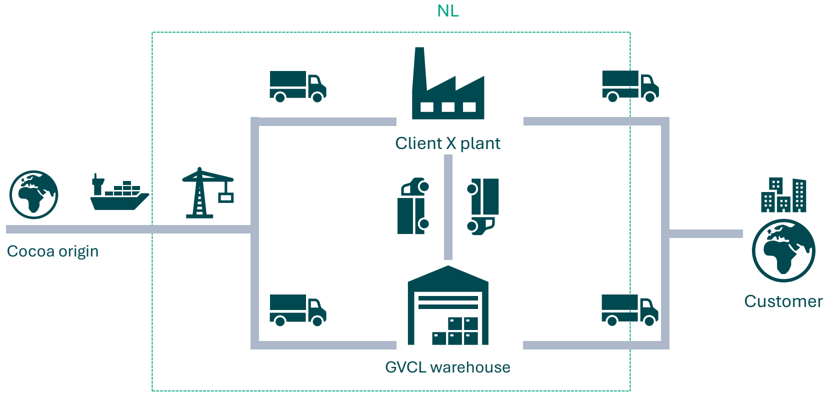


Figure 1.1: Schematic overview of Client X logistics

can be used to perform tasks in a warehouse. One type of automated equipment is the Automated Guided Vehicle (AGV), a material-handling vehicle that can navigate the warehouse autonomously.

1.1.2 GVCL warehouse

GVCL will become the logistics service provider for Client X. GVCL will operate a dedicated warehouse to distribute cocoa powder produced in the Western African countries Ghana and Ivory Coast and in Wormer in the Netherlands. The product flows are called West Africa Flow and Wormer Flow respectively. Cocoa from West Africa requires inspection and cleaning, part of the Value Added Logistics (VAL) activities. Processed cocoa from the Wormer plant is stored in GVCL and shipped to customers. Products from Wormer are always palletised on euro or block pallets and require no cleaning before storage. A schematic overview of the logistics of Client X is shown in Figure 1.1. The GVCL warehouse is separated into four compartments: A, B, C and D. Compartment A is dedicated to VAL. The other three compartments store palletised cocoa products, each with a receiving and shipping area near the dock doors. Two storage methods are used in GVCL: shuttle racks and VNA racks. The location of the shuttle racks and VNAs is shown in Figure 1.2.

Shuttle racks maximize storage capacity by storing pallets multiple layers deep, using shuttle carts in the rack. VNAs contain single deep racks on each side of the aisle, allowing for a balance between space saving and accessibility of the stored items. VNA forklifts, designed for efficient picking and placing within VNAs, have the required width and functionality to pick and place pallets in the narrow aisles but are not ideal for riding freely in the warehouse. Reach trucks move items between the docks, shuttle racks, and the end of VNAs in pick-and-drop shelves. GVCL utilises both reach trucks and VNA forklifts in manual and AGV variants, which are shown in Table 1.1. This comes with two main restrictions:

- AGVs are not compatible with the shuttles, so picking and placing in the shuttle rack requires a manual operator,
- Due to the required accuracy, a pallet placed by a human can not be picked by an AGV.

There are also safety considerations, as an AGV will stop moving if it detects humans nearby. To prevent the risk of human interference with AGVs, and to ensure a safe working environment, GVCL management introduces the following rule to the warehouse:

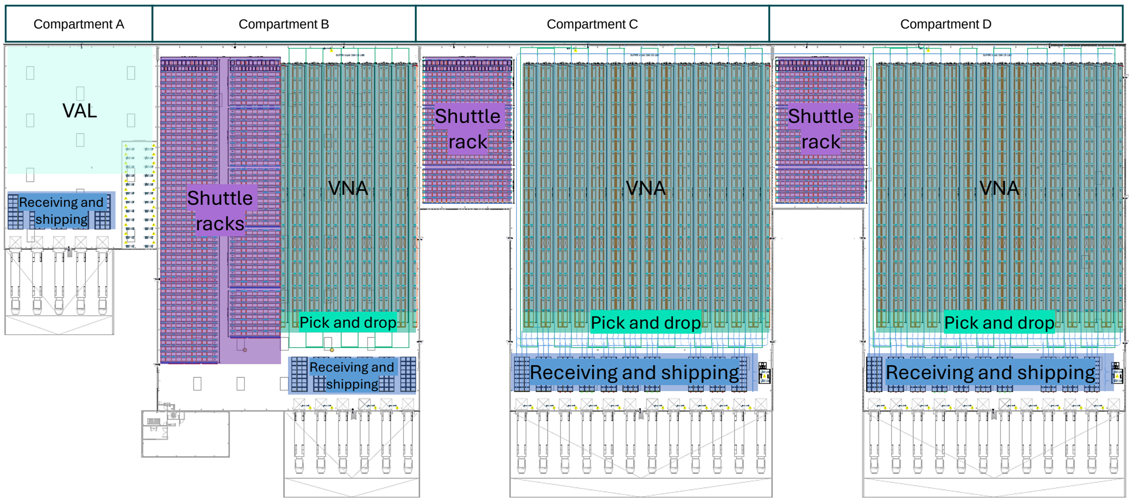


Figure 1.2: GVCL warehouse layout overview

- A VNA can be operated by an operator or AGV, but not both at the same time. It should always be clear if a VNA is classified as ‘automatic’ or ‘manual’, separating the AGV and operator work.

All warehouse activity is registered in a Warehouse Management System (WMS): software which manages the inbound and outbound orders, storage locations and material handling activity. Based on the inbound and outbound orders in the WMS, it generates a list of tasks that operators can follow to pick and place products in the right locations. The AGVs are controlled with software called FleetControl. FleetControl receives tasks from the WMS, divides the tasks over the AGVs, and returns task data to the WMS.

Wormer product flow

The VNAs in Compartments C and D are dedicated to the Wormer Flow. The processing plant in Wormer runs continuously and has no storage capacity, only a buffer. Therefore, it is essential

Table 1.1: Description and illustration of pallet handling equipment in Compartments C and D

	Reach truck		**VNA forklift**	
Used for	Transporting pallets between docks, pick and drop zone, shuttle racks, and VAL zone		Transporting pallets between VNA storage locations and pick and drop zone	
Control	Manual	AGV	Manual	AGV
Illustration				

that all products produced in Wormer can be stored in GVCL with minimal delays. Based on preliminary calculations by BBI, the Wormer product flow expects 425 pallets per day inbound. The AGV supplier estimated that one AGV can move around 16 pallets per hour, regardless of whether this is an in- or outbound move. GVCL management opted for integrating AGVs and manual equipment, allowing GVCL to have a consistent availability from the AGVs and reducing required labour costs but remaining flexible by manually upscaling capacity during peak hours. To further decrease material handling efforts, Automatic Truck Loading- and Unloading Systems (ATLSs) are used for the inbound process of the Wormer flow. Trailers are equipped with a chain conveyor such that pallets can slide out of the trailer onto a chain conveyor in the warehouse in one smooth motion. From this chain conveyor, pallets are scanned by a contour scanner to register the product in the warehouse. Each product with the same *lot number* is packed in the same manner and has the same quality. Outbound products are requested based on lot number, meaning that GVCL can select which pallet to ship, if multiple pallets with the same lot number are available in GVCL.

1.2 Research motivation

Client X faced multiple challenges with the Former warehouse, such as error-prone automation as a bottleneck, limited inbound capacity, and scalability, as the material flow of Client X is not perfectly streamlined. GVCL wants to overcome those challenges by using a combination of manual labour and AGVs to store and pick the products from the Wormer product flow. Within GVCL, there is little experience with using AGVs alongside manual workers in the same compartment. Management foresees challenges when assigning a task to an AGV or an operator, especially given the restrictions mentioned in the previous section.

Currently, no storage policy has been chosen for the Wormer flow and there is no strategy for allocating tasks to AGVs or manual operators. Given that a high level of automation will be present in the warehouse, there is high data availability. The ideal situation is that all information available is used to make the best decision possible for each activity in the warehouse. The warehouse activity should be organised such that as much work as possible is performed by the AGVs, in as little time as possible, to reduce labour costs and have good service times towards Client X. Ideally, this solution can also be implemented easily into the existing WMS.

1.3 Problem description and research goal

To efficiently operate the warehouse, the decision maker should consider if it is better to let an AGV or operator perform a pick or place task. The storage location assignment influences this decision: a pallet stored in a narrow aisle can be placed manually or automatically, a pallet can not be picked up by an AGV if it was placed manually. Management of GVCL is looking for a tactical policy to manage all the required handling operations and to efficiently operate the manual and automatic resources.

Action Problem

When the existing situation is not as it should be, i.e. there is a difference between the norm and reality perceived by the problem owner, this is an action problem (Heerkens & van Winden, 2017).

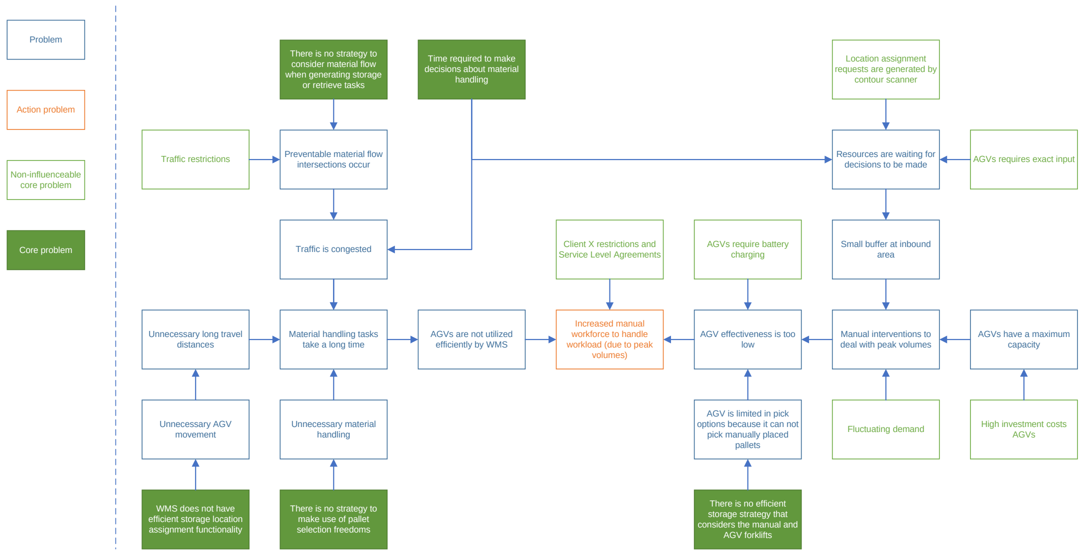


Figure 1.3: Problem cluster

The problem owner is GVCL. The norm is that GVCL can meet the demands from Client X as agreed per contract, but in the perceived reality there may be insufficient capacity to handle the inbound and outbound workflow. Therefore, the action problem is formulated as:

"Risk of insufficient capacity for handling the Wormer flow of Client X"

1.3.1 Problem identification

An observation study is conducted by interviewing stakeholders to understand the context and cause of the action problem. The WMS and Fleetcontrol functionality was investigated by analysing the contracts between the providers and GVCL. The design of the GVCL warehouse was examined by reviewing the floor plans and strategic and tactical decisions made so far. The problem cluster is shown in Figure 1.3. The risk of insufficient material handling capacity can be reduced in three ways: by redefining what is sufficient, as per the contract with Client X, or by using AGVs more efficiently, and increasing AGV effectiveness. Material handling time can be high due to missing efficient storage assignment functionality causing unnecessary AGV movement and long travel times. Not using the option to choose the best pallet from a lot number to pick can also increase the item pick time. High material handling time can be cause by traffic congestion and long decision times. Traffic congestion can be caused by insufficient consideration of the equipment requirements and restrictions. The lack of a storage strategy that considers the combination of manual operators and AGVs can reduce the options for AGVs to be able to do work, as an AGV can not pick a manually placed product. Fluctuating demand and a fixed AGV capacity can require manual interventions to handle peak volumes. The small buffer at the ATLS requires a quick location assignment for each pallet since an AGV can only pick up a pallet when given exact pick and place locations.

1.3.2 Core problem

Heerkens and van Winden (2017) describe a core problem as a problem that, when solved, can make a difference in the action problem. To select the core problem for this research, we consider the problems in the problem cluster which do not have a cause by themselves.

There are 8 non-influenceable core problems within the scope of this thesis. The influence on these problems is limited because this depends on the contracts or quality of external parties such as the AGV supplier or Client X.

By excluding the non-influenceable problems, five problems without identified cause remain:

- The WMS does not have efficient storage location assignment functionality;
- There is no strategy to leverage the freedom to pick any pallet from a lot number;
- There is no strategy to consider material flow when generating storage or retrieve tasks;
- There is no efficient storage strategy that considers the manual and AGV forklifts;
- Time required to make decisions about material handling needs to be low, to prevent unnecessary material handling delays.

Heerkens and van Winden (2017) advise to limit the number of core problems to solve, as it is better to solve one problem properly than to solve a multitude of problems only partly. Based on the restrictions in the new warehouse, we identify a relationship between the influenceable problems. Where and how a product is placed influences to how it can be retrieved. Solving the five influenceable problems together reduces unnecessary travel distance, time of material handling tasks, and improves the efficiency and effectiveness of the AGVs, therefore reducing the amount of manual workforce to handle workload.

By solving these problems, it is assumed that the solutions to each problem are more promising than solutions to the problems separately since we can formulate a well-aligned set of strategies. Leon, Li, Peyman, Calvet, and Juan (2023, p. 2) support this argument by noting the impact of location assignment decisions on other operational areas of the warehouse. They focus on storage location assignment whilst integrating routing planning and order fulfillment.

1.3.3 Research goal

The goal of this research is to present a solution to the GVCL action problem. This is done by solving the selected core problems. The research goal is:

> “To develop a storage location assignment policy and retrieval policy, considering task division between automatic and manual handling, that reduces the material handling and intersecting flow, under the given restrictions in the new GVCL warehouse.”

1.4 Research questions

The main research question is formulated based on the research problem.

> “How can GVCL assign a storage location to incoming pallets to ensure timely completion of all storage and picking tasks, considering the shared workspace between AGVs and human workers in the new warehouse?”

Sub-questions stated below have been formulated to answer the research question.

1. What is the required performance of the new GVCL warehouse?
   (a) What is the designed process flow of the internal logistics of GVCL currently?
   (b) What do the in- and outbound product flow look like?
   (c) Which are important KPIs for GVCL?
   (d) What is the desired performance on the KPIs for GVCL?
   (e) Which restrictions can we formulate based on the service level agreement and warehouse design?
2. What can literature tell us to help formulate an optimal material handling strategy for GVCL?
   (a) Which warehouse characteristics are relevant to this problem?
   (b) Which storage and retrieval methods are suitable in this situation?
   (c) How to evaluate and compare different strategies?
   (d) Which KPIs are used in literature?
   (e) Which restrictions are used in literature?
3. How can the storage location assignment policy in the GVCL warehouse be designed to have efficient and effective warehouse performance?
   (a) How can we model the Adaptive Storage Location Assignment problem and retrieval problem to represent the GVCL situation?
   (b) What input data do we need, and what is available?
   (c) How does the warehouse perform under basic policies?
   (d) How can a storage location assignment policy be formulated that considers the shared workspace requirements of humans and AGVs?
   (e) What are the differences between a basic policy and a newly formulated policy, and what are the main differences between the performance of these policies?
4. What can we conclude from the models and results?
   (a) What is the best policy we found?
   (b) What is the performance of this policy?
5. What is required for effective implementation of the proposed solution?
   (a) Which steps are recommended to implement the solutions?
   (b) Which possible complications exist?
   (c) Which solutions can we propose to overcome these complications?
   (d) Can we apply our solution to other situations?

1.5 Research scope

Managing a warehouse is a complex process in which many decisions must be made, described by Heragu, Du, Mantel, and Schuur (2005, p. 327) as 'interrelated decisions among the warehouse processes, warehouse resources, and warehouse organisations'. Due to time limitations, in this thesis, we cannot provide GVCL with advice on all decisions that can be made. Therefore, we need to set the scope of this research.

Recall the research goal: developing a storage location assignment policy that supports using of manual and AGV forklifts and reach trucks. This mix of resources only operates in Compartments C and D of the warehouse, and the AGV setup is specifically designed for the VNAs, with a well-defined purpose: storing the Wormer flow of Client X. Therefore, we limit our research of the working area of the AGVs, including the storage of the Wormer product flow. Other parts of the warehouse are out of scope, so the storage of the West Africa flow is not considered in this project. Furthermore, we define the scope to be the internal warehouse logistics, because Client X determines the inbound shipments from Wormer, and outbound orders are placed by Client X or their customers. We focus on how GVCL can handle this inbound and outbound demand. We research the internal logistics, from when products are inbound on the ATLS, until they are outbound at the shipping dock.

1.6 Approach

This chapter introduced the research by providing the reader with background information about the logistics of Client X and the operational setup of the GVCL warehouse. The new setup of GVCL using reach trucks and VNA forklifts, both in an AGV and manual variant raises questions about how to organise the internal logistics. The problem identification shows that GVCL currently has no strategy to deal with the new operational setup, the logistics of Client X, or implementation in the WMS. We formulated the research goal and questions to be answered to reach the research goal. Finally, the scope is defined to focus on the Wormer product flow of Client X, stored in the VNAs of Compartments C and D.

In Chapter 2, the reader is provided with the full context of the GVCL warehouse relevant to this research. Process flows are mapped by reviewing the design documents of the warehouse and discussing the process with the GVCL project manager and stakeholders such as the provider of the WMS. The complete functionality of Compartments C and D is discussed, including all restrictions to the storage assignment following the warehouse design and selected equipment. Supply and demand patterns are analysed using historical data. A literature review will be performed to answer research question 2. The literature review in Chapter 3 includes a warehouse classification and places the research problem into the context discussed in the literature. Approaches to the problem are assessed for suitability to our problem, and methods for comparing strategies are presented. To answer research question 3, we use findings from the context analysis and literature review (RQ 1 and RQ 2) to formulate requirements for the storage policy, which we use as a basis for a new storage policy suggestion. Chapter 4 proposes a solution to reach the research goal. In Chapter 5 we present the evaluation method for the proposed policy. The results are discussed in Chapter 6. We finish the research by providing GVCL with recommendations in Chapter 7. Here, we also discuss the practical and theoretical contributions, and finally, limitations and future research recommendations are included.

2 CONTEXT ANALYSIS

In this chapter, we discuss the context in which this research takes place. We begin by describing the old logistic organisation of Client X in Section 2.1. Next, we provide an overview of the requirements that Client X has for their logistic operations. This is followed by a description of the design of the new GVCL warehouse in Sections 2.2 and 2.3, followed by warehouse restrictions applicable to this new warehouse in Section 2.4. We describe the in- and outbound product flow in Section 2.5 by means of data analysis. Finally, we elaborate on the desired performance of the new GVCL warehouse in Section 2.6.

2.1 Client X operations background and requirements

The history of Client X operations and requirements is discussed in this section. We describe the challenges with the previous logistic operations of Client X that led to the decision to opt for the GVCL warehouse, which will help to understand their requirements and logistic activities. The requirements of Client X are a driver for warehouse management improvements.

2.1.1 Previous operational setup

Before the GVCL project initiation, the Client X logistics were already handled in the Netherlands. Gam Bakker was responsible for the product flow from Africa. They used shuttle racks and the storage policy was class 'attempted' based on lot number. Products are ordered based on lot number. The Former warehouse was responsible for the product flow from Wormer, NL. Here, products were stored in fully automated shuttle racks. Little information is available about the operations of the Former warehouse, because this company is not a partner in the new project. Past challenges that Client X encountered with the Former warehouse are bottlenecks caused by the inability of the automated system to handle errors. This led to delayed warehouse operations, disrupting the supply chain of Client X.

2.1.2 Client X requirements

Client X has selected GVCL as a third-party logistics provider for the outbound cocoa products from the production facility in Wormer, and cocoa powder from West Africa. Client X expects a solution that minimizes downtime and provides logistics solutions for unplanned challenges. Due to potential changes in the market or production facilities, scalability in volume and flexibility will be important aspects of the new setup. Other important criteria for Client X are operational efficiency towards the Wormer plant, cost efficiency, and commitment and contract terms. Finally, the storage facility must comply with the latest fire regulations and food safety standards.

2.1.3 Service level agreement

The contract with the client includes agreements which dictate the main decisions made in the design of the GVCL warehouse. The service level agreement (SLA) specifies the required performance of the warehouse activities, measured with performance metrics. Relevant performance metrics are further discussed in Section 2.6. During the planning phase, Client X and GVCL agreed that GVCL must handle on average 400 inbound pallets from the Wormer plant.

2.1.4 Product characteristics

Products are characterized by cocoa type and physical characteristics. Cocoa type is defined based on fat percentage, powder name, batch number and lot number. The cocoa type characteristics can be used to group products, as there is a relationship between the cocoa type and supply and demand. Physical characteristics are bag type (big bag, small bag), pallet type (block pallet or euro pallet), height- and weight of the unit load. All goods are palletised. A euro pallet and block pallet are both industry-standard pallet types, with fixed dimensions. Both pallet types can be picked up from all four sides. A euro pallet is 80×120cm and a block pallet is 100×120cm. In Wormer, products are produced in batches and after sampling, pallets from a batch are assigned to a lot number by Client X. One production batch contains several identical pallets: they share the same product code and packaging type. After sampling, each pallet receives a lot number. One batch can lead to multiple lot numbers, this depends on the product quality. Therefore the lot numbers only become known after production. GVCL is not informed about the production plans of Client X, only about the outcome: the lot numbers that are shipped to the warehouse.

2.1.5 Functional design decisions

In this subsection, we describe the solution approach GVCL used to design the new warehouse. This is visualised in Figure 2.1 There is no storage space at the production facility (1), only a buffer in the expedition zone. Customer X outsources the storage of products to GVCL. The factory of Client X runs 24 hours per day (4), so therefore a reliable warehouse is required (5). This GVCL warehouse has to adhere to the SLA described in the contract (6). Both the inbound and outbound activity is stochastic (2, 8), therefore the material handling capacity should be scalable (7). GVCL has no complete control over the transport decisions from the factory to the warehouse (3). Manual capacity is more flexible than AGV capacity (9). The incoming goods are not always stacked properly on pallets (10), but AGVs require well-defined and consistent products (11). Therefore, a fully automated warehouse has the risk of becoming blocked (12), e.g. when an overhang causes a bag to bump into a pallet rack, resulting in manual intervention needed. With these requirements, the decision to operate a hybrid warehouse (13) was made, where humans and AGVs can work together on material handling.

2.1.6 Conclusions

In summary, the description of the background of Client X's operations highlights logistical challenges that Client X experienced, which have led to requirements for their new logistics service provider. Client X expects GVCL to handle the flow of goods from West Africa and the Wormer plant, without causing excessive delays. Based on the external requirements, GVCL management has made design decisions about the warehouse layout, equipment selection, and process flow

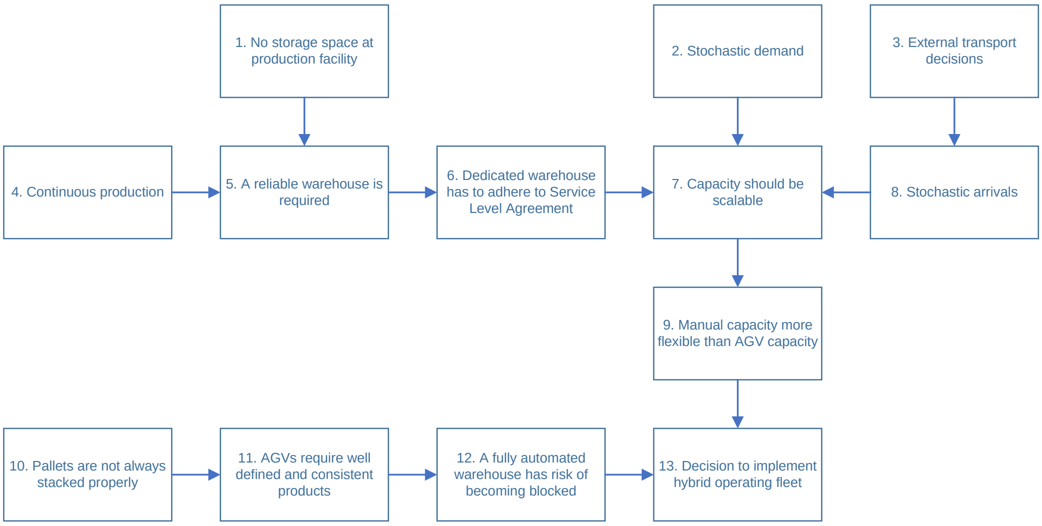


Figure 2.1: Overview of design decisions made for warehouse logistics

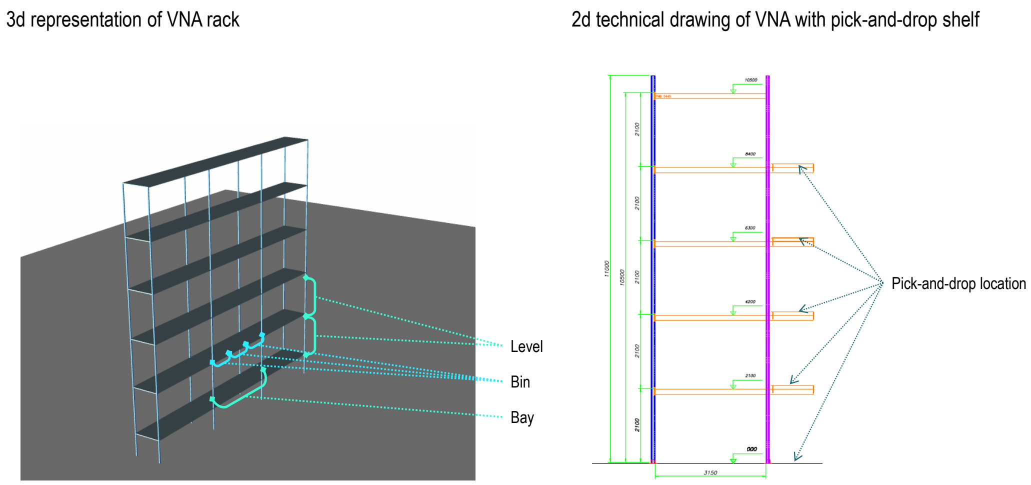
design. In the next sections, we provide the reader with details about the design decisions, identifying challenges with efficiency and performance that can be solved by addressing the research problems.

2.2 Resources and equipment in the warehouse

This section provides the reader with a detailed explanation of the storage locations in the VNAs in Compartments C and D and the material handling equipment that will be used for the Wormer flow. Remind from Section 1.1.2 and Figure 1.2 that compartment C and D have shuttle racks and VNAs.

2.2.1 Storage locations

GVCL has shuttle racking and VNA storage spaces. The scope of this research is the VNA area in Compartments C and D. The VNA storage system aims to reduce the required storage area by minimizing the aisle width between pallet racks. Gue, Meller, and Skufca (2006) say that narrow aisles increase space utilization, but can also lead to increased travel and congestion since the aisles do not allow order pickers to pass each other in the aisle, as there is no space to do this. A 2d and 3d representation of VNA racks is shown in figure 2.2. Each aisle in GVCL consists of two racks, on the right and left side of the aisle. The space on horizontal beams between vertical pillars is called a *bay*. Each position in a bay where a pallet can be placed is called a *bin*. A rack can store pallets on beams above other pallets. Each vertical layer is called a *level*. The end of each VNA rack has a *pick-and-drop shelf*, serving as an intermediate point between the reach trucks and VNA forklifts, as it can be accessed from the front and the side. Each level of the rack has a pick-and-drop shelf, except the top level.



Note. 2d figure adapted from technical drawing of material supplier.

Figure 2.2: Illustrations of VNA storage racks

2.2.2 Equipment to move pallets

A description and illustration of the vehicle types were given in Section 1.1.2. Recall that GVCL opted for vehicle setup with four different types: reach trucks and VNA forklifts, each in manual and AGV variants. These four equipment types will operate in Compartments C and D to handle the Wormer product flow. As can be seen in table 2.1, the manual equipment has a higher travel speed than the AGV system. The different load capacities do not cause challenges for the Wormer product flow, as the agreed-upon maximum pallet weight is 1,050 kg. The maximum speed of the VNA forklifts is reached only within the VNAs, where the forklifts are guided by induction lines installed in the floor surface of the aisles. A VNA forklift must come to a full stop at the end of the aisle before it can exit the aisle.

2.2.3 Equipment at expedition area

The expedition area is outfitted with special equipment to speed up the unloading process and to provide a reliable pickup point for the AGVs. The expedition area of the compartment is equipped with an Automatic Truck Loading- and Unloading System (ATLS), which is a chain conveyor. In GVCL, the ATLS efficiently unloads the shuttle trucks driving between the Wormer factory and the warehouse. Since the trailers are also fitted with chain conveyors, the entire truckload can be

Table 2.1: Technical details of reach trucks and VNA forklifts dedicated to Wormer product flow

	Manual reach truck	Manual VNA forklift	AGV reach truck	AGV VNA forklift
Load capacity	2,000 kg	1,160 kg	1,600 kg	1,200 kg
Max. load transfer height	10,800 mm	10,200 mm	9,900 mm	10,500 mm
Max. speed forwards	3.61 m/s	3.33 m/s	2.0 m/s	1.2 m/s
Max. speed backwards	n.a.	3.33 m/s	0.3 m/s	1.2 m/s
System availability	n.a.	n.a.	98% for whole AGV system	
Quantity for Wormer flow	4	4	4	4

extracted in one motion. The result is that the pallets in the load are received just like how they were loaded in the truck. At the end of the chain conveyor, pallets are automatically transferred one by one onto another conveyor. This conveyor carries the pallets to the contour scanner, which inspects the load and label on each pallet. If contour scanner accepts the pallet, it will be sent to the pallet-AGV pickup point. However, if the contour scanner rejects a pallet - due to issues such as improper stacking of the load or an unreadable label - the rejected pallet must be picked up and placed in the reject area.

2.2.4 Information management

The warehouse operations rely on several digital systems. The three primary systems are described in this subsection.

Warehouse Management System

All important warehouse information is stored in the WMS. The WMS used in GVCL offers most functionality required to efficiently manage a warehouse. Inbound products are registered in the WMS. The WMS can assign a storage location based on a simple decision rule. When a product is stored, the storage location is registered in the WMS. Customer orders can also be gathered in the WMS, and generate pick lists.

FleetControl

The AGVs are controlled by a system called FleetControl. Input to the FleetControl system is the warehouse layout, and tasks for the AGVs. Tasks are sent from the WMS to FleetControl, and contain a begin and end location, and pallet information. Based on the tasks in the FleetControl system, the FleetControl assigns these tasks to the AGVs. The AGVs move to the begin location, scan the pallet to check, and transport the pallet to the end location. The move is registered in FleetControl and fed back to the WMS.

Hand Scanners

Hand scanners show employees which tasks are available. Employees use the hand scanners to select a task, and register the work they do by scanning pallets and locations when they pick or place a product. This ensures that all activities are registered in the WMS.

2.3 Warehouse layout and process flows

In this section, we present the design of the green field warehouse of GVCL in the port of Amsterdam. Because this research only focuses on the Wormer flow, which will be stored in Compartments C and D, we provide a more detailed description of these compartments. Combined with the previous section, this section provides the answer to research question 1.a by describing the process flows of the internal logistics of GVCL.

2.3.1 Warehouse layout

The warehouse has two compartments designated for the Wormer flow. Refer to Figure 1.2 for general layout overview. The VNA area of each compartment consists of 15 aisles. Every aisle

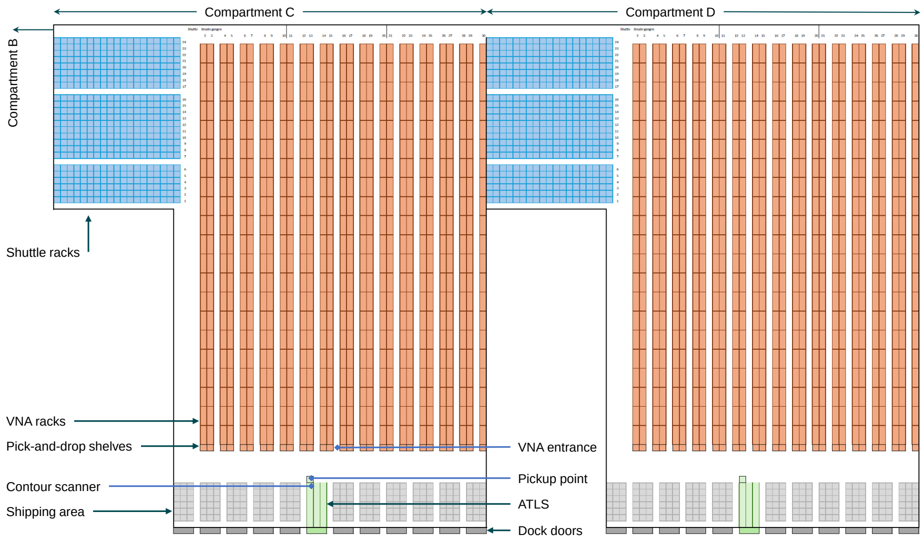


Figure 2.3: Important locations in Compartments C and D

has two racks, one on either side, except the first aisle, which only has a rack on the right side. Each VNA rack consists of a pick-and-drop shelf, followed by 21 bays. Each bay is 3.15 metres wide and 1.1 metres deep. A bay can be subdivided into three bins, each representing a pallet storage position. A bay can either store 3 euro pallets or 2 block pallets. If 2 block pallets are stored in one bay, there is not enough space left for a third pallet, effectively blocking a bin. The ATLS is positioned centrally in the shipping side of the compartment. The ATLS is followed by the contour scanner, after which the scanned pallets can be picked up. The position of the ATLS is shown in Figure 2.3. The VNAs are accessible from the expedition side of the warehouse.

2.3.2 Process flows

This subsection describes the movement of Wormer products through the warehouse and the resources used to accomplish this. We can divide the operations of GVCL into four processes: receiving, storing, order-picking and shipping.

The flowchart in Figure 2.4 shows the main activities required for the Wormer flow. The following process description will refer to the activities indicated by a number in the figure. Products are shipped from Wormer in trailers equipped with a chain conveyor. Trailers dock at the ATLS and unload the pallets onto the ATLS (0.1). The ATLS forwards the pallets through the contour scanner, which registers accepted pallets as 'inbound' in the WMS. After this, the pallets arrive at the pick-up point: a conveyor where pallets can be picked up one at a time. An AGV reach truck can pick up a pallet from the conveyor, and place it in a pick-and-drop rack (1.1). From the pick-and-drop rack, the pallet can be picked up by an AGV- (1.2) or Manual VNA forklift (2.2), to store the pallet in a VNA storage location. A pallet that needs to be shipped out is picked from the storage location by an AGV- or Manual VNA forklift (1.3; 2.3), and placed on the pick-and-drop rack. A pallet is moved from the pick and drop rack to the assigned dock of the outbound order, either by Manual- (2.4) or AGV reach truck (1.4). If all products of an order are collected at the dock, the products are checked and scanned. Once the trailer arrives, the products are loaded into the trailer, and registered as outbound in the WMS (0.3).

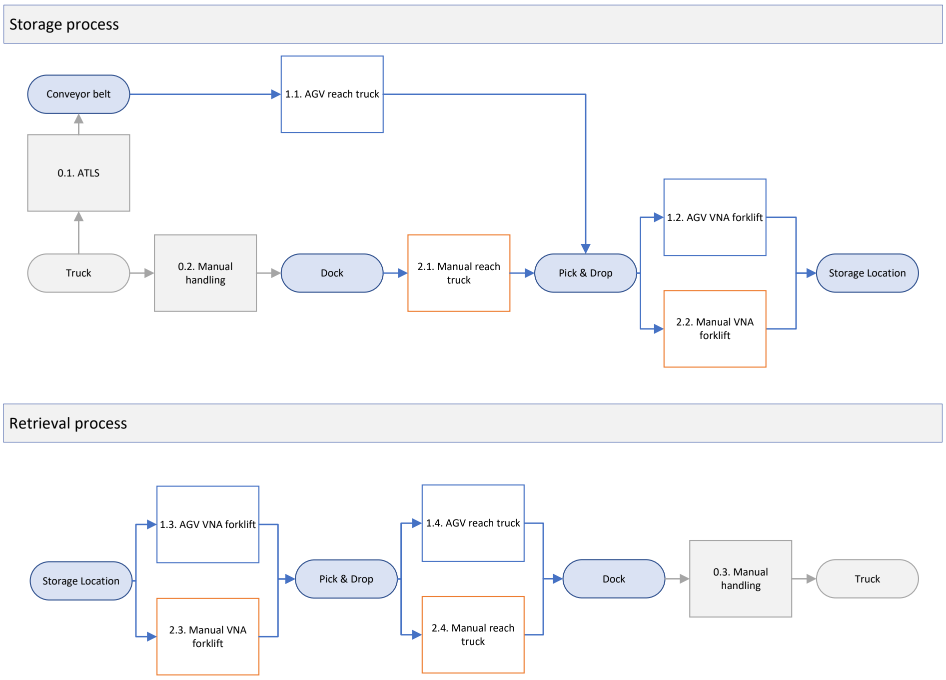


Figure 2.4: Wormer process flow overview divided per vehicle type

2.4 Warehouse limitations and restrictions

The previous sections in this chapter outlined the warehouse layout and processes, resources, equipment and operational requirements. Continuing from this understanding of the physical and functional warehouse setup, this section presents additional warehouse details about the operational setup of the warehouse, elaborating on the factors influencing warehouse decision-making.

2.4.1 Work weeks

The GVCL warehouse works two 8-hour shifts daily and is closed on Sundays. The Wormer production plant continues production while GVCL is closed, increasing expected inbound pallets on Mondays.

2.4.2 Product positions

For each inbound product, a location needs to be assigned. Most products will be on a pallet and registered as inbound at the moment they are scanned by the contour scanner. After that, the product has to be picked up by an AGV and moved to a storage location. Therefore, it is important that a product is assigned a storage location not long after it is accepted by the contour scanner, otherwise this will become a bottleneck.

Fire safety constraints impact the relationship between empty and occupied shelves in the warehouse. Where Mendes et al. (2023) mention constraints like ventilation or refrigeration constraints, product cell incompatibility (PCI) problems can also be caused by constraints such as fire safety and carrier type because not all pallet types fit all cell types. One fire safety measure in GVCL is the sprinkler system. The sprinkler system requires that pallets of equal width are stored in the same bin on each level. All pallets above or below each other should be the same pallet type.

2.4.3 AGV and manual shared workspace

An AGV cannot retrieve a pallet placed manually. This is a limitation in the accuracy of the manual operators, and the accuracy required by the AGVs to locate the pallet. This limitation applies to the reach trucks as well as the VNA forklifts. The AGV supplier requires that manual and AGV tasks are assigned to separate areas, with the separation at least at the aisle level. Only VNA forklifts can work in VNAs, moving pallets in other areas must be done by reach trucks. Pallets can only be picked up by AGV from the conveyor after contour scan. This restriction is set by GVCL management to prevent congestion caused by manual and AGV reach trucks attempting to access the same pickup location. There is no equipment restriction determining in which compartment the vehicles work. The four AGV reach trucks and four AGV narrow aisle trucks are all allowed to work in Compartments C and D. Covering the travel distance between compartments will cost time.

2.4.4 Data interface

The fleet of AGVs receives transport orders via an API interface and uses its decision rules to assign operations to specific AGVs. A transport order must contain exact pickup and drop-off locations in the warehouse. The existing WMS can only assign a location based on a simple decision rule. Outbound orders are placed based on lot number. Client X agreed that GVCL can decide which pallet of the requested lot will be fulfilled. For each inbound product, a location needs to be assigned. Most products will be on a pallet and registered as inbound at the moment they are scanned by the contour scanner. After that, the product has to be picked up by an AGV and moved to a storage location. Therefore, it is important that a product is assigned a storage location not long after it is accepted by the contour scanner, otherwise this will become a bottleneck.

2.4.5 Conclusion

Based on the complete warehouse description, we can formulate a set of restrictions that must be considered for the storage assignment policy, see Table 2.2. These restrictions show that deciding where to place a product can become a complex decision, especially if this decision needs to be made within a time window and also result in a convenient position to place and pick. The available product characteristics also show some opportunities to deal with product allocation in a smart manner, with the goal of achieving operational efficiency and effectiveness.

2.5 Data analysis

This section illustrates the product flows from the inbound- and outbound perspective, to answer Research Question 1.b. By quantifying the processes that influence GVCL, we can identify potential issues and solution areas. The available datasets span 2 years, from March 2022 to March 2024. However, information on lot numbers is only part of the dataset from May 2022. Therefore, in the remainder of this data analysis, we focus on the period from May 2022 to March 2024.

The outbound product flow is the flow from the warehouse to customers of Client X. Outbound data is provided by a contact person from Client X, who indicated that their data source is scattered

Table 2.2: Summary of restriction for storage location assignment decisions

Restriction	Description	Impact
AGV compatibility	A manually placed pallet can not be picked up by an AGV	Placing pallet manually limits options for picking
Fire safety compliance	Pallets on all levels of the same bin must be the same pallet type	Limited flexibility placing pallets. A pallet stored forces all shelf above and below that pallet to be empty, or the same pallet type.
AGV conveyor pickup	Pallets inbound via contour scan can only be picked up by AGVs	All inbound pallets form ATLS are placed in pick-and-drop automatically
AGV working zone	AGVs are assigned to VNAs as working zones. AGV working zones are prohibited for manual operators	Increased safety, reduced flexibility of resources.
Resource purpose	VNA forklifts can only move pallets between pick-and-drop and VNA storage locations, reach trucks can only move pallets between the expedition area and pick-and-drop locations	Resources only work in their specialized area

in different menus and requires multiple extractions and complications. Despite the conclusion that the outbound data relies on more assumptions and simplifications, it is decided to use this data to gain insight into the processes required for Client X. The pallet amounts are calculated based on the quantity ordered and the product weight on the pallet. Data contains order number, item number, item description, ordered quantity in metric tonnes, lot number (if known), and requested date.

The inbound product flow is the flow of products from the Wormer plant to the warehouse. Historic data on the inbound flow is collected from Gam Bakker, the current transportation partner of Client X. This data was retrieved from a database, and validated by Sander from BBI. We used this data because it is more detailed than the data received from Client X. Client X also provided a master dataset, which we can use to connect an item number to product information. The master data contains a description, production details, product type, how products are stacked on pallets, carrier type and weight on a pallet.

2.5.1 Product data

The data shows that a handful of products are responsible for the majority of the volume (pallet-wise). The frequency of the (anonymized) product codes is shown in figure 2.5. By grouping the inbound data based on product code and sorting based on their contribution to total inbound pallet volume, we see that 10% of the product types in the dataset are responsible for 56.6% of the inbound pallets. The next 20% is responsible for 26.7% of the inbound pallets. The final 70% of products are 16.7% of the inbound pallets.

2.5.2 Lot numbers

Products sharing the same lot number do not necessarily arrive all on the same day. 58% of the lot numbers arrive on one day, but it is not rare that a lot number arrives on two days (28%). This is illustrated in Figure 2.6. The size of each lot number greatly varies, as shown in Figure 2.8. The

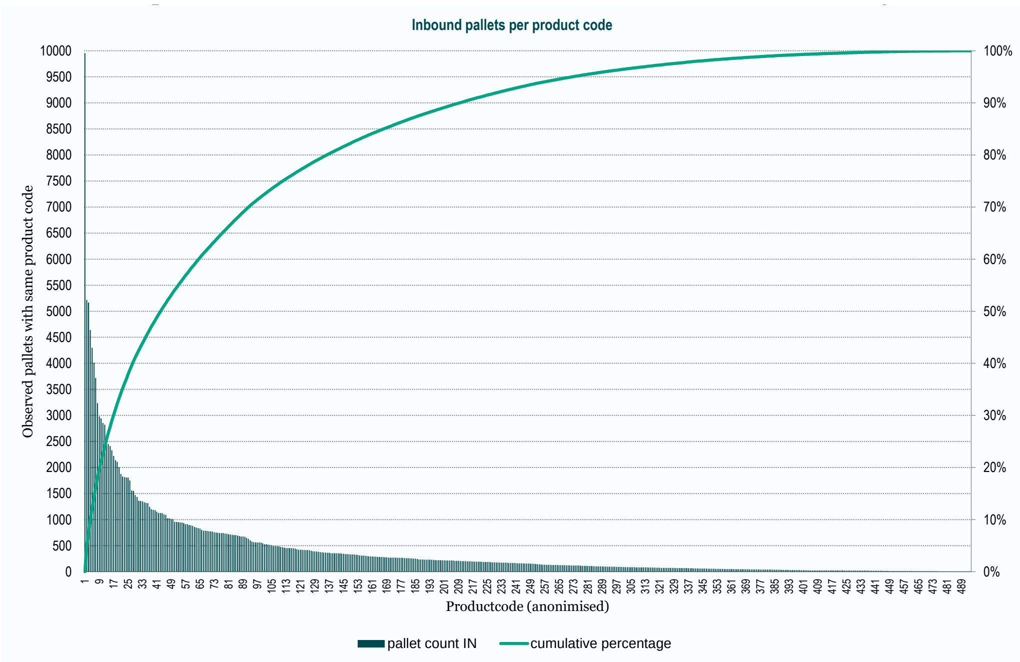


Figure 2.5: Frequency of product codes compared

most common quantity is 13 pallets per lot number. A reason for the variety in lot number size is that a production batch, which is already of variable size, can be further split up into multiple lot numbers, based on the sample quality. This depends on many variables within the Wormer plant, and there is no further information available about the logic behind lot number assignment.

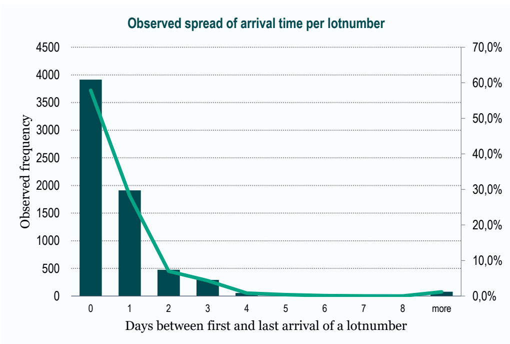


Figure 2.6: Overview of days between arrivals of lot numbers

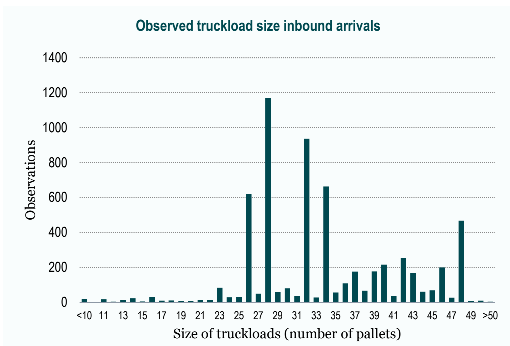


Figure 2.7: Observed quantity of pallets in trucklaods

2.5.3 Inbound product flow

The products are shipped by truck from the Wormer factory to the warehouse. The historical data represent the historic shipments from Wormer to the Former warehouse. These shipments were done by a variety of vehicle types. This subsection discusses the contents and composition of the truck shipments.

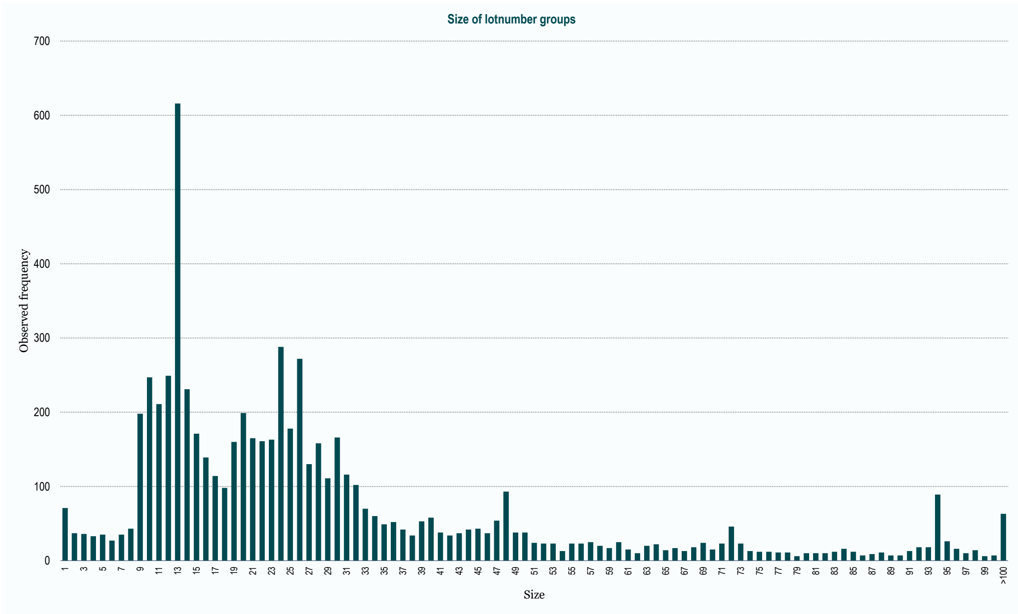


Figure 2.8: Size of lot number groups observed

Quantity in trucks

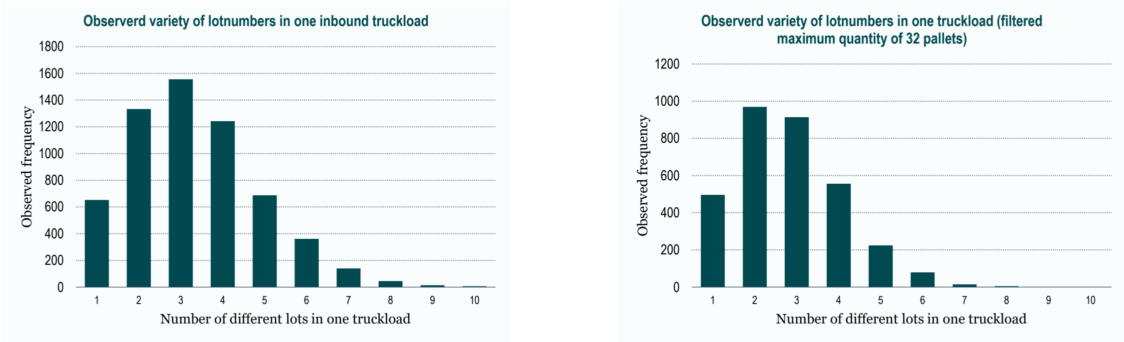
The shipments from Wormer to the former warehouse show a variety in truckload sizes. Six load sizes stand out and can be explained by describing the type of truck and pallet types in the truck. Two truck variants are most used by Gam Bakker: trailers and Longer Heavier Vehicles (LHVs). An LHV vehicle combination with a maximum length of 25.25 meters and a maximum weight of 60 metric tonnes (RDW, 2024). The LHVs used by Gam Bakker have a maximum allowed weight of 37,200 kg, whereas their trailers have a maximum weight of 30,000 kg.

This information, combined with the space available in each transport configuration leads to 8 maximum load configurations, based on pallet type and weight of the unit load, for space and weight restrictions respectively. Table 2.3 shows the maximum configurations per truck. These maximum load configurations can be seen in the historical data. Figure 2.7 shows the observed quantity of pallets per truckload, and the maximum load configurations are the most common.

In the new warehouse, only trailers will be used for the flow of Wormer products, because the trailers are outfitted with a chain conveyor system for the ATLS. LHVs can not be used for transport from the Wormer plant to GVCL. Therefore, the maximum number of pallets in a shipment depends on the carrier type. One trailer with a chain conveyor can carry a maximum of 26 block or 32 euro pallets. Given these boundaries, we are interested in the observed pallet types. Based on the inbound data, we see that 31% of the items come on a block pallet and 69% of the items on a euro pallet.

Content of trucks

Most trucks contain a mix of products. This is because the Wormer plant produces products with different lot numbers simultaneously, and the transportation crew selects groups of products available when trucks are loaded. Figure 2.9(a) shows that trucks contain between 1 and 10



(a) (b)

Figure 2.9: Number of different lot numbers in one truck: (a) observed data, (b) filtered data (max. 32 pallets per truck)

different lot numbers. This is a count of the unique lot numbers in each shipping document. The most observed number of lot numbers in a shipment is 3 lot numbers.

Filtering this data to fit within the boundary of 32 pallets maximum in a trailer, we see a reduction in lot numbers in each shipment. Figure 2.9(b) shows that most truck arrivals contain between one and six different lot numbers.

Inbound demand

The demand on the inbound process is analysed based on the quantity of pallets that arrive per day. The distribution of number of pallets per day is shown in figure 2.10. By plotting the difference in demand per day for each month, see figure 2.11, we can see that the distribution of busier and less busy days occur each month. If we omit may 2022 due to missing data, we can see that the median inbound pallets per month varies between 275 and 350 pallets per day. We also see the extreme days, for example in august 2023 there is a day where more than 581 pallets arrive. It is known that the factory of client X is continuously producing cocoa powder. However, the data shows that there are some days where 0 pallets arrive to the warehouse. This can be explained by comparing the data to the dates of the holidays. The data is limited to date as level of detail, there is no data available on the historic arrival times of the inbound trucks. Note that the average inbound demand of 285 pallets per day is lower than the agreed-upon 400 pallets per day. This

Table 2.3: Overview of maximum allowed content of inbound truck types, based on pallet type and weight

Vehicle type and pallets	Weight pallet	Reason
LHV (not used for GVCL)		
34 euro pallet	1050 kg	Maximum weight
48 euro pallet	750 kg	Maximum space
40 block pallet (bigbags)	700 to 900 kg	Maximum space
36 block pallet (LBs bags)	907 kg	Maximum space
Trailer		
28 euro pallet	1050 kg	Maximum weight
32 euro pallet	750 kg	Maximum space
26 block pallet (bigbags)	700 to 900 kg	Maximum space
23 block pallet (LBs bags)	907 kg	Maximum space

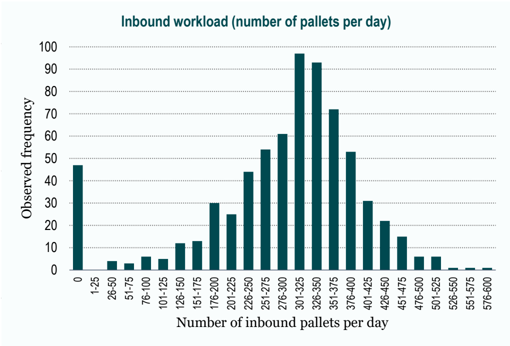


Figure 2.10: Observed workload per day expressed in number of inbound pallets

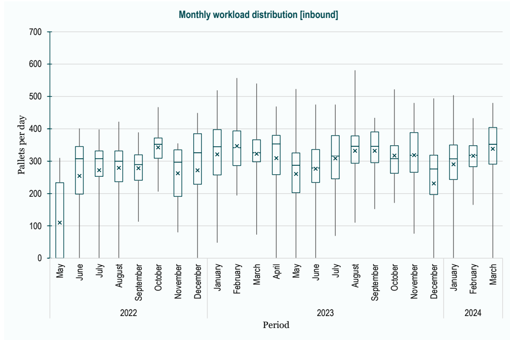


Figure 2.11: Distribution of workload on inbound pallets per day

difference depends on the production numbers of Client X. In this thesis, we assume that the increased production rate of Client X is in effect.

2.5.4 Outbound

The available historic data on the outbound demand are supplied by Client X, and consists of the historic order lines from the competitor warehouse to the customers of Client X. Some outbound orders are shipped in a trailer, and other orders are shipped in containers.

Length of stay

There is no data available per pallet about how long they are stored in the warehouse. By comparing the first date that a lot number is demanded outbound, and the last date that a lot number is received as inbound, we can see the minimum shelf life. Figure 2.12 shows the shelf life in number of weeks for the lot numbers. This data shows that the length of stay of lot numbers is rarely less than a week, and most often at least three weeks. Note that these observations only include the minimum length of stay.

Demand

The outbound demand per day can be retrieved from the order lines by summing the number of pallets ordered per day. Figure 2.14 shows that the outbound demand is spread out between days with 0 pallets demand and the maximum observed demand was 1286 pallets on one day. Note that on 50% of the measured days, the outbound demand is between 450 and 900 pallets daily. In Figure 2.14 the daily outbound demand is shown in a monthly boxplot. Each month has days with zero outbound demand and occasional busy days with demand for more than 800 pallets per day.

The data analysis shows a discrepancy between the inbound and outbound product flow in terms of average numbers. With this data, it looks like more products are requested from- than sent to the warehouse. Multiple reasons are causing this difference. First, the sources from the two datasets are different. The outbound data lacks information about the origin of the products, whereas the inbound data strictly covers products from the Wormer factory. Secondly, the processes rely on external factors, such as market forces influencing the cocoa price, thus influencing

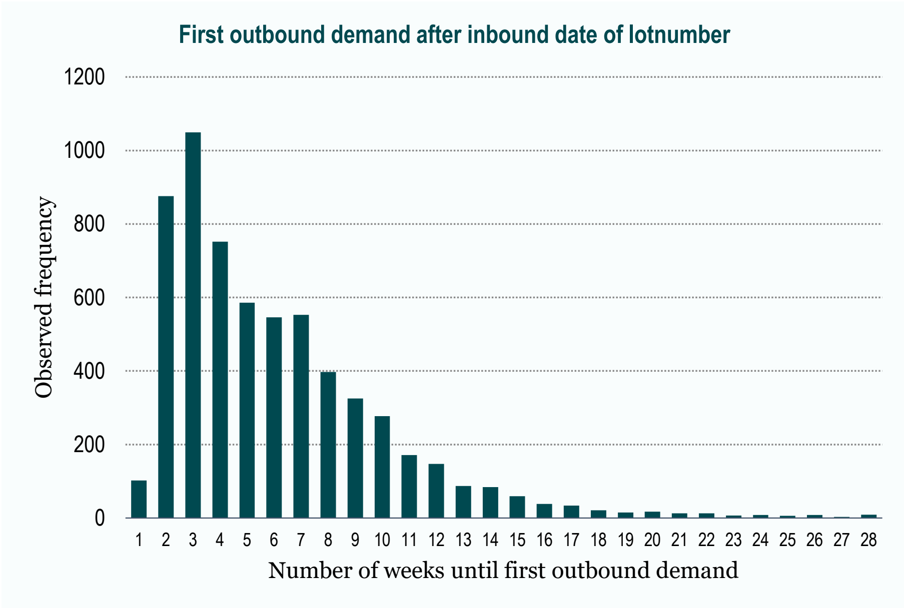


Figure 2.12: Observed minimum length of stay per lot number

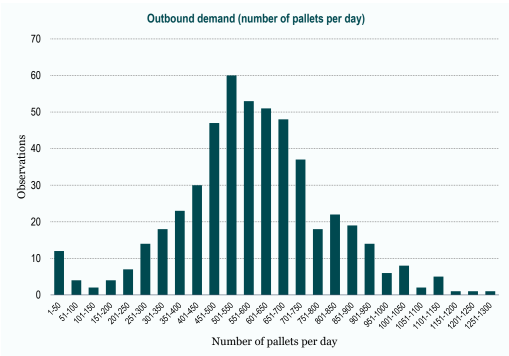


Figure 2.13: Observed outbound demand expressed as number of pallets per day

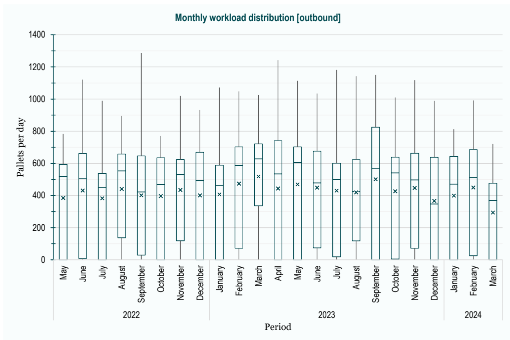


Figure 2.14: Distribution of workload on outbound pallets per day, omitted days with 0 demand

the production and order demand numbers. A third reason is the aforementioned less reliable data of the outbound data, as it is based on more assumptions than the inbound data.

The number of pallets with the same lot number, i.e. the size of the lot, impacts the number of outbound orders it is included in. The larger the lot size, the more outbound orders it appears in. This is shown in Figure 2.17, which shows that as the lot size increases, the number of appearances in outbound orders also increases. Figure 2.16 shows that up to 15 pallets per lot number, most lot numbers appear on one outbound order, which means that the whole lot is outbound in one order. As the lot size increases, the chance of being outbound in one order decreases. 30.52% of the lot numbers with a maximum size of 15 pallets appear in only one order. For lot sizes larger than 15, this is only 16.07%.

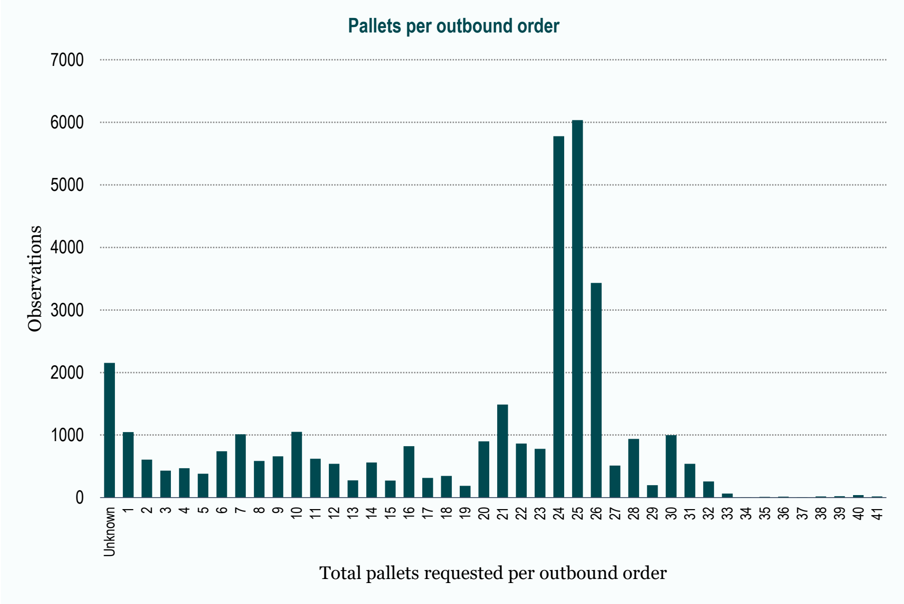


Figure 2.15: Observed number of pallets per outbound order

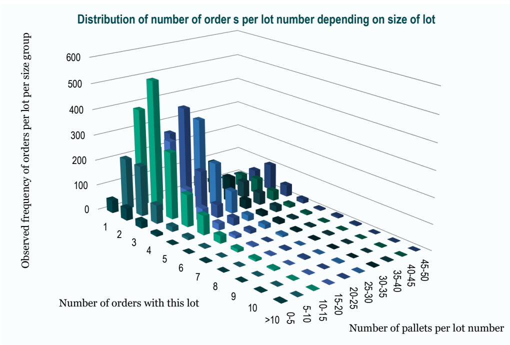


Figure 2.16: Number of observations of outbound orders per lot size group

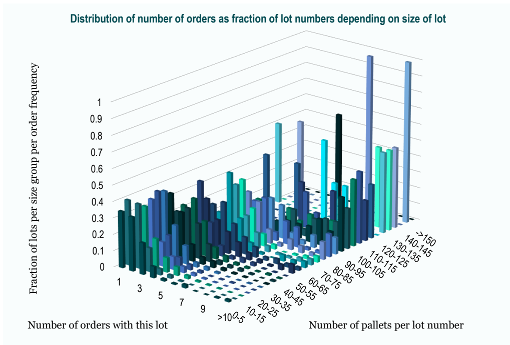


Figure 2.17: Larger lot sizes appear on more outbound orders

2.5.5 Daily workload

By combining the inbound and outbound demand per day, we can see the total workload expressed as the number of storage and retrieval tasks per day. Refer to Figure 2.18 for a distribution of the total daily workload per month. The boxplot shows that the average daily workload per month varies between 500 and 800 pallets. On peak days, more than 1600 pallet moves are required historically. Assuming the increased average of 40 pallets inbound per day, these peaks can become even larger. Based on the data provided by the AGV supplier, a setup with an AGV VNA forklift and AGV reach truck can handle an average of 16 loads per hour, and with ideal load cycles up to 20 loads per hour, assuming no charging. That means that an AGV can handle $16 \times 16 = 256$ loads per day, or $20 \times 16 = 320$ loads per day. With four AGVs that means an ideal capacity of $20 \times 16 \times 4 = 1280$ pallets per day. The warehouse will not have perfect demand spread over the day, but experience peaks, for example when inbound trucks arrive at the same time, or peak demands in outbound volumes. Optimal play cycles can also not be guaranteed, as this depends on the balance between inbound and outbound demand, and the location assignment of the pallets. Charging and maintenance of the AGVs further reduces the capacity of the AGV setup. Four AGV VNA forklifts is not sufficient to handle the peak demands. Therefore, GVCL uses manual operators to handle the peak demands.

Figure 2.18: Distribution of daily workload per month, combined inbound and outbound flow

2.5.6 Data analysis conclusions

With the data analysis we can answer research question 1.b: what do the in- and outbound product flow look like? Based on the historic data and agreements between Client X and GVCL, we expect a mean input of 400 pallet per day for the Wormer flow. We used historical data to identify how products are produced and shipped from the Wormer plant, and how the customers of Client X order products. We can use the data combined with information about the new warehouse, to formulate the expected in- and outbound product flow for GVCL.

- Between 1 and 6 different lot numbers are present in one inbound truckload.
- Lot numbers are assigned to groups of 1 to 100 pallets, the most common lot number size is 13 pallets.
- Most outbound orders demand 25 pallets.
- The historical average daily workload is storing and picking 713 pallets. The daily workload fluctuates and GVCL can expect peaks of 1600 pallets per day.
- Using the purchased AGVs (4 VNA forklifts and 4 reach trucks) will be insufficient to handle the workload on busy days.

2.6 Requirements from GVCL management

Management of GVCL has no predetermined performance evaluation methods. It is known that the operations in GVCL should be efficient and effective, which we can influence by how products are assigned a location. Effectiveness is important because GVCL is responsible for completing its tasks as a third-party logistics provider for Client X. Key Performance Indicators (KPIs) can be used to manage and evaluate operations. Comparing performance of different KPIs gives managers an insight into the warehouse performance, and to adjust operations if performance is not as desired. In this section, we focus on KPIs that can be influenced on an operational level.

2.6.1 Order picker efficiency

Efficiency is important because considerable investments were made to build and equip the new warehouse.This means that management wishes to use resources optimally, reducing costs, minimizing time spent on tasks, and reducing delays. The manual operators and the AGVs need to be productive. Efficiently using these costly resources ensures that GVCL is a profitable business. Order picker efficiency is determined by the time an order picker spends on a storage or retrieval task. The goal is to keep this time at a minimum. The efficiency of the VNA forklifts (applies to both AGVs and manual) is also influenced by how often the VNA forklift has to change between aisles.

2.6.2 Warehouse effectiveness

Where efficiency increases profits, effective operations ensure that goals are met in the first place. Effective operations help GVCL reach its goal of being a reliable logistics service provider. The storage policy influences the waiting times at the docks, and thus whether or not the agreed-upon unloading time and delivery time are met. This in turn influences effectiveness, as these are service-level aspects.

2.6.3 Material handling restrictions

As elaborated in section 2.4, there are many restrictions which influence the operations in the warehouse. The policy must consider the material handling, traffic, and information restrictions, and make the best possible decisions under these limitations. This can be tracked by assessing how often a restriction is violated, counting how often a pallet must be retrieved manually from an aisle assigned to AGVs.

2.6.4 Practical aspects

There are some practical aspects which must be considered. First, an aisle must be reserved for either manual or AGV activities. It is known that manual operators prefer knowing in which aisle they are not allowed to work. Therefore, it is preferred to make the aisle assignment known at logical moments, for example before the start of a shift, or before the start of a workweek. Secondly, manual operators prefer that they understand the logic behind their work, to some extent. An example could be that the operator is instructed to store a batch of one product type in the warehouse according to a random assignment per pallet, even though the operator sees an aisle in which there is space to store the whole batch together, which would be less work for them.

In this decision, the illogical decision should be prevented, or it should be clear to the operator why this decision was made. The storage policy must produce up-to-date storage assignments. The storage assignment must fit in the current state of the warehouse, and adjust according to the current expected workloads. Due to the process design of the GVCL warehouse, incoming pallets need to be assigned a location in the warehouse in a matter of seconds. It is inefficient if a pallet that is ready for pickup at the contour scanner first has to wait for an algorithm to run for a long time to determine the optimal location of the pallet. Therefore, a fast method is required. Inbound goods from the Wormer production plant are pre-announced when a truck departs to the warehouse. This pre-announcement contains information on the products in transit, which takes around half an hour until delivery. This pre-announcement can be used as a trigger and input to calculate a predetermined storage assignment for all unit loads in transit and assign this to the product as soon as they are registered as inbound in the GVCL warehouse.

GVCL management is not looking for an optimal solution, but a good solution. A good solution is generated in a timely manner, and assigns products to reasonable locations, such that it fits within the restrictions, and allows the warehouse to operate efficiently and effectively.

2.6.5 Selected KPIs

Based on the analysis of the warehouse design and requirements from management, we formulate a set of KPIs that are influenced by the storage policy and have to be maximized or minimized. The summary of KPIs is shown in Table 2.4. Eight KPIs are included, divided into three categories based on the requirements. This list of important KPIs answers research question 1.c. The desired performance on the KPIs is not made explicit by GVCL management. For each KPI, Table 2.4 shows whether this KPI must be minimised or maximised. There is no baseline performance available since the warehouse does not have a performance history.

Table 2.4: Overview of KPIs determining GVCL performance

KPI	Abbreviation	Description	Objective
Order picker efficiency			
Ratio of aisle changes	RatioAisleCh	Fraction of aisle changes required by NA-equipment per total moves	Min.
Average store time	AvgStoreT	Average time spent per pallet to store it, from the moment it is inbound at the contour scanner until it is placed in a storage location	Min.
Average retrieve time	AvgRetrieveT	Average time spent per pallet to retrieve it, from the moment the pick order is released, until it is placed on the outbound dock	Min.
Warehouse effectiveness			
Dock to stock time	AvgDockToStockT	Time to complete storing all products from one truckload, from arrival of the truck until storage time of last item in truck.	Min.
Shipping time	AvgShippingT	Time to complete picking all products from one order, from order release time until end of pick time of last item in truck.	Min.
Ratio products stored with AGVs	RatioStoreAuto	Fraction of products stored by AGVs	Max.
Ratio of products picked with AGVs	RatioPickAuto	Fraction of products picked by AGVs	Max.
Restrictions			
Ratio of traffic violations	RatioTrafficFault	Fraction of storage or pick tasks completed that violated the aisle assignment	Min.

2.7 Conclusions

The context analysis was carried out to answer Research Question 1. The descriptions of the old situation, the requirements from Client X, and the new GVCL warehouse design provide context about the challenges that GVCL experiences with operating a hybrid fleet in Compartments C and D of the warehouse. The process flow explains how the warehouse design leads to the question how to store the incoming goods to optimally use the available equipment. The product flow analysis shows that using manual labour in the warehouse is required during peak periods. We identified the important KPIs for GVCL. The most important performance measures are how long trucks have to wait to load or unload at GVCL, the average pick and place times, and the fraction of work done by the AGVs in the warehouse. The constraints of the AGV setup, requirements from Client X and GVCL management, combined with the dynamic inbound and outbound demand profiles have shown us that the decision of where to store the incoming pallets can become a complex decision. These insights into the operations of GVCL will be used for the selection of a suitable storage location assignment selection, which we discuss in the literature review in Chapter 3 and policy proposal in Chapter 4.

3 LITERATURE REVIEW

In this chapter, we review the literature to help us formulate our research in a conceptual framework. Section 3.1 discusses the relevant warehouse characteristics. In Section 3.2 we provide context for the problem classification. In Section 3.3 we discuss possible solution methods used in literature. KPIs used in literature are discussed in Section 3.4.1, and evaluation methods in Section 3.5. We conclude the chapter by highlighting the gap in the literature and the solution approach for the research problem.

3.1 Which warehouse characteristics are relevant to this problem?

By answering Research Question 2.a we know which warehouse characteristics are relevant to this problem. This can help us identify the situation, and connect the problem in practice with scenarios described in the literature.

3.1.1 Warehouse type

GVCL is located near the Wormer plant of Client X, and it stores incoming raw goods which can be transported to the plant, and finished goods awaiting distribution. Following the role identification of Frazelle, we can classify the GVCL warehouse as a raw-material and overflow warehouse (Frazelle, 2015). The compartments in the scope of this research are only serving as an overflow warehouse, as only produced goods are stored here. GVCL is a third-party service provider, therefore warehouse is a contract warehouse (Frazelle, 2015). The warehouse is dedicated to a single user, Client X.

The warehouse compartments C and D have around 15500 m^2 of combined area, the functions include receiving, put-away, and order picking of goods for distribution and therefore fits in the warehousing (w) functional criterion (Onstein, Bharadwaj, Tavasszy, van Damme, & el Makhloufi, 2021), but it also includes storage and VAL. Based on these characteristics, it is classified as a manufacturer DC facility in the new typology of Onstein et al. (2021). Given the area of the warehouse and the functions it fulfils, we can see that Onstein et al. (2021) have found around 300 warehouses in the Netherlands which have similar characteristics. They emphasize that, given the differences within this size category, the category still covers different facility types, which each deserves a tailored spatial policy. In this research, we are not focused on spatial policies, but this does indicate that there exist similar warehouses in the Netherlands and that different warehouses require different approaches in management.

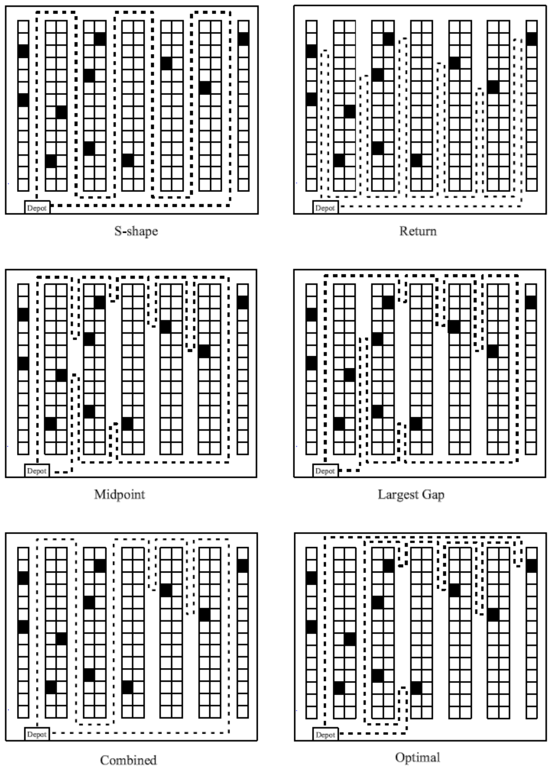


Figure 3.1: Example routing methods for a single-block warehouse layout (Roodbergen, 2001, p. 36)

3.1.2 Product and process characteristics

Since there is a strong relationship between the product- and process characteristics, these will be considered together. According to Park (2012); Ang, Lim, and Sim (2012), the storage system can be classified as a unit load storage system, since it stores large loads such as full pallets. In a unit-load warehouse, each pallet is handled separately at a time, and one pallet carries one product type (Ang et al., 2012). The order picking system that will be used in the GVCL warehouse is picker-to-stock: the picker rides to the pick location to retrieve items (Park, 2012). In this context, a picker can be an AGV, or operator on a manual forklift. Park (2012) concludes that the most important principle in this context is considering put-away, storage, and order-picking simultaneously in both design and operation.

3.1.3 Routing

The routing of pickers, i.e. manual operators on a forklift, or AGVs, is a well-discussed topic in literature. The VNAs in a compartment of GVCL can be viewed as a layout with one block (Roodbergen, 2001), because it is a set of aisles with a cross aisle on both ends of the aisles. Roodbergen (2001, p. 32) places routing policies into two categories: optimal algorithms and heuristics. While there exist optimal routing policies for block layouts, heuristics might be preferred in some cases, as they are easy to understand or implement. Roodbergen (2001) highlight the most common routing policies for one-block layouts, see Figure 3.1. A limitation in the GVCL warehouse is that forklifts can only change aisles on the cross-aisle between the VNAs and the expedition area. Therefore, the return routing policy is most applicable.

3.2 Problem classification

This section places the problem at hand into a theoretical context. The research field of warehousing has discourse on several storage location assignment-related problems. By identifying how the research problem aligns with operational research problems in the literature, we can identify suitable solution strategies. We start this section broadly by discussing the basics of the storage location assignment problem. Next, we specify the adaptive storage location assignment problem variants. Finally, this section provides a contextualisation of this research problem.

3.2.1 Storage Location Assignment Problem (SLAP)

A common problem in the field of warehousing is the storage location assignment problem (SLAP). This problem concerns the ideal assignment of products to storage locations in the warehouse, under certain constraints and with an objective, such as minimizing costs or maximizing efficiency. Mendes, Bolsi, and Iori (2023) describe the SLAP as a variant of the Assignment Problem where a set of objects must be assigned to a specific position in a storage area. Gorbe, Bódis, and Botzheim (2020) emphasize that Storage Location Assignment methods allocate products to picking positions, and the aim is to optimize effective order picking.

In their literature review, Reyes, Solano-Charris, and Montoya-Torres (2019) mention that solving the SLAP optimizes the material handling costs or storage space utilization. Leon et al. (2023) warn that isolating the product assignment to a storage location, as commonly done in evaluations of the SLAP, can result in an overall drop in warehouse efficiency because other operational areas of the warehouse are not considered.

Our problem is similar to the SRLAP-HF formulated by Ballestín, Ángeles Pérez, and Quintanilla (2020). The main similarities are the presence of heterogeneous forklifts and restrictions on the working zone. The difference is that our problem must consider the impact of the storage decision, effectively setting constraints for the retrieval decision. Our type of heterogeneous fleet is also different: GVLC has AGVs and manual vehicles, which have different working speeds, while Ballestín et al. (2020) assumes all forklifts work at the same speed. Additionally, GVCL must consider the cooperation between reach trucks and VNA forklifts. Our situation is not deterministic, and in- and outbound orders can arrive throughout the day.

The static storage location assignment can be modelled as a quadratic assignment problem (Kübler, Glock, & Bauernhansl, 2020). In the quadratic assignment problem (QAP), it is implied that the amount of products to assign to a location is equal to the number of available locations (Kübler et al., 2020). In practice this is not the case, as the warehouse is not at full capacity, and locations are left unassigned to be available for new product arrivals.

In the reviewed literature we see that research is often focused on finding a suitable policy based on one specific restriction, or a simplified scenario where the constraints are relaxed, or where warehouse, equipment, or product variety is reduced. However, as shown in section 2.4, there are restrictions in the warehouse that cannot be ignored in practice. Paying attention to the restriction with a certain level of detail is crucial in order to effectively and efficiently operate the warehouse.

3.2.2 Adaptive Storage Location Assignment (ASLA)

The GVCL warehouse has a dynamic demand profile, the inbound and outbound flows of products are relatively dynamic in the planning horizon (Accorsi, Baruffaldi, & Manzini, 2018). Where the

SLAP typically assigns products to locations from scratch (Chiang, Lin, & Chen, 2011, p. 220), in the scope of this research the focus is on assigning a location to newly arriving products, into a warehouse where other products already occupy some storage locations. In (Accorsi et al., 2018; Chiang et al., 2011; Tsamis, Giannikas, McFarlane, Lu, & Strachan, 2015) this is called adaptive storage location assignment. In adaptive storage location assignment, the optimal location to store goods is determined upon entry into the system (de Puiseau, Nanfack, Tercan, Löbbert-Plattfaut, & Meisen, 2022), and is especially relevant in the context of fluctuating demand patterns, as Kübler et al. (2020) describe.

The storage location assignment problem and the *adaptive* storage location assignment problem aim to minimize the total picking time, for which the total travel distance is often used as a metric. Li, Moghaddam, and Nof (2016) state that long-term strategic inventory control decisions, such as the storage location assignment policy may be inefficient or non-optimal due to the uncertainty and dynamicity associated with warehousing operations. However, when considering the storage location assignment when a product enters the warehouse, this can be classified as an operational management decision. Decisions made on the operational level are made under the predetermined constraints following strategic and tactical management decisions and are generally more narrow and short-term (Berg, 1999, p. 752).

Several papers discuss the ASLA problem, each with a specific warehouse setting or objective. Chiang et al. (2011) aim to reduce the number of times a picker needs to enter an aisle by using an adaptive approach. They use a rectangular warehouse with single-deep aisles. Furthermore, they assume an S-shape picking tour, single commands, and order picking with a first-come-first-served policy. Li et al. (2016) describe a case of the ASLA problem that they call the Dynamic Storage Assignment Problem (DSAP), where truck arrivals containing different quantities of product types must be assigned to a storage location. They use a single layer rectangular shaped warehouse and assume that the number of products that need allocation is equal to the number of available storage locations. Accorsi et al. (2018) propose an ASLA policy for temperature-sensitive products, assuming unit loads which are single SKU. Their problem formulation has two decision variables, determining whether the product is stored in a storage location or buffer location. They also use a bi-objective function, considering efficiency in terms of total travel for picking, and safety in terms of temperature stresses experienced by the products. Ballestín et al. (2020) combine the storage problem with a retrieval problem linked to the use of different forklifts, a so-called *heterogeneous fleet*. The heterogeneous fleet implies that not all forklifts can reach all storage locations safely. The authors consider the objective of minimising the workload, i.e. the total time spent storing and retrieving a set of pallets.

The subsection shows that different studies cover ASLA policies for specific warehouse settings, considering equipment types, warehouse layouts and product constraints. Considering the dynamic demand profile that GVCL deals with, and the fact that incoming products need to be assigned a new location, we need to find a suitable ASLA policy. The following subsection provides a full problem classification that places the research problem into the literature context.

3.2.3 Research problem contextualisation

This subsection shows similarities and differences between the ALSA problems addressed in the literature.

Demand type

Gorbe et al. (2020) emphasize that repositioning items is a labour-intensive activity. They propose a storage location assignment method that is continuously applied via the WMS during the 'picking position replenishment' (Gorbe et al., 2020, p. 611). In the GVCL setting, each pallet is stored and picked as a unit load. Applying the conceptual framework of Gorbe et al. (2020) in this context would mean evaluating the best storage positions of all incoming pallets at the moment they are registered in the WMS. Li et al. (2016), Guo, Chen, Du, and Yu (2021) and Accorsi et al. (2018) also consider a storage problem that must assign each incoming item to one storage location, and each location can hold at most one item.

Some studies assume that the amount of items that to be assigned to a location is equal to the amount of available storage spaces and formulate it as a QAP, see for example Li et al. (2016). Other literature, such as Chiang et al. (2011) do not use the assumption of equality between the number of open spaces and items to assign to a location.

Similarities with AS/RS systems

A well-known automated system for warehousing operations is an automatic storage/retrieval system (AS/RS). We follow the description by Groover (2015, p. 319) to describe an AS/RS. An AS/RS consists of aisles which are equipped with storage/retrieval (S/R) machines (Groover, 2015). The AS/RS is a fixed-aisle system, meaning that each aisle in the automated warehouse is operated by one S/R machine. The S/R picks and delivers items to the input/output stations, which are referred to as pickup-and-deposit stations (P&D stations) in AS/RS terminology (Groover, 2015). The main difference between an AS/RS and the ART/AWT setup in the GVCL warehouse is that the AWT are not fixed to one aisle. An AWT can move to a different aisle, using a cross aisle, to perform storage and retrieval tasks. Because an AWT can leave an aisle, the aisle could be occupied with an order picker operating a VNA-forklift instead. A similarity between the two systems is that the input/output stations are used as P&D stations, in the GVCL warehouse located on one side at the end of each aisle.

Picker types

Ballestín et al. (2020) consider a warehouse with multiple forklift types and address the storage problem with a retrieval problem. GVCL also has to consider multiple forklift types, namely automatic and manual equipment, reach trucks and narrow aisle trucks. In Ballestín et al. (2020) not all forklifts can reach all locations based on the level and depth of the storage location. In GVCL, different limitations play a role in the problem formulation:

- Storage locations can only be accessed by VNA equipment, so they need to use a pick-and-drop station at the end of the aisle.
- Products placed by an operator cannot be picked up with an AGV, due to accuracy limitations.

Warehouse layout

Similar to the SRLAP-HF problem introduced by Ballestín et al. (2020), GVCL deals with the safety constraint that each forklift must work alone in a sub-working zone. They define a subworking zone as a section of an aisle with an entrance, so an aisle with two cross aisles is divided into two subworking zones. For safety reasons, they allow a maximum of one forklift at a time into a subworking zone. The difference is that each aisle in GVCL only has one cross aisle, hence the whole aisle is considered a working zone, effectively limiting the flexibility of the working area of equipment in GVCL.

Objective function

In the generic formulation of the static SLAP, provided by Leon et al. (2023), the authors specify that the cost function can be a metric or combination of metrics deemed important by warehouse management. This generic formulation can be adjusted the ASLA problem taking into account multiple planning periods (Kübler et al., 2020), whilst maintaining the liberal definition of the cost function. This can be seen in how other papers approach the ASLA. Li et al. (2016) use the objective of minimising the travel distances of order pickers. Kübler et al. (2020) but extend the objective function of minimizing total travel distance by including a measure for relocation effort (changing the storage location of products). This measure depends on the distance between the restoring locations, administrative effort, and time required for the retrieving and storing activity. Other literature uses the minimization of pick time or travel distance with the addition of warehouse-specific considerations. For example, Accorsi et al. (2018) assign incoming items to available storage locations based on minimizing travel distance for picking and minimizing the temperature stresses experienced by the perishable goods.

Literature justifies using a detailed objective function depending on important warehouse aspects according to management. This is achieved by expressing the warehouse activities through cost, time or effort.

Complexity

Several authors have re-evaluated the ASLA problem to deal with the complexity. Ballestín et al. (2020, p. 1714) prove that their SRLAP-HF problem is NP-hard, and introduce a decomposition into sub-problems to solve sequentially. Xu, Lim, Shen, and Li (2008) model a deterministic storage assignment problem and show that it is NP-hard. They propose a heuristic method is solve the deterministic problem and transform it into an online algorithm to solve the stochastic variant of the problem. These papers confirm the conclusions from Berg (1999, p. 759), who say that most warehousing problems are NP-hard, which is a motivation for using heuristics to use heuristic approaches.

Conclusions

To conclude this subsection, we define a research category for our research problem, adding to the literature by helping compare the type of problem at a glance. The problem is to assign a storage location to incoming products in a unit load warehouse. The warehouse is random because each pallet can technically be stored anywhere, except in positions where it does not fit. This product fit constraint can be called Product Cell Incompatibility (PCI), adapted from Mendes et al. (2023). Our problem is constrained by the functionality of AGVs and accuracy constraints when a pallet is placed by a manual operator, which can be generalized as Heterogeneous Fleet constraints. We deal with an *Adaptive Storage Location Assignment Problem in a Heterogeneous Fleet warehouse with Product Cell Incompatibility* ($ASLA$-HF-PCI) in a unit load random warehouse.

3.3 ASLA solution methods

Several methods exist to assign storage locations to incoming goods. In operational research, a distinction can be made between mathematical models to find exact solutions, approximation techniques, and simulation models.

3.3.1 Exact solutions

Many papers about ASLA start by describing the problem set as a mathematical Linear Programming (LP) model. An LP has a linear function of decision variables that we aim to minimize or maximize, this is known as the objective function (Winston, 2004). The decision variables must also satisfy a set of constraints, which are linear equations or inequalities (Winston, 2004) and each decision variable has sign restrictions.

3.3.2 Approximation techniques

Researchers have used different approaches to find near-optimal, or approximate, solutions to the ASLA problem. Based on a case study or theoretical warehouse, researchers formulate a model that represents the goals of the ASLA and use different techniques to find solutions that result in feasible and near-optimal solutions.

Genetic algorithms

Li et al. (2016) formulate the problem as a QAP and develop a genetic algorithm (GA) to handle the computational complexity. A genetic algorithm is a metaheuristic which can search for good solutions. A GA is population-based, meaning that it consists of a population of potential solutions (Li et al., 2016). The solutions are encoded in chromosomes, and new generations, consisting also of feasible potential solutions, is based on the good traits of the previous generation. The good traits are found by calculating a fitness value for each individual, which is based on the objective value function of the QAP (Li et al., 2016).

Biased randomized heuristic

The biased randomized heuristic (BRA) is adapted from a greedy ABC heuristic, and used by Leon et al. (2023) to solve the SLAP. The idea is that items are sorted based on pick frequencies (descending), and locations sorted based on travel distance to depot (ascending), and instead of matching these lists 1-to-1 as storage assignment solution, the BRA applies a skewed probability distribution to the task of selecting the items (Leon et al., 2023). They introduce a simulation heuristic (simheuristic) framework. With this method, the study can consider an integrated approach to embrace the complexity of the problem, and us simulation to to reduce the effect of stochastic events (Leon et al., 2023).

Epsilon constrained method

In storage situations, locations have to be assigned under contradicting objectives. For example, Accorsi et al. (2018) discuss a bi-objective policy which aims to maximize efficiency by minimizing travel distance and to maximize safety by minimizing the temperature stresses on the perishable goods. In this example, the bi-objective model is solved using the ε-constrained method to get an approximation of the Pareto front (Accorsi et al., 2018). This approximation can then be used to choose between the trade-off of the two objectives. In the example, a rolling time window index is used to assign a weight to the objectives, as it is assumed that the importance of the objectives is variable depending on seasonal factors, in this case, the weather (Accorsi et al., 2018).

Deep reinforcement learning

Some authors have implemented a deep reinforcement learning approach to solve the storage location assignment problem. Troch, Mannens, and Mercelis (2023) define a Markov decision process in the context of a warehouse. They formulate a reinforcement agent that optimises a product layout by swapping item positions, starting from a random layout. de Puiseau et al. (2022) develop a reinforcement learning approach that deals with the dynamic storage location assignment and assigns new pallets to a zone (following the ABC classification system).

3.4 KPIs in literature

If we want to implement new policies in the warehouse, we must know how these policies will influence the performance of GVCL. In this subsection we describe KPIs used in literature that are used for testing policies and warehouse designs, to answer research question 2.d. Staudt, Alpan, Mascolo, and Rodriguez (2015) provide an overview of performance measures used in warehousing, with a focus on the operations of the warehouse. The purpose of performance analysis is to help managers to evaluate the performance of the business and to make decisions based on this (Staudt et al., 2015, p.1).

3.4.1 Type of measures

KPIs can be organized based on what they measure, which can be either time, quality, cost or productivity (Staudt et al., 2015). If KPIs can be calculated with a ‘simple’ equation, they are called hard KPIs, and if they are more based on managers’ perceptions, they are called soft KPIs (Chow, Heaver, & Henriksson, 1994). Staudt et al. (2015) use the term direct measure for hard metrics and indirect measure for soft metrics.

3.4.2 KPIs discussed per dimension

Staudt et al. (2015) classify direct KPIs in four warehouse dimensions: time, quality, cost, and productivity. Table 3.1 shows an overview of direct indicators classified based on the warehouse dimensions and activities boundaries, which can help understand the context in which the KPIs are relevant, based on the classification of Staudt et al. (2015).

- **Time** related KPIs track the time of activities. Examples are: receiving time, put-away time, dock-to-stock time, or order lead time.
- **Quality** related KPIs track the extent to which the performance meets customer expectations and requirements. Quality indicators can be classified into five groups: punctuality, completeness, correctness, breakage and customer satisfaction. Examples are: storage accuracy, stock-out rate, shipping accuracy, and on-time delivery.

Table 3.1: Direct indicators in dimensions and activities framework

Dimensions	Activity - Specific Indicators					
	Receiving	**Storage**	**Inventory**	**Picking**	**Shipping**	**Delivery**
Time	receiving time	putaway time		order picking time	shipping time	delivery lead time
Quality		storage accuracy	physical inventory accuracy; stock-out rate	picking accuracy	shipping accuracy; orders shipped on time	delivery accuracy; on-time delivery; cargo damage rate
Cost			inventory cost			distribution cost
Productivity	receiving productivity		inventory space utilization; turnover	picking productivity	shipping productivity	transport utilization
Dimensions	**Process - Transversal Indicators**					
	Inbound Processes			**Outbound Processes**		
Time	Dock to stock time			Order lead time		
	Global= Queuing time					
Quality				Order fill rate, Perfect orders		
	Global= Customer satisfaction, Scrap rate					
Cost				Order processing cost		
	Global= Cost as a % of sales					
Productivity				Outbound space utilization		
	Global= Throughput					

Note. Adapted from Staudt et al. (2015, p. 15)

- **Cost** related KPIs track all financial aspects of the warehousing activities. We note here that cost related KPIs are a less popular metric compared to the other three dimensions (Staudt et al., 2015). Chow et al. (1994) explain that this is primarily due to the fact that this aspect is incorporated in decision makers customer-oriented approach and that profitability is reached by fulfilling customer needs, i.e. by performing well in the other three dimensions. Additionally, major cost components are part of strategic level decision making, whereas most warehousing activities are in the operational management level (Staudt et al., 2015, p. 10) Examples are: order processing costs, inventory cost, direct labour costs, and distribution costs.

- **Productivity** related KPIs track the level of utilization or resources, or how well resources are combined to achieve goals. Productivity is described as the ratio of input-output. Examples are: inventory space utilization, picking productivity, and outbound space utilization.

3.4.3 Dealing with multiple relevant KPIs

Decision-making between comparable alternatives when there is one objective can be straightforward, as it is best to choose the alternative that scores best on the objective. When managers decide between alternatives, there are often multiple objectives to consider. To make a decision when multiple objectives are present, one can use the Analytical Hierarchy Process (AHP) to make a decision (Winston, 2004, p. 785). Vaidya and Kumar (2006) describe how AHP uses pairwise comparison to assign a weight to each measurement and can be used for both quantitative and qualitative measures.

3.5 Evaluation techniques

It is important to test new policies before implementation, as this reduces the risk of implementing an inefficient or ineffective policy, wasting time and effort. Testing the new policy in the real system is not possible and not desired, the system is currently under construction, and testing in the real system will take a lot of time to gather the required data for evaluation. In this section, we answer research question 2.b by discussing how to evaluate and compare different strategies.

To evaluate how different storage policies influence the behaviour of a warehouse system, we need to measure the impact of the strategies on the key performance indicators. Real measuring of the implemented policies is not feasible for this study because implementing methods and measuring the performance in real life would take too much time and is infeasible as this would also impact the service level to the client. Hence, this section provides an overview of methods to analyse the impact of new storage policies in a warehouse system.

3.5.1 Analytical modelling

Analytical modelling is a way to measure the expected warehouse performance. A set of equations that represent the system or problem instance is called an analytical model (Chiadamrong & Piyathanavong, 2017). Analytical modelling requires simplifying assumptions to ensure that the system can be represented in the form of equations to compute the performance. Additionally, Silver, Pyke, and Thomas (2017) illustrate that management must develop a single measure of output that represents the performance metric and describes the system performance.

Gu, Goetschalckx, and McGinnis (2010) describe two main categories of analytical models used for storage systems: aisle-based models and integrated models. For aisle-based models, queueing models have been developed (Gu et al., 2010). The authors conclude that, although many travel time and performance models exist for warehouse systems, each model requires a specific set of assumptions and simplification steps, and therefore there is no unified approach.

3.5.2 Simulation

Simulation can be an effective method to test policies before real implementation. “A simulation is an imitation of the operation of a real-world process or system over time” (Banks, Carson, Nelson, & Nicol, 2005, p. 2). A simulation model is used to study the behaviour of a system as it evolves and is based on a set of assumptions about the system operations (Banks et al., 2005). A simulation model can be seen as an abstraction of reality (Law, 2015, p. 496), but with a sufficient level of detail such that the model outputs provide an estimate of the system behaviour.

Simulation types

Two well-known types of simulation are continuous simulation and discrete-event simulation. In a continuous simulation time passes continuously, just like in the real world. When you follow a part through a system, you will not detect leaps in time (Mes, 2021).

On the other hand, in a Discrete Event Simulation (DES), state variables describe how the system evolves over time. In DES, variables only change when an ‘event’ occurs, and the state of the system changes instantaneously (Law, 2015, p. 6). In DES, the program can jump over the moments in time which are not of interest (i.e. where nothing happens), and only consider actual events (Mes, 2021).

Use of simulation in optimization

There are different ways to use simulation in optimization. Leon et al. (2023) use DES as a method to calculate the objective value of a potential solution and use this result in a heuristic which iterates over several potential solutions, until a good enough set of potential solutions is acquired, or until the stopping criterion is reached. The set of best potential solutions is then simulated for more replications, which results in statistics that indicate the performance of the solution (Leon et al., 2023). The authors have coined the term 'simheuristics' to describe this approach (Leon et al., 2023).

Simulation is also used as a means to evaluate new interventions. Ha and Jiang (2023) model a warehouse in Python to evaluate their new algorithm that optimizes cube storage using a GA. Here, they use the simulation to test the performance of the new policy and to compare this to other storage methods which are also simulated. Jiao, Xing, Zhang, Xu, and Liu (2018) use FlexSim to evaluate their multi-objective storage location allocation algorithm. Pierre, Vannieuwenhuyse, Dominanta, and Dessel (2003) have developed a dynamic ABC heuristic. Since it is not a result of a mathematically optimal solution, but a solution based on a heuristic, they test the effectiveness by testing the outcomes in a simulator, in this case via a simulation constructed in Matlab.

3.6 Conclusions literature review

The literature has shown that there are no policies known to consider the allocation of resources to specific locations, the restrictions imposed by the AGV system, combined with the adaptive nature of the warehousing process in GVCL. We place our problem into the framework by considering the heterogeneous fleet and product cell incompatibility, so we call this instance of the adaptive storage location assignment $ASLA$-HF-PCI in a unit load random warehouse. Solutions from the literature differ in the objective, often only minimizing travel distance, or differ in warehouse type. We are dealing with a unit load warehouse with AGVs and manual vehicles, and have to assign a storage location to incoming products adaptively. Based on the literature review, we organize this thesis as follows. Due to complexity, the MILP we will formulate cannot be solved to optimality. In Chapter 4 we propose a two-stage approach, in line with Ballestín et al. (2020), Chiang et al. (2011) and Tabrizi, Vahdani, Etebari, and Amiri (2023), and the requirements from GVCL. We use a simulation study to assess the performance of the proposed algorithms. The AHP described by Winston (2004) will be used to compare the simulated performance on the different objectives important to GVCL management.

4 ADAPTIVE STORAGE POLICY FOR HYBRID PICKER FLEET

In this chapter, we discuss adaptive storage location assignment policies which might be suitable within the scope of this research in GVCL. We highlight the relevant problem context in Section 4.1. Next, a mathematical formulation of the problem is provided in Section 4.2. Section 4.3 introduces policies that could be used in GVCL to assign storage locations to incoming products. In Section 4.4 we provide a decision-making framework following the AHP approach.

4.1 Problem context

The goal of this research is to find a storage policy that fits the specific warehouse characteristics, where we focus on efficient operation of the hybrid fleet and the freedom to select a product from based on a lot number. The warehouse design phase has already finished, and the material handling equipment has been selected. However, there is room for designing the operational policies within the warehouse.

This research focuses on warehouse Compartments C and D, which will store the cocoa powder flow from the Wormer factory. It is preferred to let all inbound material handling activity is done with AGVs. The first reason is that the incoming trucks can be automatically unloaded by means of the ATLS in dock C and D. The second reason is that storing a product with an AGV allows the flexibility to pick the pallet either with an AGV or manually. The AGV performance is heavily influenced by manual traffic. Therefore, it is restricted to mix traffic, meaning that a storage aisle in the warehouse can be only operated by manual operators, or AGVs, but not both. A point of interest is to analyse the effect of the time-window of this separation. Theoretically, as soon as an aisle is empty, either an operator or AGV can enter the aisle. Stakeholders believe that it is preferred change the assignment of automatic or AGV per aisle to at most on a daily basis.

4.2 Mathematical formulation

In this section, we present the mathematical formulation of our problem, based on the formulation by Ballestín et al. (2020), with the necessary adjustments to fit the GVCL problem. In this model, we assume two forklift types: AGV and manual. We do not include the pick-and-drop level of detail, a task from inbound to storage, or storage to outbound is considered one action. We assume that each pallet inbound will not be outbound in this timeframe. Ballestín et al. (2020) are not explicit about the time horizon. In our model, it must be solved for each time horizon in which inbound and outbound orders are known. For example, the expected trucks from Wormer and trucks to pick up orders are known each morning. Our objective is also different. The standard model from Ballestín et al. (2020) solves for the minimum ’flow time’, but we are interested in maximizing order picking efficiency, and warehouse effectiveness while respecting material handling restrictions and other practical aspects important to GVCL management.

4.2.1 Model

Ballestín et al. (2020) use the term *order* to define ’storing or retrieving one pallet’. In Ballestín et al. (2020), each order consists of two elements: whether it is a storage or retrieval order, and the pallet type that must be stored or retrieved. In our model, we expand this definition. In our model, each operation belongs to an inbound or outbound truckload, a set of pallets that comes in or goes out of the warehouse. Therefore, we define each ’order’ as $o_i = (p(o_i), S/R(o_i), Tr(o_i), Lot(o_i), r_l)$. $Tr(o_i)$ indicates which truckload the operation belongs to. Each order in a truckload has the same release time.

The objective function 4.1 incorporates the average storage time, retrieval time, and required aisle changes to track resource efficiency. It also tracks the time to complete inbound and outbound orders as a whole, and the fraction of tasks performed by AGVs. The objective function incorporates the KPIs formulated in Table 2.4. Each KPI is assigned a weight, representing the importance of the KPI.

Indices

$h = 1, ..., a$	number of aisles
$i = 1, ..., n$	number of operations to perform
$j = 1, ..., m$	number of storage locations in the warehouse
$k = 1, ..., nf$	number of forklifts
$k^{AGV} \subset k$	subset of forklifts that is of the type AGV
$t = 1, ..., T$	time index
$l = 1, ..., L$	number of truckloads to serve

Variables

$x_{ijk} = 1$ if operation i is performed in location j by forklift k, 0 otherwise

$f_{ijkt} = 1$ if operation i is performed in location j by forklift k and finishes at time t, 0 otherwise

$a_{hv} = 1$ if aisle h allows forklifts of type v in this aisle, 0 otherwise

$s^k_{ht} = 1$ if forklift k is in aisle h at time t, 0 otherwise (support variable)

$ct^{Tr}_l =$ the completion time of storing/retrieving all products belonging to one truckload

$v_i = 1$ if operation i if performed by a forklift in the set k^{AGV}, 0 otherwise

Constants

$b_{ijk} = 1$ if operation i can be performed in location j by vehicle k, and 0 otherwise

$c_{ijk} =$ time required to perform operation i in location j by vehicle k

$d_{jh} = 1$ if location j is in aisle h, and 0 otherwise

$p(o_i)$ The pallet that must be stored or the type of pallet requested in o_i

$Lot(o_i)$ The lot number of order o_i

$$S/R(o_i) \begin{cases} 1, & \text{if } o_i \text{ is a storage operation} \\ 0, & \text{if } o_i \text{ is a retrieval operation} \end{cases}$$

$Tr(o_i)$ Indicates which truckload the operation o_i belongs to

r_l The release time of all orders in truckload l

Objective function

$$\begin{aligned} \text{min. } z = & \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{nf}(\alpha_1 \frac{1}{\sum_{i=1}^{n} S/R(o_i)} c_{ijk} S/R(o_i) x_{ijk} \\ & + \alpha_2 \frac{1}{\sum_{i=1}^{n}(1 - S/R(o_i))} c_{ijk}(1 - S/R(o_i))x_{ijk}) + \alpha_3 \sum_{k=1}^{nf}\sum_{t=1}^{T-1} ac_k t) \\ & + \beta_1 \sum_{L}^{l=1}(ct_l^{Tr} - r_l) S/R(o_i) + \beta_2 \sum_{L}^{l=1}(ct_l^{Tr} - r_l)(1 - S/R(o_i)) \\ & - \beta_3 \sum_{i=1}^{n} v_i S/R(o_i) - \beta_4 \sum_{i=1}^{n} v_i (1 - S/R(o_i)) \end{aligned} \tag{4.1}$$

Constraints:

$$\sum_{j=1}^{m}\sum_{k=1}^{nf} x_{ijk} = 1 \qquad \forall i \tag{4.2}$$

$$\sum_{i=1}^{n_i}\sum_{k=1}^{nf} x_{ijk} \leq 1 \qquad \forall j \tag{4.3}$$

$$x_{ijk} \leq b_{ijk} \qquad \forall i, j, k \tag{4.4}$$

$$x_{ijk} \leq a_{h_j v_k} \qquad \forall i, j, k \tag{4.5}$$

$$\sum_{t=1}^{T} f_{ijkt} = x_{ijk} \qquad \forall i, j, k \tag{4.6}$$

$$f_{ijkt} = 0 \qquad \forall i, j, k, t = 1, ..., r_{Tr(o_i)} + c_{ijk} - 1 \tag{4.7}$$

$$\sum_{j=1}^{m}\sum_{i=1}^{n_i}\sum_{q=t}^{t+c_{ijk}-1} f_{ijkq} \leq 1 \qquad \forall k, t \tag{4.8}$$

$$\sum_{j=1}^{m}\sum_{i=1}^{n_i}\sum_{k=1}^{nf} d_{jh} \sum_{q=t}^{t+c_{ijk}-1} f_{ijqk} \leq 1 \qquad \forall h, t \tag{4.9}$$

$$\sum_{h=1}^{a} s_{kt}^{h} = 1 \qquad \forall k, t \tag{4.10}$$

$$s_{kt}^{h_j} \geq f_{ijkt} \qquad \forall i, j, k, t \tag{4.11}$$

$$ac_{kt} \geq s_{kt}^{h} - s_{k(t+1)}^{h} \qquad \forall k, h, t \tag{4.12}$$

$$ct_l^{Tr} \geq t \cdot f_{ijkt} \qquad \forall i \in l, \forall j, k, t \tag{4.13}$$

$$v_i \geq f_{ijkt} \qquad \forall i, j, t, \forall k \in k^{AGV} \tag{4.14}$$

$$x_{ijk} \in \{0, 1\} \qquad \forall i, j, k \tag{4.15}$$

$$f_{ijkt} \in \{0, 1\} \qquad \forall i, j, k, t \tag{4.16}$$

$$a_{hv} \in \{0, 1\} \qquad \forall h, v \tag{4.17}$$

$$s^k_{ht} \in \{0, 1\} \qquad \forall h, t \tag{4.18}$$

$$v_i \in \{0, 1\} \qquad \forall i \tag{4.19}$$

$$cl^{Tr}_l \geq 0 \qquad \forall l, Tr \tag{4.20}$$

Constraint 4.2 ensures that each pallet is stored exactly once, 4.3 ensures that at most one pallet is stored in one location. An operation can only be performed if the pallet fits and the vehicle can pick up the pallet 4.4. Constraint 4.5 prohibits actions that the forklift cannot do due to aisle classification and placement. Each operation has exactly one finish time 4.6. Constraint 4.7 ensures that at least c_{ijk} time units have to pass after the release of the orders from truckload $Tr(o_i)$ before an operation i can finish. Constraint 4.8 prohibits each forklift from performing more than one operation at a time. Constraint 4.9 ensures that at most 1 operation can be performed in an aisle at a time. Each forklift k is assigned to one aisle at each time t, see constraint 4.10. With constraint 4.11, the spot of the forklift at time t belongs to the location j of the operation assigned to the forklift at time t. If the aisle where the forklift k works at time $t + 1$ is different than at time t, set the aisle change variable to 1 with constraint 4.12, to track the number of aisle changes. Constraint 4.13 sets the support variable ct^{Tr}_l to represent the completion time of the last finished task of that order. Constraint 4.14 tracks the support variable v_i to represent whether an AGV or operator finished the task. Constraints 4.15 to 4.20 ensure that all variables have the correct sign, and distinguish whether the variables are binary or integers.

The use of c_{ijk} is limited to the extent that it considers an operation's start and end point. This formulation also assumes an AGV blocks only the aisle of the storage location. It omits that reach trucks travel between pick-and-drop stations. However, this model could represent GVCL under the assumption that a reach truck and forklift act as 'one'.

4.2.2 Complexity

As Ballestín et al. (2020, p. 1714) have proven, their mathematical model for the SRLAP-HF can be decomposed into a number partitioning problem, which is NP-Hard. This means that solving the problem exactly is infeasible for a large scenario. Our formulation introduced more complexity by adding more variables and using multiple objectives in the objective function. Similar to the approach of Ballestín et al. (2020), we recommend decomposing the problem into sub-problems which are solved with heuristics. The performance of the heuristics will be assessed with a discrete event simulation study.

4.3 Proposed adaptive storage policy for hybrid picker fleet

Our context analysis and literature review have revealed that:

- It is preferred to separate vehicle types on aisle level.
- It is preferred to store products with an AGV.

- Mathematically solving the problem to optimality is infeasible.

The MILP problem is known to be NP-hard, which means that it can not be solved to optimality in polynomial time, but in the context of GVCL, storage assignment decisions are required in a limited timeframe. Therefore, mathematically solving the storage assignment problem to optimality is not desired. Moreover, the warehouse does not require optimal solutions, but a storage assignment that allows for manageable workloads and good performance. In literature, we have seen that subdividing the warehousing problems into multiple stages can yield acceptable solutions to implement in practice, recall the three-stage heuristic for clustering, storage, and joint-online order batching method from Tabrizi et al. (2023), and three-stage data mining storage assignment approach from Chiang et al. (2011). Ballestín et al. (2020) also introduced a multistage heuristic for dealing with a $SRLAP - HF$ problem.

Given these descriptions, we choose to implement a two-stage heuristic. We connect the two stages to two moments in the storage process. The first stage of the heuristic determines the aisle allocation (manual or AGV) at the start of each period, e.g. each morning. The second stage of the heuristic determines where to store the pallets for each incoming shipment, given the equipment restrictions set during the first stage of the heuristic. We suggest two policies tailored to the two-stage heuristic in the GVCL scenario and additionally describe reference policies that can be used to compare the performance.

4.3.1 First stage policy: Occupation Based Resource Assignment

This first stage policy aims to classify each VNA and assign either AGV or manual VNA forklifts to VNA classes of the VNAs.

This policy uses the fraction of utilised storage spaces per VNA (occupation ratio) to assign each aisle to a resource type, hence we call it *occupation based resource assignment*. This algorithm aims to determine which aisles can handle the most inbound workload by assessing the occupation ratio. Based on the occupation ratio, we assign each aisle to one of three classes: full, empty, mix. Full aisles, which contain most pallets, receive priority for picking. The empty aisles have the most open spaces available, making these aisles ideal for assigning inbound pallets. The mix aisles are introduced to remain flexible, depending on the warehouse state. Mix aisles can be used for storage when a product does not fit in the full aisles and for picking by AGVs if the product is not available in a full aisle. AGVs will fill the empty aisles, so in the next period, other aisles are classified as full and empty, effectively shifting the working area of the AGVs and operators. The pseudo-code of the algorithm is shown in Algorithm 1. This classification already suggests how to approach the second-stage policy. Since storing items automatically leaves the most freedom when picking (remaining choice for either manual or AGV picking), the empty aisles will be used as storage aisles for this period, and the AGVs are assigned to these aisles. The aisles in class full will only be used for picking this period, and are assigned to manual resources.

4.3.2 First stage policy: Restricted Occupation Based Resource Assignment

We propose a restricted iteration of the occupation-based resource assignment, designed to be more predictable over the week. This algorithm maintains the logic of the occupation based resource assignment but is implemented more statically, by keeping the same aisle classifications for a week. It uses the occupation ratio per aisle to manage the inbound and outbound workload in different areas. The difference is that mix aisles are reassigned to either manual- or AGV forklifts

Algorithm 1: Occupation based resource assignment

Data: Free spaces per aisle a; total spaces per aisle a; # pallets expected inbound; # pallets expected outbound; AisleDivision $\leftarrow \{numFull, numMix, numEmpty\}$

Result: Class$_a$ $\in$ {full, mix, empty}; Assignment$_a$ $\in$ {AGV, Manual }

```
foreach Aisle a do
    OccupationRatio_a ← (free spaces in aisle a) / (total spaces aisle a);
end
foreach compartment c ∈ {C, D} do
    Sort aisles in c by aisleOccupationRatio from low to high;
    for i ← 1 to numAisles in compartment c (sorted) do
        if i ≤ numEmpty then
            Class_i ← "empty";
        else
            if i ≤ numEmpty + numMix then
                Class_i ← "mix";
            else
                Class_i ← "full";
            end
        end
    end
end
foreach aisle a in warehouse do
    if Class_a = "full" then
        Assignment_a ← "manual";
    else
        Assignment_a ← "auto";
    end
end
```

each day, depending on the daily expected business. If the outbound workload is higher than the inbound workload, mix aisles are assigned to the AGV equipment. With this policy, the employees can work in a smaller area and thus have to make fewer aisle changes, and the AGVs can help out with picking orders located in the mix aisles.

4.3.3 Second stage policy: Split lot workload location assignment

The second stage policy aims to assign incoming pallets to a storage location. At the moment the second stage policy is applied, the contents of the truckload is known, the VNA assignment is known from the first-stage policy, and data about known lot numbers can be accessed. The goal of the second stage policy is to fill the empty aisles while maintaining a manageable workload in the warehouse. From the data analysis we know that smaller lots are more likely to be included in the same outbound order (see section 2.5.4). Therefore, this policy assesses whether it is preferred to store a lot number together or if it can be split up over multiple aisles, based on the size of the lot. Since the aisle changes cause longer pick times and are meant to be reduced according to management, smaller lots should be stored in the same aisle. Larger lot sizes are expected to come into the warehouse spread over multiple truckloads, and are present on different outbound orders. Therefore, it is not required to store these items all in the same aisle. Pallets from a lot that is preferred to be stored together are assigned to empty aisles. Lots that are preferred to be split can be stored in mix aisles when the daily workload is low, as this causes more aisle changes. If the workload is high, pallets can be stored manually in full aisles, allowing order pickers to make dual load trips in the VNAs. A consequence of this policy is that it must accept exceptions. It can happen that an operator stored an item in an aisle that is now classified as automatic. In this case, the aisle is set to manual at the start of the period and manually picked with priority, after which the aisle is blocked for AGVs.

Algorithm explanation

The pseudocode is shown in Algorithm 2. For each lot number contained in an inbound truckload, it is determined whether it is preferred to split the lot or not, based on the known lot size. If lot splitting is not preferred, the lot is assigned to the empty aisle class, increasing the chance these pallets can be stored in the same aisle. After determining whether to split the lot or not, the lot is assigned to a class. If the lot is small, it is assigned to class full. If the lot is large, it is assigned to class full on days with a high workload, and to class mix on days with a low workload. After assigning a lot to an aisle class, the algorithm selects aisles from that class which have an open space, in the compartment where the pallet is inbound, adding these aisles to the $preferredArray$. The algorithm checks if the lot is already stored in one of the aisles from the aisles fitting these criteria, making these aisles the $idealArray$. If the lot is not stored already in one of the aisles, the $preferredArray$ becomes the $idealArray$.

4.3.4 Reference policies

Because GVCL is a greenfield warehouse, there are no performance metrics available about current storage process in GVCL. Therefore, it is valuable to test the warehouse performance also with other policies, as there is no knowledge about the behaviour of the warehouse at all. By assessing multiple policies of varying complexity, we can accurately determine the best policy to implement in the warehouse. This is also valuable as a means to reduce the lack of knowledge about the GVCL system behaviour. We include two policies that represent the approach that was suggested by GVCL management in the transition phase, the period when the warehouse is filled with products from the Former warehouse. This is also the period where the AGVs will be taken into use.

As first stage reference policy we use a so called *static resource assignment policy*. Aisles on the left side of the compartment are assigned to manual operators, aisles on the right side are assigned to AGVs. As second stage reference policy we use a variation of greedy location assignment, which we call *advanced greedy location assignment*. Each item is assigned to the nearest open location. If a pallet with the same lot number is already stored in an aisle in the compartment, the new pallet will first be assigned to that aisle. The advanced greedy location assignment is formulated to represent the basic logic that operators could use if they were responsible for determining where to store a pallet. An operator seeing pallets from the same lot number coming in will store them together. If an operator has no information to base this decision on, they will choose the nearest open location.

4.4 Decision making between alternatives

As discussed in sections 2.6, multiple aspects become essential objectives for the storage policy. To decide between the available policies, objectives are divided into different categories: order picking efficiency, warehouse effectiveness, restrictions, and practical aspects. Each category covers one or more important objectives. The literature summary has revealed that there are several methods to use for multi-criteria decision-making. This study focuses on choosing a good policy that can assign products to reasonable locations on time (see section 2.6).

Based on discussions with GVCL management, the requirements from Section 2.6, and the examples from literature in Section 3.4.1 we use the KPIs listed in Table 2.4 as measures for determining how the warehouse performs under different storage policies. Additionally, we consider the practical aspects of the policy which need to be considered:

- *Extent to which future data is required:* qualitative rating differentiating extent to which more data is required for the policy to work
- *Extent to which state of the warehouse is considered:* qualitative rating differentiating between the extent to which current warehouse state is considered
- *Decision moment aisle considerations:* comparative rating differentiating between the decision moment of aisle classification (auto or manual)

There are other measures which influence the warehouse performance and can have an impact on managerial decisions. For example, the amount of times that a truck has to wait for more than x minutes before docking. This tells something about the risk of receiving penalties for the waiting time of external parties. Another example of a relevant measure is the utilisation of individual resources, which can help management in scheduling and investment considerations. The reason those measures are not considered is because there are no clear target values. However, the measures can be included in implementation advice.

4.4.1 Assigning weight to objectives

To compare the performance of different policies, we use the AHP described in section 3.4.3 of the literature review. First, we obtain a weight for each category by filling out a pairwise comparison matrix. Following the description of Winston (2004, p. 786), the value in row i and column j of the matrix indicates the importance of objective i over objective j. A scale of 1 to 9 is used, where 1 indicates that the objectives are of equal importance, and 9 is given if the 'objective i is 'absolutely more important than objective j' (Winston, 2004, p. 787). Within each category, measures are also weighted using this methodology. Here, the weighted performance of the measures is counted as the score on a category. The filled-out pairwise comparison matrices are shown in Figure 4.1. The warehouse effectiveness is considered the most important since GVCL must be a good logistics service provider for Client X. The second most important category is the order picker efficiency, as this impacts the costs of running the warehouse. Within each category, the KPIs are also compared. The GVCL project manager has emphasised the importance of minimizing the required aisle changes, as this reduces the efficiency of VNA forklifts and operators also know that preventing aisle changes is preferred. The store time and retrieve time are considered equally important. The most important warehouse effectiveness KPI is shipping time. This is primarily because the importance of the dock-to-stock time is reduced as a result of the emphasis on storing inbound products with AGVs. Picking products with AGVs is considered less important. The resulting weights are shown in Table 4.1, and the normalised matrices used for calculating the weights are included in Appendix B.2.

To compare the results, we normalize the quantitative outputs, adapting the calculation method described by Beeldman (2022). Each alternative achieves a normalized score, where score 1 is best and score 0 is worst. Normalization happens as follows: per KPI, the minimum and maximum

Decision matrix importance of categories

	Order picker efficiency	Warehouse effectiveness	Restrictions	Practical aspects
Order picker efficiency	1	1/3	5	7
Warehouse effectiveness	3	1	4	7
Restrictions	1/5	1/4	1	3
Practical aspects	1/7	1/7	1/3	1

Decision matrix order picker efficiency

	Aisle changes	Store time	Retrieve time
Aisle changes	1	3	3
Store time	1/3	1	1
Retrieve time	1/3	1	1

Decision matrix warehouse effectiveness

	dock to stock time	shipping time	Ratio of products stored automatically	Ratio of products retrieved automatically
dock to stock time	1	1	1/7	4
shipping time	1	1	4	4
Ratio of products stored automatically	7	1/4	1	4
Ratio of products retrieved automatically	1/4	1/4	1/4	1

Decision matrix practical aspects

	future data is required	state of warehouse is considered	Decision moment aisle considerations
future data is required	1	1/2	1
state of warehouse is considered	2	1	2
Decision moment aisle considerations	1	1/2	1

Figure 4.1: Pairwise comparison matrices comparing performance categories, and KPIs per category

observed values are noted. In case the direction 'lower is better', the following formula is applied to calculate the score of each alternative$_i$:

$$\text{Score}_i^{\text{lower is better}} = \frac{\text{maximum observed value} - \text{observed value}_i}{|\text{maximum observed value} - \text{minimum observed value}|} \tag{4.21}$$

as described by Beeldman (2022, p. 36). In case 'higher is better', the minimum observed value is subtracted from the observed value of alternative i in the numerator of the equation.

4.5 Conclusions

In this chapter, we have proposed adaptive storage location assignment policies to implement in GVCL to answer Research Question 3. The mathematical formulation of the problem shows that solving the adaptive storage location assignment problem to optimality in a limited time frame is infeasible. Therefore, we proposed a two-stage heuristic. Stage one is connected to the aisle

Table 4.1: Table overview of weighted category and KPI importance for comparative analysis

Category	Category weight	Measure	Measure weight within category	Direction
Order picker efficiency	0,324	Aisle changes Store time Retrieve time	0,600 0,200 0,200	Lower is better
Warehouse effectiveness	0,512	Dock to stock time Shipping time Ratio of products stored automatically Ratio of products retrieved automatically	0,211 0,389 0,337 0,063	Lower is better Lower is better Higher is better Higher is better
Restrictions	0,114	Number of times the aisle assignment is violated	1	Lower is better
Practical aspects	0,051	Extent to which future data is required Extent to which state of warehouse is considered Decision moment aisle considerations	0,250 0,500 0,250	Lower is better Lower is better Less frequent is better

allocation decisions, determining for each VNA whether AGVs or manual operators are allowed to work there. The second stage determines for each incoming unit load where to store it, restricted by the decisions of the first stage. The second stage policy we proposed uses available warehouse information to store the pallets in a logical location primarily based on their lot number. The first stage occupation based resource assignment policy raises the question of how to divide the aisles. Specifically, how many aisles per compartment to assign to the classes 'full', 'mix' and 'empty'. We have also considered a reference policy to compare performance. This policy splits each warehouse compartment into an automatic- and a manual zone. It uses some logic to store lot numbers in the same aisle where possible. This reference policy closely resembles the logic implemented in the transition phase, which can be applied by operators in the warehouse without much background knowledge.

The policies can be evaluated based on a set of KPIs that describe the GVCL warehouse performance in the categories of efficiency, effectiveness, compliance with restrictions, and practical implementation. We place these KPIs into the AHP framework from literature to utilise the mixed set of KPIs. In the next chapter, we discuss how the policies can be evaluated by using them in a discrete event simulation representing the GVCL warehouse operations.

Algorithm 2: Split lot workload

Data: OrderData= $\{$arrival compartment AC; list of pallets= $\{$pallet number p, lot number $l\}\}$; known existing lot numbers; lot numbers of all pallets stored in GVCL; $splitBoundary$; $workloadToday \in \{low, high\}$

Result: Assigned location m for each pallet p

```
foreach Pallet p in OrderData do
    if # pallets existing of lot number l ≥ splitBoundary then
        lot l ← SplitThisLot;
    else
        lot l ← dontSplitThisLot;
    end
    if lot l = dontSplitThisLot then
        aisleType ← empty;
        foreach aisle i in compartment AC do
            if Class_i = aisleType and Compartment_i = AC and openSpaces_i > 0 then
                add aisle a to idealArray;
            end
        end
    else
        if workloadToday = high then
            aisleType ← full;
        else
            idealArray
        end
        foreach aisle i in compartment AC do
            if Class_i = aisleType and Compartment_i = AC and openSpaces_i > 0 then
                add aisle i to preferenceArray;
            end
        end
        foreach aisle j in preferenceArray do
            if Lot number l stored in aisle j then
                add aisle j to idealArray;
            end
        end
        if idealArray = Void then
            idealArray ← preferenceArray;
        end
    end
    AssignedLocation ← false ;
    for aisle i in idealArray do
        if Open space for pallet p in aisle i then
            Assign pallet p to location in aisle i;
            AssignedLocation ← true ;
            ExitForLoop;
        end
    end
    if AssignedLocation = false then
        AssignGreeedyLocation(p);
    end
end
```

5 SIMULATION STUDY

In this chapter, we present our answer to research question 4: "How can we validate and test the formulated policy?"

This chapter describes the simulation modelling used to analyse the warehouse processes. In Section 5.1 we discuss the modelling scope, provided an overview of the simulation model, and note the assumptions and simplifications made in the simulation model. In Section 5.2 we describe the input data used to represent the GVCL situation. Finally, in Section 5.3 the verification and validation approach of this study is presented.

5.1 Conceptual model

In this research, Siemens Tecnomatix Plant Simulation 16.1 is used for discrete event simulation. Given that there is no physical warehouse that can be used for researching performance, we resort to other means to test and evaluate possible solutions. Simulation modelling is an effective method to predict warehouse performance under different storage and retrieval policies. The aim of the simulation is to quantify the performance of different policies in the warehouse, and to make a well-underpinned choice to recommend to GVCL. This section shows how processes are modelled in Plant Simulation. First, the scope of the simulation model is discussed. Next, the logic used to represent the warehouse is discussed by showing the different sub-processes. Finally, assumptions and simplifications are explained.

5.1.1 Modelling scope

The simulation must represent the GVCL warehouse compartments C and D. It must include the narrow aisles and the performance of the manual- and AGV processes. The goal of the simulation study is to judge the performance of the internal logistics and to establish which storage policy performs best under the expected circumstances.

The simulation must measure the performance in two different areas: the internal and external performance. The internal performance measures how employees and equipment are utilized, and how aisles are occupied with stored goods. The external performance measures to what extent the internal decisions impact the external parties, i.e. 'How good can GVCL meet the demands of the inbound and outbound flow?' The simulation must include options for deciding where to store pallets, which products to retrieve, and whether tasks are performed manually or automatically.

5.1.2 Simulation overview

This section describes how the warehouse functionality was implemented in the discrete event simulation software.

Inbound product flow

A basic overview of the simulation methods is shown in the form of a paper model in Figure 5.1. At the start of each day, based on the day of the week the expected inbound workload is generated. Trucks are operating as a shuttle between the factory and warehouse, the amount of trucks depends on the expected inbound workload. Arrival times are generated accordingly. In case the warehouse's available storage space is less than a predetermined minimum, no inbound orders are generated. This represents the real process because either Client X reduces production if the stock levels are very high, or GVCL management tells Client X that full capacity is reached. In both cases, the number of pallets inbound temporarily decreases.

Each truck contains either 28 euro or 23 block pallets. Management has decided to always let trailers with a chain conveyor connect to the ATLS in Compartments C and D in alternating order.

In the simulation, the unit load objects are created per truckload in an ATLS object at the time of a truck's arrival. One by one they move to the contour scanner object. Here, the unit load is registered as inbound, and the contour scanner triggers the location assignment method for the unit load. The output of the location assignment method is the decision variable x_{ijk}. x_{ijk} can only be 1 if the product fits in the storage location, the location is currently empty and not reserved, so if $b_{ijk} = 1$, and if the vehicle type k is allowed in the aisle at that moment, so if $a_{h_j v_k} = 1$. This way, the simulation model represents constraints 4.2 to 4.5. At this moment in the DES, for this pallet object, the order information o_i as described in the mathematical model in Section 4.2. The order receives the following information:

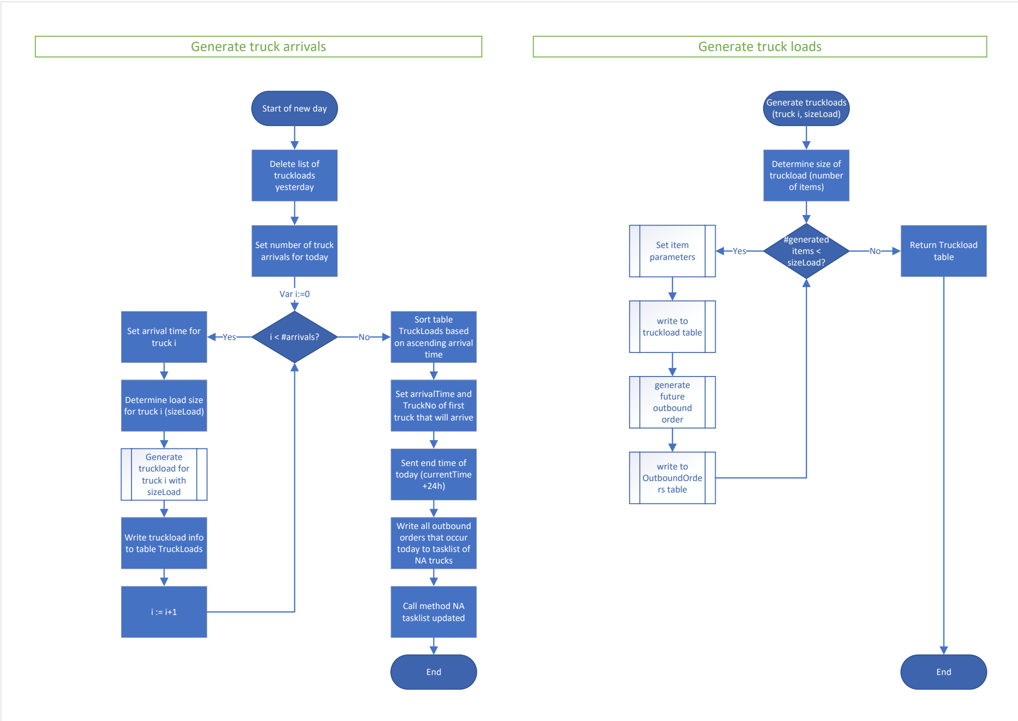
$$o_i \begin{cases} p(o_i) & = \text{Pallet unique identifier} \\ S/R(o_i) & = \text{1 (storage operation)} \\ Tr(o_i) & = \text{Truck number} \\ Lot(o_i) & = \text{Lot number} \\ r_l & = \text{Current time (can be stored from this moment)} \end{cases}$$

After the contour scanner, the unit load moves to the pickup queue, which has space for two pallets. As soon as the unit load enters the pickup queue, it registers a task to move the object from the pickup queue towards its storage destination.

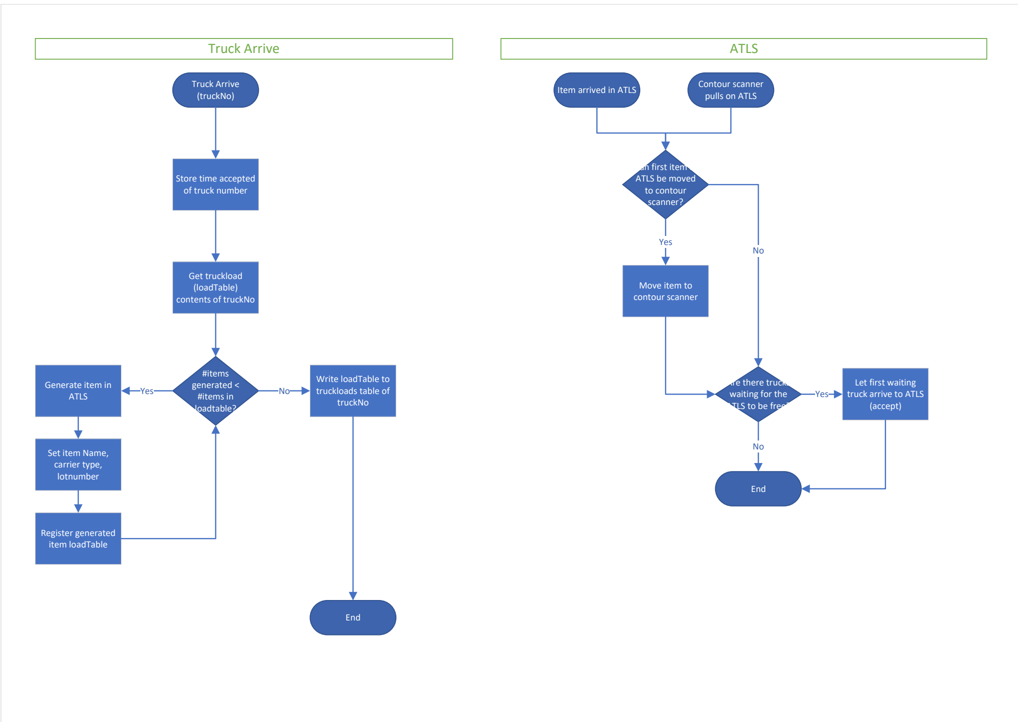
Outbound product flow

Outbound orders are generated at the start of each day if the warehouse is sufficiently filled with products. First, the number of outbound orders on that day is generated. Next, the order lines are generated, by selecting from the list of lot numbers stored in the warehouse. Finally, the arrival times are generated.

When an order arrives, it is assigned to a random dock, since it assumed that most lots are stored in both compartments, given that the inbound products arrive alternating between Compartments C and D. For each order line, a product is selected in the warehouse based on the requested lot number. All products selected are registered as a task to move from the storage to the dock.



(a)



(b)

Figure 5.1: Paper model of the inbound process: (a) Methods executed at the start of workday (b) Methods triggered at the arrival time of truck

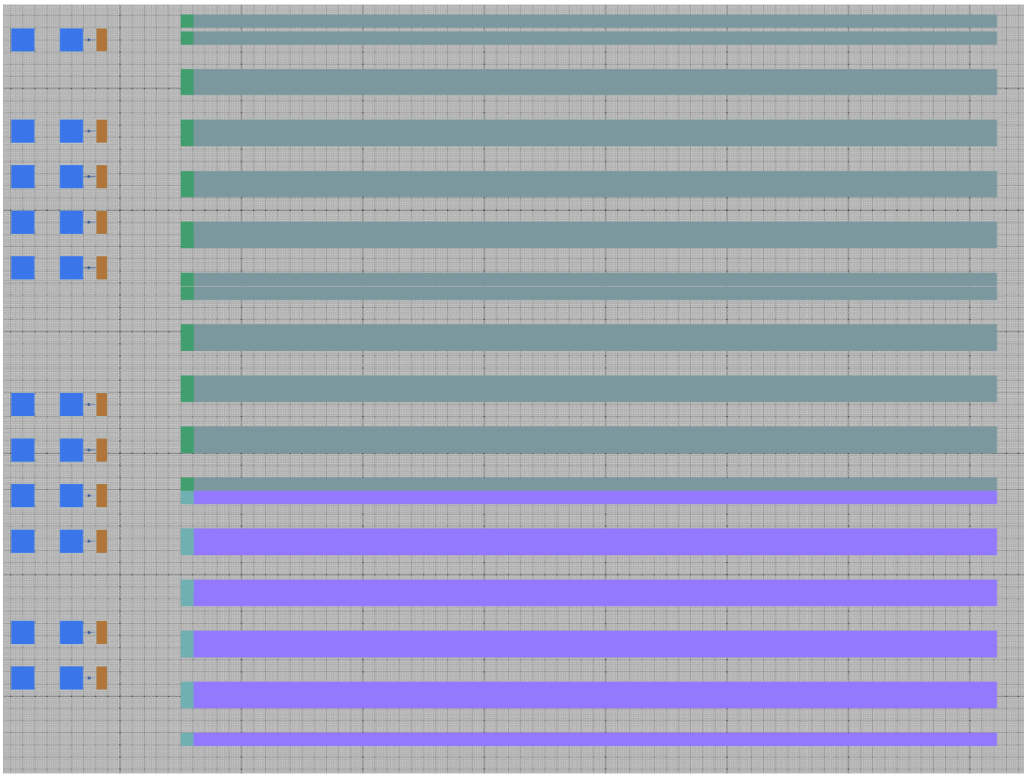
Each pallet on an order line represents an order from the MILP:

$$o_i \begin{cases} p(o_i) & = \text{Selected pallet unique identifier} \\ S/R(o_i) & = \text{0 (pick operation)} \\ Tr(o_i) & = \text{Order number (representing outbound truck)} \\ Lot(o_i) & = \text{Lot number} \\ r_l & = \text{Current time (can be picked from this moment)} \end{cases}$$

Warehouse layout

The frame *storage area* represents the GVCL Compartments C and D. Included in this frame are the narrow aisles, dock areas, and the equipment is also located here. Each aisle consists of a pick-and-drop store material flow object for the two sides of the aisle, as well as a store object that represents the full storage rack on one side of the aisle. Following the real aisle layout, aisles one to ten (of each compartment) consist of 21 bays and 5 levels, and the rest of the five aisles consist of racks with 21 bays and 6 levels. This frame also mimics the WMS and fleetcontrol, which are further explained in the next paragraphs.

Figure 5.2: Snapshot of top-view of one compartment in Technomatix Plant Simulation 16.1



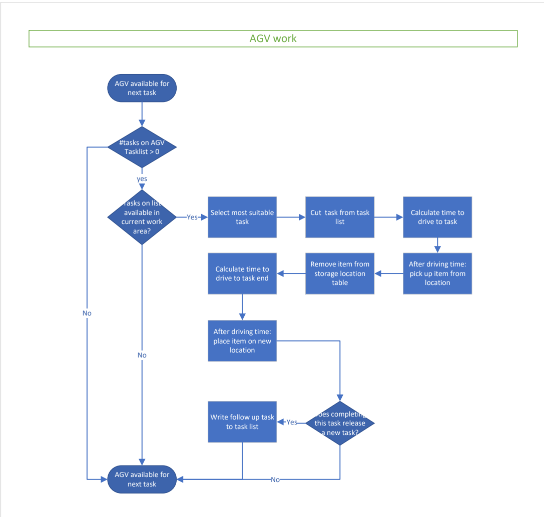
Note. Objects on left hand side represent dock locations. Right-hand side shows pick and drop locations and storage racks.

WMS in simulation

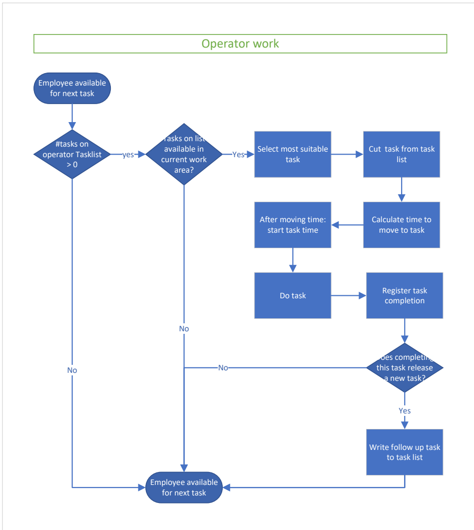
The main purpose of the WMS is tracking locations. In the simulation, this task is fulfilled by maintaining a table containing each possible storage space, identified by a unique identifier. For each storage space, this table contains specifics about the location (e.g. the details about which compartment, aisle, bay, level and bin this location is in), as well as information about which product is stored there, or whether this location is reserved for a product that is on its way, or if the product is claimed for a pick. Similar tables exist for the pick and drop locations, as well as the docks.

Fleetcontrol

All the warehouse tasks are triggered in the frame *Inbound*. This frame generates the inbound products, as well as the orders for outbound demand. A product that arrives at the contour scanner object triggers the location assignment algorithm, which assigns a location to the product. When the product arrives at the pickup point, it generates a task. A task is a table entry that contains the pickup location, the place destination, and the object that needs to be moved. The table entry is written to the respective tasklist depending the vehicle type: VNA forklift or reach truck. The general logic of AGVs and operators is shown in Figure 5.3.



(a)



(b)

Figure 5.3: Paper model pick and place: (a) General AGV logic (b) General operator logic

Routing logic

For the routing of vehicles, a return routing approach is assumed. The description can be found in appendix A.1. The time c_{ijk} to perform operation i in location j by vehicle k is calculated by adding the time to drive to the start of the task, picking the item, driving to the end of the task, and placing the item. The actual time to complete a full operation one a pallet is then the addition of $c_{ij,\text{reachtruck}}$, $c_{ij,\text{VNA forklift}}$ and the time between the two tasks: the waiting time in the pick-and-drop rack. A VNA forklift working on a task involved with location i will block aisle h_i whilst performing the task. A VNA forklift cannot start a task in aisle h if it is blocked by another VNA forklift. This represents Constraint 4.9. The completion time of a storage task is registered when a product is stored in a VNA, the completion time of a pick task is registered when the item is placed at a dock location.

5.1.3 Assumptions and simplifications

Recall that simulation is an abstraction of reality (section 3.5.2). Therefore, assumptions and simplifications are included in the simulation model, which therefore deviates from reality.

- *Equipment is fixed to a compartment:* Half of the available equipment is assigned to compartment C, and the other half to compartment D. Because the inbound products alternate between the compartments, a relatively balanced workload is assumed. If a product needs to be moved between compartments, the equipment assigned to the compartment of the pick location will perform the task, after which it returns to its compartment.
- *Charging of equipment* is assumed to be handled after working hours, and therefore not taken into account in the simulation.
- *Pick and drop restrictions:* The place location of a product in pick and drop zone must be on the same side of the aisle as the storage location of the product in the aisle. This deviates from the real situation, where each pick and drop location is fixed as either an inbound or outbound location.
- *Product dimensions:* are assumed to be equal for each unit load. The pallet type is the only distinction that is made.
- *Resource blocks aisle:* A resource in an aisle blocks the whole aisle, so no other resources can enter. This holds for both manual- as well as automatic equipment.
- *Operators:*
  - Each working day consists of two consecutive eight-hour shifts. Operator breaks are not considered in the simulation model.
  - Operators are all capable of switching between a narrow aisle truck and a reach truck. An operator can work on only one vehicle at a time.
  - The amount of operators and vehicles to operate does not have to be equal. A manual vehicle can only perform work when an operator is assigned to it, and vice versa.
- *Working days:* The warehouse is closed on Sundays and during holidays. These days are not simulated.
  - The result of closing on Sunday is considered an increased demand after the weekend.
  - There are no production and outbound orders during the holidays, therefore these can be skipped completely in the simulation.
- *Value added logistics:* The time required to perform value-added logistics is not considered in this study. It is assumed that this happens at the shipping area, and is billed accordingly. Therefore, it is assumed that this has no impact on the storage policy.
- *Outbound orders:* items can only be ordered from the warehouse if all items from that lot have been inbound to the warehouse. This prevents the possibility from an item being ordered out of the warehouse while it is still being moved to its storage location.

5.2 Input data

The information that we have available are historical data, equipment information and warehouse design decisions. Using this data, we can model the relevant parts of the warehouse. Historic order data is used to generate representative behaviour of external factors, specifically the inbound and outbound product demand, and related variables such as truck arrival times and batch sizes. For stochastic processes which influence the simulation, we introduce probability distributions. These processes are the inbound and outbound pallet demand, truck arrival times and pallet type per lot.

5.2.1 Inbound product flow

For the inbound product flow, we are interested in the arrival times of trucks, and the contents of those trucks. The contents are defined based on batch size, and a lot number assigned to each product in the truck.

Inbound demand

The demand for inbound products, i.e. product arrivals, is calculated as number of pallets per day. A stochastic variable is generated based on the normal distribution with mean $\mu = 400$ and standard deviation $\sigma = 86,5$. This variable is then multiplied by the seasonality factor of that day. Because GVCL made a new agreement with Client X, this input deviates from what the data analysis shows. The contract states that 400 pallets per day are expected. The data analysis shows a mean of 285 pallets per day. It is decided to increase the expected pallets to 400, but to keep the standard deviation found in the historic data.

Number of inbound truck arrivals

The number of trucks that arrive on a day is simulated by dividing the inbound demand for a day by the average size of a truckload.

$$NumTrucks = \frac{NumPallets}{AvgTruckSize}$$

Inbound truck arrival times

Each day, when the number of outbound truck arrivals is generated, the amount of different vehicles driving between the plant and the warehouse is calculated. Based on a rough estimate of 30 minutes driving between the two sites, and 30 minutes loading on the Wormer site, it is determined that one truck can unload at GVCL 8 times per day. The resulting number of vehicles is then:

$$\text{Number Vehicles} = \left\lceil \frac{\text{Total daily truck arrivals}}{8} \right\rceil$$

Based on the number of different vehicles, the interarrival times per vehicle is generated. There is no data available on truck arrival times to GVCL, therefore it is assumed that each active truck arrives spread over the day, following a Poisson process. The Poisson process is widely used in literature to simulate arrivals (e.g., Zhao et al. (2020), Ekren, Sari, and Lerher (2015)).

Table 5.1: Overview of seasonal factors used as input to generate arrivals and orders in the simulation

Number day	Weekday	Inbound seasonal factor	Outbound seasonal factor
1	Monday	2.0722	1.1507
2	Tuesday	1.0087	1.0036
3	Wednesday	0.9889	1.0001
4	Thursday	0.9717	0.9174
5	Friday	0.9799	0.9281
6	Saturday	0.9785	-

Since the 'expected arrivals' per day are known, the exponential distribution is used to generate the inter-arrival times. We used:

rate $\lambda = \frac{\text{length workday}}{\text{average arrivals per vehicle}}$, with a lower bound of one hour, and upper bound of 2,5 hours.

Size of truckload

GVCL and the transportation company have agreed to always drive with full trailers in the new situation. Therefore, a truckload always contains either 32 euro pallets or 26 block pallets. Data analysis in section 2.5.3 showed that there is a 31% probability that a lot number belongs on a block pallet. Converting this probability to truck sizes, there is a 35% probability that a truckload contains lots stored on block pallets (and thus 65% of the trailers bring euro pallets).

Minimum available storage space

The minimum available storage space is set to 5% of the total capacity. This means that the warehouse requires at least 928 available spaces at the start of the day to generate an inbound workload. Because pallet slots are fixed, the constraint is added that at least 5% of the assigned block pallet spaces, as well as 5% of the assigned euro pallet spaces, must be available before inbound products are generated.

5.2.2 Seasonality

The seasonality is taken into account by setting the target products per day based on the outcome of the Normal probability distribution, multiplied by the daily seasonal factor. Since we are simulating six days per week, the seasonality of 6 weekdays is provided, see table 5.1. Note that for the outbound seasonality, only the working days are considered.

5.2.3 Outbound product flow

For the outbound product flow, a top down approach is followed for generating the required data. As shown in the data analysis 2.5, the available dataset for outbound demand shows a normal distribution for the total demand per day. Further details about the outbound demand are based on external decisions and many variables, such as overall cocoa market forces and agreements between Client X and its customers. In this simulation study, the overall demand is estimated following the daily demand probability with a Normal distribution. Based on this estimated demand, the number of orders and order size is determined.

Outbound demand

As per the agreement between GVCL and Client X, the minimum stock level is 80%. Therefore, outbound demand is only generated if the stock level at the start of the day is greater than 80%.

The demand for outbound products is determined as number of pallets per day, just like the inbound demand. This research assumes that the warehouse observes steady-state behaviour (after the introduction period), and therefore that over time the number of units into the warehouse equals the number of units outbound. Just like the inbound demand, the input data deviates from the data analysis: the expected pallets demanded is decreased to 400, but we keep the standard deviation found in the historic data. A stochastic variable is generated based on the normal distribution with mean $\mu = 400$ and standard deviation $\sigma = 207,44$, with a lower bound of 0 products. This variable is then multiplied by the seasonality factor of that day.

Number of outbound orders

The number of orders arriving daily is simulated by dividing the outbound demand for a day by the average size of an order.

$$NumOrders = \frac{NumPallets}{AvgOrderSize}$$

Number of pallets per order

Since there is no underlying explanation available about how the outbound orders are realized, we use an empirical distribution. For the number of pallets per order, the empirical distribution shown in the data analysis figure 2.15 is used. The unknown and orders larger than 40 are left out. The reason that the orders of over 48 pallets are not generated, is because in reality these will be split up into multiple pickup moments or locations. Recall that the maximum configuration is 48 pallets in an LHV.

Arrival times

Given the lack of available data on the arrival times of the outbound trucks, the assumption is made that they can arrive any time of day, during working hours. A uniform distribution is used to generate an arrival time for each outbound order.

5.2.4 Input for algorithms

In Section 4.3 we introduced a two-stage storage assignment approach, for which we formulated several policies to compare. Implementation of these policies requires setting the parameters in the algorithm to correct values. The occupation based resource assignment policy requires aisle division parameters: the number of full, mix and empty aisles, see Algorithm 1. The values for this assignment are explored in Section 6.3. The split lot workload assignment policy requires a value as $splitBoundary$, as can be seen in Algorithm 2. Based on the conclusions in the data analysis in Section 2.5 we set the boundary to 15 pallets, as this cut-off ensures that historically 30.52% of the numbers of this size appear in one order. The static resource assignment policy requires only input for where to split the compartment, i.e. how many aisles are fixed to manual equipment. Recall that the leftmost aisle only has a storage rack on one side of the aisle. Furthermore, the rightmost five VNAs have racks of 6 layers high, compared to the five layers in the other VNAs.

Table 5.2: Overview of simulation settings used in this study

Setting	Value
Warehouse	
Simulated area	GVCL warehouse Compartments C and D, VNA and expedition areas
Carrier type allocation	Fixed
Working times	06:00 – 18:00
Working days	Monday to Saturday
Maximum allowed arrival time inbound	17:00
Resources	
AGV VNA forklifts	4
Manual VNA forklifts	4
AGV reach trucks	4
Manual reach trucks	4
Operators	4
Aisle violation penalty	5 minutes
External parameters	
Distribution inbound demand	N ~(400; 86.5)
Distribution outbound demand	N ~(400; 207.44)
Seasonality	As per Table 5.1

Therfore, we split the warehouse between aisle 8 and 9. Aisles 1 to 8 are assigned to manual operators, containing 4125 storage spaces, and aisles 9 to 15 are assigned to AGVs, containing 4400 storage spaces.

5.2.5 Warehouse parameters

In the simulation study, both compartments C and D are included simultaneously. Each compartment consists of 15 aisles. 14 of those aisles have racks on both sides. The layout of the real warehouse is copied to help with validation, only the distance between the two compartments is reduced because there is no need for shuttle racks. The real distance is still considered when considering activity between the compartments. Each rack consists of 21 bays, 8 of which are reserved for block pallets. A bay can fit three euro pallets, or two block pallets per level. Each compartment has 11 dock doors for outbound activity, and one ATLS chain conveyor for inbound truck arrivals. The distance between the pick and drop racks, i.e., the start of the aisle, and the access points of the ATLS and Dock locations is set to 12 meters. Four manual Narrow Aisle trucks and four manual Reach Trucks are included, as well as 4 of both AGV types. Four employees work spread over the two compartments. The penalty for retrieving a manually placed product from an aisle assigned to AGV equipment is set to 5 minutes extra working time. The maximum allowed arrival time of trucks with inbound goods is set to 17:00 each day. Refer to Table 5.2 for a summarized overview of the parameters used in the simulation study.

5.3 Model verification and validation

Before using the simulation model to conduct experiments and evaluate solutions, it is necessary to verify and validate the simulation model. It is important to have good accuracy of the model in

Table 5.3: Overview of simulation input variables compared to observed simulation behaviour

KPI	Sample (mean, standard deviation)	Sample size after filtering	Input variables
Pallets IN per day (excluded days with no arrivals)	(403.51, 86.51)	555	(400, 86.5)
Pallets OUT per day (excluded Saturdays)	(410.21, 206.30)	609	(400, 207.44)
	Observed average		**Expected**
Trucks IN per day (excluded days with no arrivals)	16.51	555	15.24
Trucks OUT per day (excluded Saturdays)	20.76	609	20.15

order to draw valuable conclusions that are useful in practice.

Following the simulation approach described by Law (2015), validation determines whether the simulation is an accurate representation of the system, and verification determines whether the conceptual model has correctly been translated into a simulation model.

5.3.1 Verification

We use three methods as described by Law (2015) for verifying the simulation model.

The simulation process is followed step-by-step in debugging mode, to verify that each event simulates the expected behaviour, following *verification technique 1* (Law, 2015, p. 251). During the programming of the simulation model, the functionality is split up into inbound product flow, storage activity, and outbound product flow. Each process is added separately, and tested by using dummy data to simulate parts of the process. Finally, the simulation is tested by running the program and following items through the warehouse, following the flow from inbound to storage to outbound.

Law's *verification technique 3* (Law, 2015, p. 252) is to run the simulation with some input parameters and check for a reasonable output. In this study, this is done by assessing some KPIs using a single inbound order as input data.

Finally, this study uses Law's *verification technique 7* (Law, 2015, p. 255). In this technique, the sample mean and variance for each simulation input probability distribution is computed.

To verify the input data generation in the simulation model, a total of 735 simulation days after the warmup period is assessed (for an explanation about the warmup period, see section 6.2.1). The following variables are assessed: number of pallets inbound, number of trucks inbound, number of pallets outbound, and number of outbound orders. See table 5.3 for an overview of the verification data. To compare the generated values to the desired values, first, the observations are deseasonalized. Next, the inbound values are filtered to exclude 0 days, because the simulation functionality sometimes blocks inbound orders to prevent a full warehouse. In the outbound data, the Saturday values (all 0) are removed, because the simulation setup only generates outbound demand from Monday to Friday.

5.3.2 Validation

Checking whether the simulation model represents reality to the required extent of the study is an important step in the simulation study. This process is called validation; Fishman and Kiviat

(1968) define validation as establishing that a model resembles “its actual system reasonably well” (Fishman & Kiviat, 1968, p. 191). Law later added to this definition that validation tests if the model represents the reality *“for the particular objectives of the study”* (Law, 2015, p. 247).

During this study, the physical warehouse is under construction and therefore unavailable for evaluation of the performance based on metrics mentioned in section 4.4. However, there are several methods to validate the simulation model. First, we can use the expertise of the team of BBI to gain insight into the expected behaviour of the model. Robinson (1997) suggests to let a programming expert review the code, or to let a non-expert check the simulation data and logic. Law (2015, p. 268) also suggests to discuss the model with ‘Subject Matter Experts’. A second method to validate the model without the ability to compare to a real scenario is to compare the model to another model (Law, 2015, p. 268). An informal comparison of both systems is suggested, by comparing statistics or graphical plots of both systems.

Expert opinions

A presentation of the assumptions and simulation logic was shown to two subject matter experts (GVCL project manager, and GVCL transition manager). Input- and output data, modelling assumptions and specific warehouse behaviour logic were discussed. Based on the feedback from the experts, some aspects were adjusted.

Model comparison

We can also use the output of quotations from the AGV supplier and compare the estimates (item throughput per hour) to the simulation performance. From the AGV supplier, it is known that “one VNA AGV could transfer 16 loads per hour and with optimal task profile and double play cycles even 20 loads per hour, excluding charge time” (Bolk Business Improvement, 2023)[1].

The AGV capacity in the simulation model is calculated by dividing the total NA AGV moves per day by the total NA AGV available working hours per day. The same simulation data used in the verification step is used. We calculate the mean AGV moves per AGV per hour, resulting in a sampe mean of $\bar{x} = 14.158$ with a standard deviation of $s = 7,227$.

Based on the expert opinions and comparison with the model from the AGV supplier, we conclude that the simulation model sufficiently represents reality to assess storage policies in Compartments C and D of GVCL.

5.4 Conclusions

In this chapter, we have answered research question 4: “How can we validate and test the formulated policy? We can test the formulated policy by measuring performance in a discrete event simulation study. In this study, the narrow aisles of Compartments C and D of GVCL are modelled. The simulation logic, relevant assumptions, and model verification and validation steps are described in this chapter. We can now focus on assessing the performance of the policies by performing experiments, which will be discussed in the next chapter.

[1]This source is the quotation provided by the AGV supplier, who used two different calculation methods to get to this number. This source document originates from BBI intranet, and is not available to the public.

6 EXPERIMENTS AND RESULTS

In this chapter, we describe the experimental setup and discuss the experimental results. The experimental design is introduced in Section 6.1. Initial experiments are described in Section 6.2, and experiments used for finetuning policies are shown in 6.3. A final comparison between the Baseline and new policy is made in Section 6.5. The AHP decision-making calculations are shown in Section 6.4.

6.1 Experimental design

In this section, we describe experiments to test policy performance and to generate results. We distinguish three types of experiments:

1. **Pilot runs**: determine required number orf replications and warmup period
2. **Policy exploration**: find preferred parameters for policies
3. **Policy evaluation**: use the settings from experiments 1 and 2 to run experiments and compare performance

We will research three policy configurations to provide insight into the storage approaches. The policy evaluation experiments are used to compare the different policy performances. These configurations are summarised in Table 6.1. Policy Configuration 1 uses the proposed occupation based resource assignment and split load location assignment as stage 1 and 2 approaches respectively. Policy Configuration 2 tests the performance of the restricted occupation based resource assignment. Recall from Section 5.2.5 and Table 5.2 that we will use the same warehouse parameters for all experiments. These settings represent the design of GVCL. For the policy exploration, we investigate the preferred settings for the research policy. Specifically, in Stage 1 we explore how to divide the aisles. For the policy evaluation, we will compare the performance of the baseline and new configurations.

Table 6.1: Policies to investigate

Name	Stage 1 approach	Stage 2 approach
Baseline	Splitting the compartment	Advanced greedy location assignment
Configuration 1	Occupation based resource assignment	Split-lot workload location assignment
Configuration 2	Restricted occupation based resource assignment	Split-lot workload location assignment

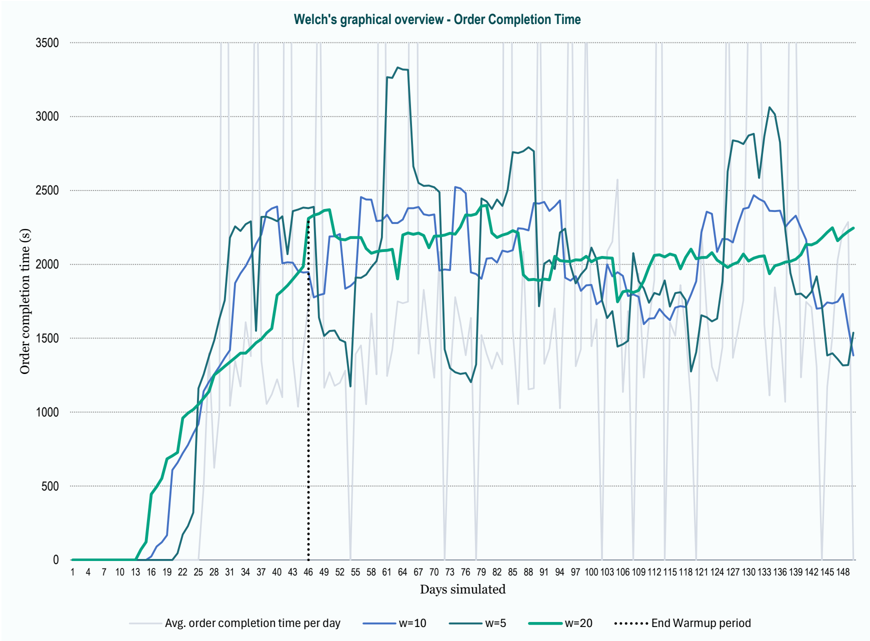


Figure 6.1: Welch's graphical procedure for Daily Average Order Completion Time (runlength=150 days, replications=10)

6.2 Pilot run experiments

This section shows the steps taken to determine the required number of replications and warmup period. We use Welch's graphical method to determine the warmup period and calculate the confidence interval half-width to assess the required number of replications. In this section, the Baseline Policy is used to gather the required data.

6.2.1 Warmup period

The simulation study starts with an empty warehouse. To accurately represent an operational warehouse situation, we introduce a warmup period in the simulation to fill the warehouse.

Initial simulation experiments are carried out to determine the appropriate warmup period. This is done with fixed aisle assignment and advanced greedy storage policy. The chosen indicators for determining the warmup period are the average daily order completion time and warehouse fill ratio. These measures cover the outbound product flow, and therefore also show the time required to fill the warehouse. The graphical representation of the daily average order completion time is shown in Figure 6.1 and the fill ratio in Figure 6.2. We can use Welch's graphical procedure to determine the warmup period (Law, 2015, p. 513). The warmup period is calculated as the number of days. At a window $w = 10$ it is clear that the warmup period has completed and a steady state is achieved after *46 days*, as indicated by the vertical dotted line in Figure 6.1 and 6.2. A general rule of thumb is to set the simulation run length to 10 times the warmup period, therefore we simulate *460 days* after the warmup period. Depending on the policy and parameters used, one replication of 460 days after warmup takes one to 1.5 hours of computing time.

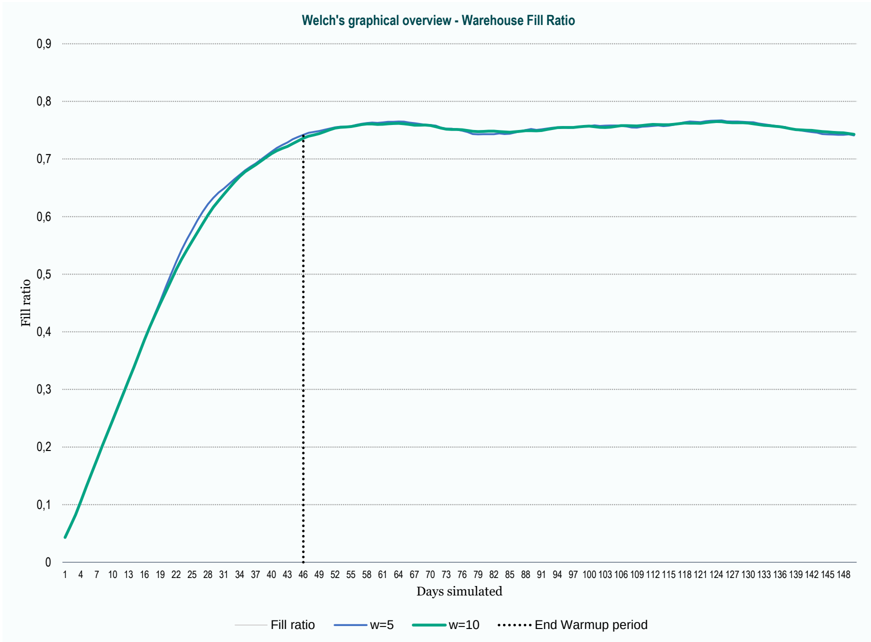


Figure 6.2: Welch's graphical procedure for Warehouse Fill Ratio time (runlength=150 days, replications=10)

6.2.2 Number of replications

In order to be sure that the output of the simulation is reliable and use a confidence interval, we perform each experiment with a predetermined number of replications. We use the *replication/deletion approach* as described in by Law (2015, p. 523). For this approach, we perform simulation runs with the warmup period of 46 days and run length of 460 days as determined before (Subsection 6.2.1). Each replication starts with a different seed value.

After each replication, we calculate the confidence interval half-width (CIHW) for each KPI. New replications are performed until the confidence interval half-width is smaller than the maximum relative error. The CIHW is calculated using the formula, adapted from (Law, 2015, p. 524):

$$\text{CIHW} = \frac{t_{n-1,1-\alpha/2}\frac{s}{\sqrt{n}}}{\overline{X}} \tag{6.1}$$

Where $t_{n-1,1-\alpha/2}$ the t-value, s the sample standard deviation, n the number of replications, and $\overline{X}$ the average observed objective from the replications so far. We aim for a confidence interval of 95%, so accept an error of 5%. Following Law (2015, p.505), we calculate the maximum relative error as $\gamma' = \frac{\gamma}{1+\gamma} = \frac{0.05}{1+0.05} = 0.0476...$

The results are shown in Appendix D.1. The last KPIs reach a CIHW lower than the maximum relative error after 4 replications, therefore we conclude that we need 4 replications for experiments.

6.3 Policy exploration experiments

This section discusses how the first stage policy divides the aisles into the classes 'full', 'mix' and 'empty' per compartment, as introduced in 4.3.1. The goal of these experiments is to find a setting that allows the AGVs and manual operators to work efficiently in the warehouse.

6.3.1 Setup exploration experiments

Based on the fact that the baseline policy suggests splitting the warehouse to manage the coworking space of AGVs and manual vehicles, we know that there must be a balance in the division working zones of the AGVs and manual equipment. Four different combinations are tested to determine which configuration of aisles is interesting. Each compartment has 15 aisles. It is known that at least 2 full aisles are required, as the minimum amount of automatic aisles is equal to the number of full aisles, and we have two narrow aisle AGVs per compartment. We explore settings with more and less than half of the aisles available to manual operators and use the amount of full aisles to assess the impact of inbound workspace on the resource efficiency. The combinations of aisle classifications are shown in Table 6.2, which also explains why each configuration is interesting to explore. Each exploration uses Policy Configuration 1 and is replicated 4 times. Each exploration setting uses the same random number variant as the other explorations during the same replication. This ensures that the same random data is used when comparing performance.

Table 6.2: Selected aisle division per compartment for exploration

Exploration number	# full aisles	# mix aisles	# empty aisles	Reasoning
1	9	3	3	Daily flexibility for operator, but little aisle changes
2	7	6	2	Daily flexibility for operator
3	5	4	6	Mixed flexibility for AGV and operator, more space for inbound work
4	8	5	2	Daily flexibility for operator

6.3.2 Results exploration experiments

The results per replication of the exploration experiments are included in Appendix D.2. An overview of the mean performance of the four replications per exploration is shown in Table 6.3. The average store time and average retrieve time per task under the different divisions of aisles are shown in Figure 6.3. It can be seen that the store time and retrieve time are the lowest in Exploration 1. The lowest average store time is 6.49% faster than the slowest time, in Exploration 3. The average retrieve time improves by 22.69% when comparing Exploration 1 with Exploration 3. Exploration 2 has the lowest ratio of aisle changes at 19.93%, which is 8.15% lower than the ratio in Exploration 3.

It can be seen that there are differences between the performance on the KPIs. We rely on the multi-criteria decision-making approach described in Section 4.4, specifically on the order picker efficiency category. The results of the multi-criteria decision analysis for order picker efficiency are shown in Table 6.4. We conclude that the preferred configuration for full-mix-empty aisles per compartment is 9-3-3, as this yields the best order picker efficiency.

Table 6.3: Mean performance efficiency KPIs

	Mean result 4 replications		
Exploration	RatioAisleCh	AvgStoreT (s)	AvgRetrieveT (s)
1	0.2021	815.71	264.86
2	0.1993	832.30	305.95
3	0.2169	872.35	342.61
4	0.2057	832.61	277.19

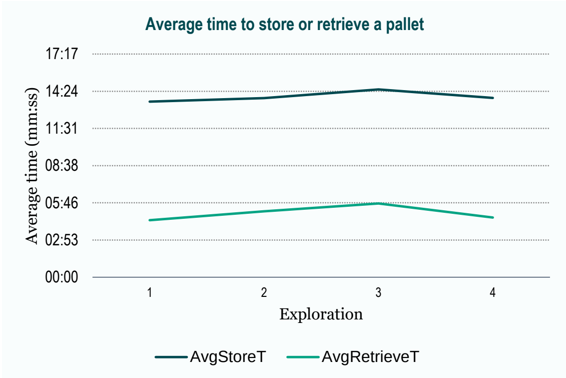


Figure 6.3: Average time of storage- and pick tasks compared

6.3.3 Determining performance on practical aspects

The KPIs for the order picker efficiency, warehouse effectiveness, and restrictions can be calculated with the simulation output. The practical aspects can not be directly quantified, hence we fill out the pairwise comparison matrix in this subsection. The final score per configuration is shown in Table 6.5. The pairwise comparison matrices per KPI are included in Table B.4 in Appendix B.3. The Baseline policy setup requires little data on the expected workload, it only requires information on if the lot number of an incoming pallet is already stored somewhere in the warehouse. Configuration 1 requires the most up-to-date information on the state of the warehouse, as it uses the expected daily workload and occupation ratio per aisle. Configuration 2 uses similar data but updates the aisle assignment less frequently. Configuration 2 scores best on decision moment aisle considerations because it changes once per week, which is more convenient for operators as this allows them to remember the aisle assignment each week. The Baseline never changes aisle assignment, which is convenient for operators, but impacts the perceived intelligence of the policy.

6.3.4 Interpretation of exploration results

The results show us that leaving not enough aisles dedicated to manual workers will impact the efficiency of the order pickers. Less space for picking specifically means that more picking must be done in the same aisles as the storage tasks. If the policy focuses on storing most products in the empty aisles, but most picks are generated in the mix aisles, there is a high amount of aisle changes required.

Table 6.4: Weighted score on order picker efficiency per exploration

	Normalized scores			Order picker efficiency
Exploration number	Aisle changes	Store time	Retrieve time	Final weighted score
Score weights	0,600	0,200	0,200	
1	0,502920269	0,2	0,2	0,902920269
2	0,6	0,141403977	0,094292861	0,835696839
3	0	0	0	0
4	0,382165661	0,140299168	0,168273398	0,690738227

Table 6.5: Research policy performance on qualitative requirements

	Future data is required	**State of warehouse is considered**	**Decision moment aisle considerations**	**Total score**
Weight	0,250	0,500	0,250	
Baseline	0,6	0,07546	0,327778	0,269674
Configuration 1	0,2	0,590719	0,261111	0,410637
Configuration 2	0,2	0,333821	0,411111	0,319688

6.4 Policy evaluation

In this section, we evaluate the proposed policies by comparing their performance to the baseline policy. From the policy exploration experiments, it is known that we should assign 9 full aisles, 3 mix aisles and 3 empty aisles in the first stage of the proposed policy setup.

6.4.1 Policy Configuration 2 bottlenecks

The restricted occupation based resource assignment results show substantial limitations with regards to the warehouse effectiveness and failure to produce usable results. This is caused by a longer average shipping time, with exceptionally long outliers. To summarize, 63.65% of the pallets are stored with AGVs, and 22.37% of pallets are picked with AGVs under policy Configuration 2. The average dock-to-stock time is 1425.47 seconds, and the average shipping time is 3369.47 seconds. In the results, we observe 38 days where the average shipping time becomes more than 12 hours. The long shipping time outliers are caused by a backlog in the outbound workload. Each replication eventually reaches a state where the outbound orders of the previous day are not completed yet, causing excessive delays in the orders of the current day, because the docks are blocked. We conclude that Configuration 2 yields no representative results, and is therefore not suitable for GVCL, as the policy results in a total bottle-neck due to too long picking times. Therefore, in the remainder of this study, we only focus on the baseline policy and the occupation based resource assignment combined with the split lot workload policy - this combination is referred to as Configuration 1.

6.4.2 Overview of performance

The results per replication are shown in Appendix D.2.2. The mean values of the selected KPIs of the four replications are shown in Table 6.6. We can see that Configuration 1 requires 10.20% fewer aisle changes than the baseline policy. The average store time and retrieve time per pallet decreased 12.43% and 16.14% respectively. Configuration 1 also results in a lower average dock-to-stock time than the Baseline, with a decrease of 11.58%. The average shipping time in the

Table 6.6: Summary statistics of policy evaluation simulations (times in seconds)

Experiment	Replications	RatioAisleCh	AvgStoreT	AvgRetrieveT	AvgDockToStockT	AvgShippingT	RatioStoreAuto	RatioPickAuto	RatioTrafficFault
Baseline	4	0.2279	933.0264	303.2323	1690.7584	2142.0601	0.4736	0.4758	0.0000
Configuration 1	4	0.2046	817.0835	254.3025	1494.9863	2330.2163	0.9260	0.4004	0.0195

warehouse under policy Configuration 1 is 8.78% higher than with the Baseline policy. The fraction of pallets stored with AGVs is increased by 95.51% compared to the baseline, and the ratio of pallet picks with AGVs is decreased by 15.84 % compared to the Baseline. The number of times a task needs to be performed manually in an AGV aisle is higher in Configuration 1, with a ratio of 0.019 aisle violations, compared to 0 in the baseline.

6.4.3 Interpretation of results

In this subsection, more details are provided about the performance of the warehouse under the policy Configuration 1 compared to the Baseline policy. In this analysis, we consider the workload per day to investigate the impact on the performance. The first point of interest is to assess how much of the workload in the warehouse is handled by the AGVs.

Work done by AGVs

The fraction of inbound pallets that are stored with AGVs ranges from 0.7143 to 1.0 under Configuration 1, and from 0.248 to 0.884. In Figure 6.4 it can be seen that the number of pallets stored with an AGV slightly decreases when the inbound workload increases under Configuration 1, whereas the opposite is true for the Baseline policy. An explanation for this is that the warehouse is split per the number of aisles in the Baseline policy, not per the number of storage spaces. The aisles on the right-hand side of the warehouse have 6 layers, versus five layers on the right-hand side of the warehouse. In configuration 1, when there is a high workload, the chance of a pallet being stored in a 'full' aisle, assigned to manual operators, is greater.

When comparing the average fraction of pallets stored with AGVs to the overall workload, Figure 6.6 the fraction is more consistent, around 0.9. We conclude that the fraction of pallets stored with AGVs depends only on the inbound workload in Configuration 1. Comparing the fraction of pallets picked by AGVs, we can see that the baseline policy allows for more AGV picks, see Figure 6.5. This is because under the Baseline policy, AGVs have a fixed working zone, and all pick and store tasks in this zone will be performed by AGVs. In the proposed policy used by Configuration 1, fewer aisles are assigned to AGVs, and the storage assignment is focused on maximizing AGV storage. Figures 6.5 and Figure 6.7 show that the fraction of pallets picked by AGVs is relatively steady among most workloads. From 900 pallets outbound per day it can be seen that the number of pallets picked by AGVs starts decreasing under Configuration 1. We conclude that both policies have a predictable amount of tasks assigned to AGVs under different workload scenarios. Policy Configuration 1 improves the fraction of pallets stored with AGVs by 95.51% against a decrease of 15.84% in pallet picks, compared to the Baseline policy.

Dock-to-stock time dependent on workload

Recall that the dock-to-stock time is the time between the arrival of a truckload on the ATLS and the storage of the last pallet in the truckload. Under policy Configuration 1, the dock-to-stock time slightly increases from 22 minutes to 28 minutes as the number of daily inbound pallets

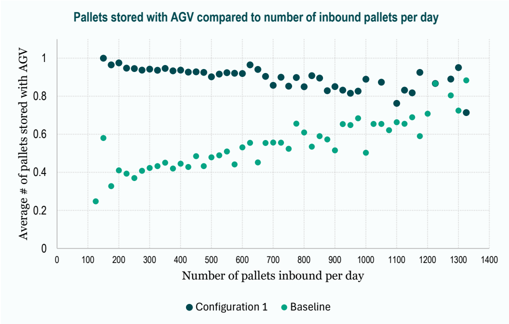


Figure 6.4: Fraction of pallet stored with AGV compared to inbound workload

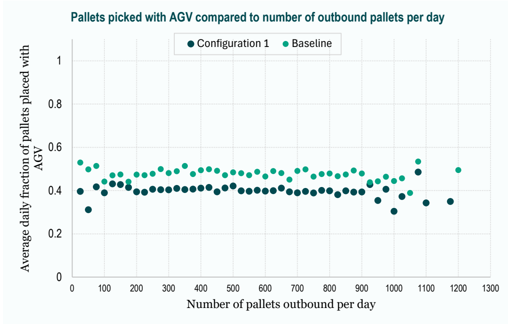


Figure 6.5: Fraction of pallet picked with AGV compared to outbound workload

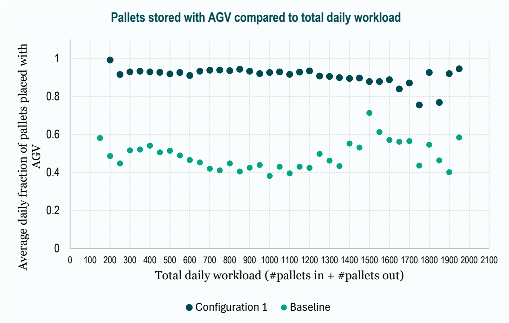


Figure 6.6: Fraction of pallet stored with AGV compared to total workload

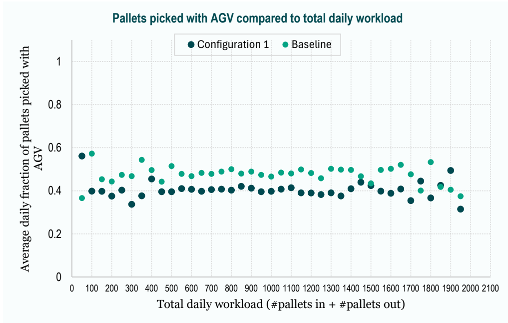


Figure 6.7: Fraction of pallet picked with AGV compared to total workload

increases, see Figure 6.8. Under the Baseline policy, the time also increases, but it starts out higher. When comparing the average dock-to-stock time to the total daily workload, we can see that it increases as the workload increases, see Figure 6.12. We conclude that in most workload scenarios, Configuration 1 has a lower dock-to-stock time than the Baseline policy.

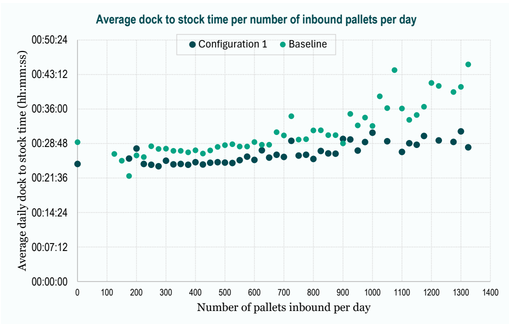


Figure 6.8: Average dock-to-stock time compared to inbound workload

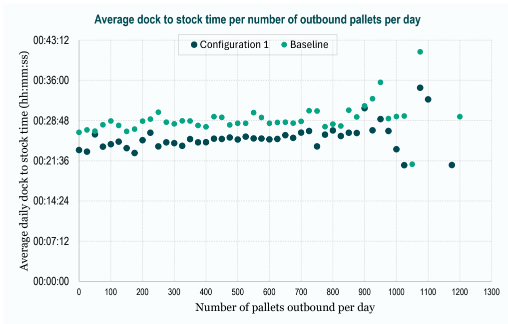


Figure 6.9: Average dock-to-stock time compared to outbound workload

Shipping time dependent on workload

The shipping time is the time between the release of an order until the last pallet from the order is placed on the shipping dock. We can see that for both the Baseline policy and policy Configuration 1, the average shipping time varies depending on the workload. The difference between the two policy combinations is on average 8.78%. The variation between average ship times can be caused by the way orders are released, as they arrive randomly at the warehouse, and in this simulation are not planned to be spread out throughout the day, or prepared the day before. We can conclude that the Baseline policy causes a lower average shipping time. We expect that improvements can be made by planning the outbound orders. Arrivals are known before, so during slow hours, some orders could potentially already be released for picking.

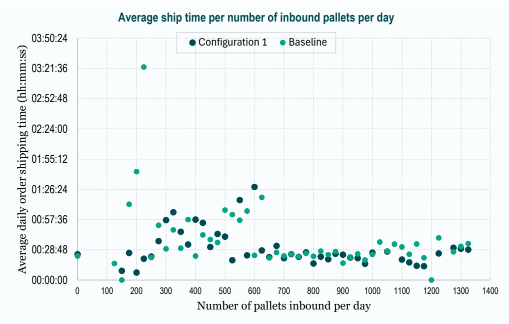


Figure 6.10: Average shipping time per order compared to inbound workload

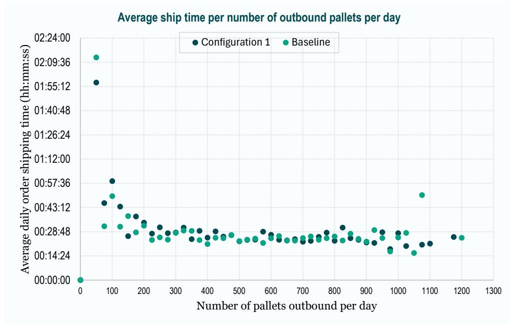


Figure 6.11: Average shipping time per order compared to outbound workload

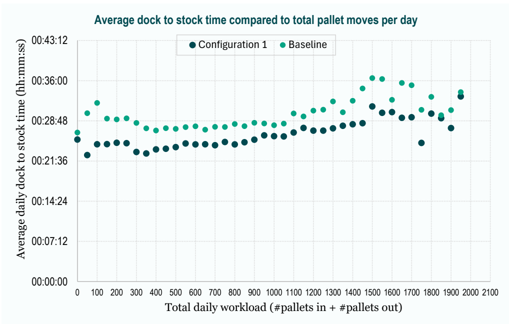


Figure 6.12: Average dock-to-stock time compared to total daily workload

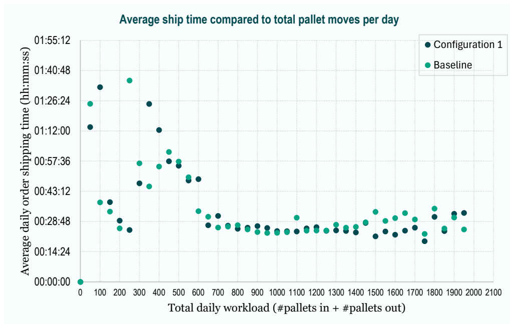


Figure 6.13: Average shipping time compared to total daily workload

Overtime

By tracking the number of tasks performed after 18:00 each day in the simulation, we can compare how the policies compare with regard to causing overtime. Figure 6.16 shows that on average, tasks are still left to do after 18:00. This amount increases as the workload per day increases. The increase under the Baseline policy is greater than under policy Configuration 1. No direct link is visible between the inbound demand and the pallet moves performed during overtime, see Figure 6.14. When looking at the tasks performed during overtime based on the number of outbound pallets per day, Configuration 1 performs better in most cases, see Figure 6.15. Similar to the impact of outbound orders on shipping time, the overtime required could be caused by how outbound orders are handled. Whereas inbound orders can arrive at most 1 hour before the end of a GVCL working day, the simulation allows outbound orders to be released at any time during working hours. An order released just before closing time will cause overtime.

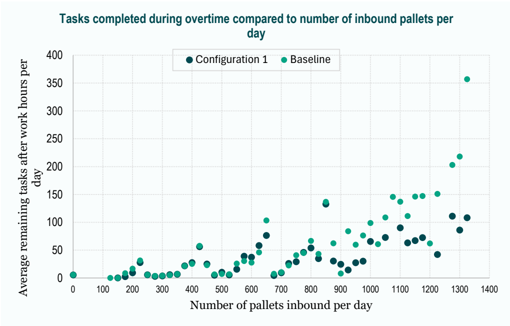


Figure 6.14: Average number of tasks performed during overtime compared to inbound workload

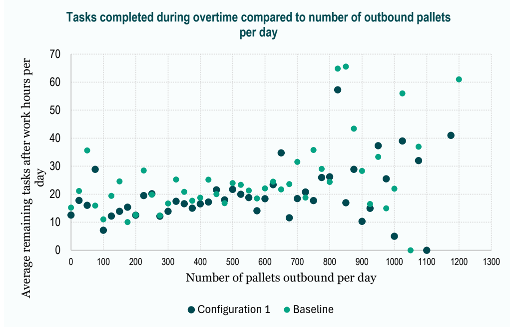


Figure 6.15: Average number of tasks performed during overtime compared to outbound workload

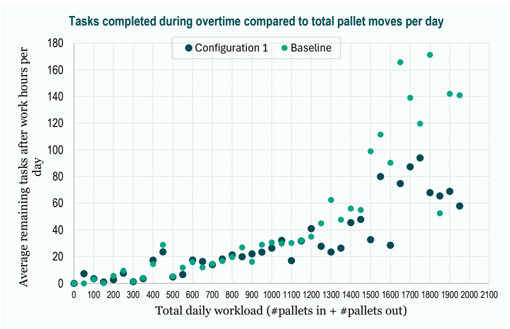


Figure 6.16: Average number of tasks performed during overtime compared to total daily workload

6.5 Policy comparison

The beginning of Section 6.4 showed that policy Configuration 1 performed better than the Baseline on most KPIs. In this section, we consider all requirements for the storage policy, and all aspects of the desired performance to make an informed decision. The average performance of the Baseline and policy Configuration 1 experiments is normalised, and multiplied by the category and KPI weight. The results are shown in Table 6.7. This also includes the qualitative assessment of the practical aspects as described in Section 6.3.3. The AHP shows that despite the Baseline outperforming Configuration 1 on the average shipping time, number of aisle assignment violations, and practical implications, overall, the policy Configuration 1 outperforms the Baseline based on the weighted performance comparison.

Table 6.7: Results Analytical Hierarchy Process decision making

	Order picker efficiency			Warehouse effectiveness			
KPI	RatioAisleCh	AvgStoreT	AvgRetrieveT	AvgDockToStockT	AvgShippingT	RatioStoreAuto	RatioPickAuto
KPI weight	0.6	0.2	0.2	0.210572621	0.389380568	0.337469882	0.06257693
Baseline	0.00000	0.00000	0.00000	0.00000	0.19918	0.00000	0.03201
Configuration 1	0.19442	0.06481	0.06481	0.10771	0.00000	0.17262	0.00000

	Restrictions	Practical aspects			
KPI	RatioTrafficFault	Future data required	State of warehouse considered	Decision moment aisle considerations	**Final score**
KPI weight	1	0.25	0.5	0.25	
Baseline	0.11358	0.00000	0.00000	0.00417	**0.34893**
Configuration 1	0.00000	0.00000	0.00000	0.00332	**0.60769**

6.6 Conclusions

In this chapter, we have used a DES to assess possible storage policy heuristics that were formulated in Chapter 4. Pilot simulation runs were performed to determine the warmup period, run length and number of replications. This results in 4 replications per experiment, with a run length of 460 days after 46 warmup days. We performed exploration experiments to identify a suitable number of aisles per class in the occupation based resource assignment. We found that 9 full aisles, 3 mix aisles, and 3 empty aisles per compartment result in the most efficient order-picking setup. Next, we compared the Baseline policy and policy Configuration 1. The Baseline policy splits the warehouse in the middle, assigns half of the aisles to AGVs, and uses a greedy storage assignment policy, which places pallets in the closest open position, or the same aisle as pallets with the same lot number. Policy Configuration 1 uses occupation based resource assignment to assign each aisle to a class (full, mix or empty), assigns manual operators to the full class, and AGVs to the mix and empty class. Configuration 1 uses the split lot workload storage assignment policy to assign storage locations to the empty and mixed aisles. Simulation experiments are used to determine the performance of the Baseline policy and policy Configuration 1, and the AHP decision-making is used to translate the mix of KPIs into a final score to determine which policy performs best for the requirements of GVCL management. The following conclusions can be drawn from the policy comparisons:

- Separating the inbound and outbound product flow by introducing aisle classification based on the occupation rate reduces the average storage time, the average pick time, and the required aisle changes per pallet move,
- The average time to store all products in an inbound truckload can be lowered by increasing the amount of pallets stored with AGVs compared to storing them with manual equipment,
- A reduction in the amount of pallets picked automatically correlates to an increase in the shipping time of outbound orders,
- A higher workload, as number of pallets to store or pick per day, leads to increased activity during overtime, despite a consistency in average dock-to-stock time and average shipping time.

The findings from this study will be evaluated in the next chapter.

7 CONCLUSIONS AND RECOMMENDATIONS

The simulation results are used to conclude this research and to answer the main research question in section 7.1. The practical implications and additional recommendations to the management of GVCL are discussed in Section 7.2, and we describe the limitations in Section 7.3. Finally, we discuss recommendations for future research in Section 7.4.

7.1 Conclusions

Recall the research goal formulated in section 1.3.3:

> "To develop a storage location assignment policy and retrieval policy, considering task division between automatic and manual handling, that reduces the material handling and intersecting flow, under the given restrictions in the new GVCL warehouse."

We reached this goal by answering the research questions formulated in 1.4. The context analysis described the required performance of the new GVCL warehouse to answer Research Question 1. The policy must enable GVCL management to run an effective warehouse with efficient order picking while considering the material handling restrictions. The policy must be practical to implement in the warehouse. The context analysis revealed the specific focus on formulating a policy that helps to:

- Prevent AGVs and manual operators needing to access the same aisle,
- Store products by AGV to not restrict the retrieval process, and efficiently use the ATLS,
- Practically, there is a strong preference to determine the aisle assignment on a daily basis, or less.

In the literature review, we provided an overview of the characteristics of GVCL and how this context helps us provide solutions to the selected core problems. Based on the literature we concluded that GVCL is a picker-to-parts unit load storage system, emphasizing the importance of considering put-away, storage, and order picking simultaneously. We classified the problem we are trying to solve as the Adaptive Storage Location Assignment problem. The problem instance of GVCL can be classified as a $ASLA$-HF-PCI problem. This problem can not be solved to optimality in polynomial time. The literature review has not revealed a ready-made or adjustable policy that can apply to the specific GVCL context, but the warehouse and problem characteristics justify a unique approach. Based on the context analysis and literature review, we conclude that the storage assignment can best be split up into two stages: stage 1 is used to determine which resource type is allowed in which aisle, and stage 2 is used to determine which aisle to assign an incoming product to.

To answer Research Question 3, we formulated a ‘basic policy’ where a compartment is split into an automatic and manual zone, and products are stored greedy, but as close to the same lot number as possible. As an improved policy, we present the Occupation Based Resource Assignment policy for stage 1, combined with Split Lot Workload Assignment policy in stage 2. The performance was then evaluated in a simulation study to answer Research Question 4.

From the results, we conclude that it is recommended to GVCL to implement the occupation based resource allocation procedure at the start of each day. Per compartment, it is decided to classify each aisle into one of three categories: full, mix, and empty. The aisles with the lowest occupation ratio are assigned to the class empty, and the aisles with the highest occupation ratio are assigned to the class full. Aisles which do not fall within these classes are classified as mix aisles. Next, AGVs are assigned to the empty and mix aisles, and manual operators are assigned to the full aisles. Exploratory simulation experiments suggest using 9 full aisles, 3 mix aisles and 3 empty aisles per compartment, as this yields the most efficient picker operations.

For each incoming truckload, we recommend the split-lot workload policy. This policy uses the knowledge that items part of a small lot size have a higher chance of all being in the same outbound order, hence reducing the number of aisle changes required by the narrow aisle equipment. Larger lot sizes are expected be split in both the inbound truckloads and outbound orders, therefore there is no need to store these all in one aisle. Lots that are not split are assigned to empty aisles. Lots that can be split are assigned to mix aisles on days with a low workload, and to full aisles on days with a high workload, to accommodate dual load trips.

By using the occupation based resource assignment combined with the split lot workload policy, improvements can be achieved compared to the baseline approach of splitting the warehouse into a manual and AGV zone and assigning products to a location based on a greedy rule of thumb. We can reduce the average number of aisle changes per pick or place task by 10.20%. The average store time per pallet is reduced by 12.43%, and the pick time is reduced by 16.14% using the new policy combination. The simulation study has shown that the average dock-to-stock time can be reduced by 11.58%, but causes an increase in the shipping time of 8.798%. This is explained by the increased fraction of pallets stored with AGVs, as our policy raises this fraction 95.51%. However, our policy reduces the fraction of pallets picked by AGVs, the results show a decrease of 15.84%. By prioritising AGV work on the inbound part of the logistic process, storage and pick time can be decreased, with the drawback of increasing the sipping time. The AHP is used to underpin the choice for the new policies. Based on the importance of the KPIs, we conclude that the occupation based resource assignment combined with the split lot workload policy does indeed perform better than the baseline policy. It scores better on the categories of order picker efficiency and warehouse effectiveness but requires flexibility when picking a pallet stored manually in an aisle assigned to AGVs, which occurs on average in 1.95% of the pallet picks. Further practical implications are discussed in the next section.

7.2 Practical implications

To best benefit from the added performance of operating a heterogeneous picker fleet in the unit load warehouse Compartments C and D of GVCL, we recommend GVCL to implement a two-stage storage policy. The Occupation Based Resource Assignment is recommended to use before the start of each workday, and for each inbound order announcement, we recommend the Split Lot Workload policy. We recommend using the first policy to assign 9 aisles per compartment to manual equipment, to allow for manual picking activity. The other 6 aisles in the compartment are

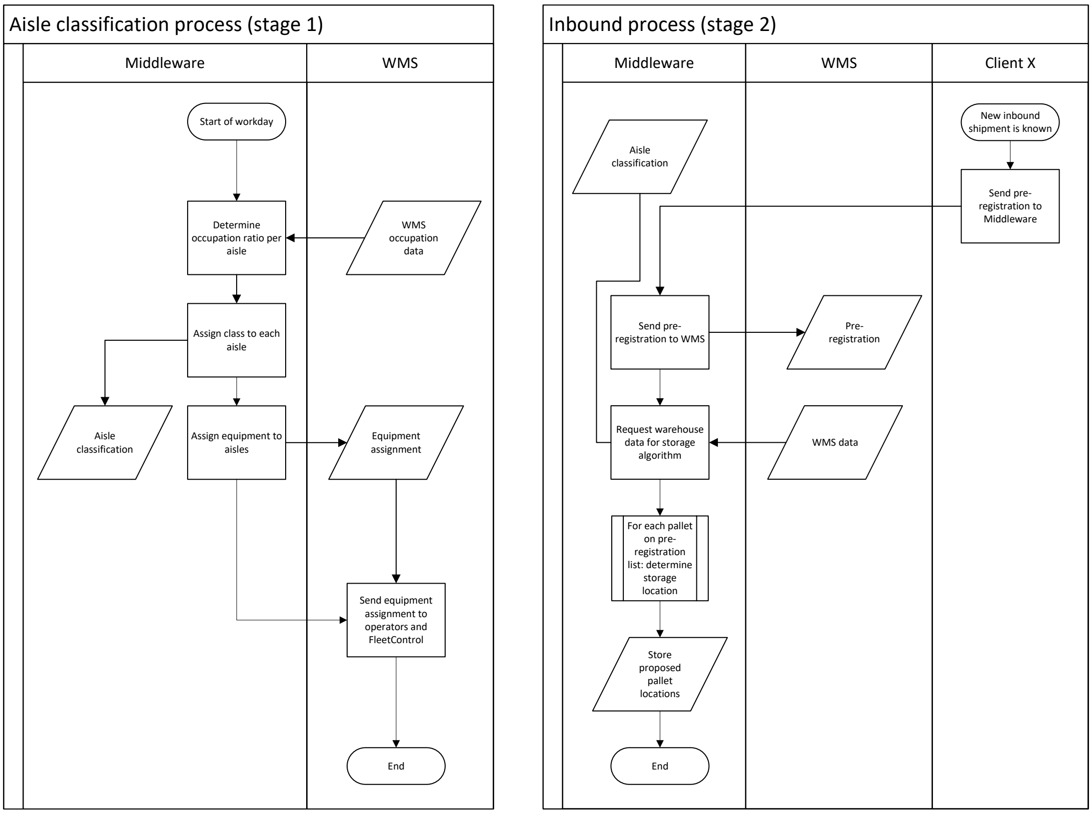


Figure 7.1: Illustration of implementation of 2-stage heuristic in the digital environment of GVCL

assigned to AGVs. The AGVs are used to primarily handle storage tasks. With this configuration, 92.60% of the inbound pallets are stored with AGVs, and 40.04 % of the outbound pallets are picked with AGVs, compared to 47,36% and 47.58% under the baseline policy respectively.

7.2.1 Implementation of heuristics

The WMS is the core of the information management and data distribution in the GVCL warehouse, and it generates pick lists which are accessed by manual operators and FleetControl for the AGVs. The WMS also contains all information about the contents of the warehouse. To implement the policy, we recommend GVCL to follow the framework of Gorbe et al. (2020). This framework uses integration between the WMS, an external module to perform the ASLA, and the Enterprise Resource Planning (ERP) system. In the context of GVCL, adjustments are made to deal with the limitations of the WMS and the interface that Client X uses. BBI can develop an external module, referred to as middleware, that acts as an interface between the WMS and the interface of Client X. The middleware can import and request data from the WMS via an API interface. We recommend that GVCL lets the middleware extract the required data to perform the occupation based resource assignment heuristic, and the split lot workload assignment. We advise against using the middleware to store warehouse data, this should be central in the WMS. An illustration of the flowchart of the required interactions between the interface of Client X, the middleware from BBI and the WMS is shown in Figure 7.1.

7.2.2 Impact on other stakeholders

Furthermore, we advice GVCL to use the simulation results to update the agreements made with Client X and the transportation companies involved with the Wormer product flow. The simulation results show that an average dock-to-stock time of 24.9 minutes is possible. That after a truck unloads at an ATLS, it can be expected that it takes 24.9 minutes until the ATLS is empty, and the next truck can unload. The average shipping time is 38.83 minutes if the recommended policies are implemented. We recommend GVCL management to release outbound orders to the warehouse at least 38.83 minutes before the transport company arrives to load the trailer or container. With the policy of alternating arrivals at the ATLS between Compartments C and D, we expect no problems with waiting times at the ATLS dock. If GVCL management wishes to prevent overtime, they can also use these times to set a maximum allowed time for inbound and outbound orders to arrive.

7.3 Limitations

This study has limitations that must be considered before accepting the conclusions of this thesis. We consider the limitations imposed by assumptions in the simulation model, as well as limitations in the extent to which the decision space that GVCL has control over is used.

Firstly, even though it was indicated that the GVCL context required a good analysis of the specific restrictions, in the simulation study, not all restrictions were included, specifically with regard to the physical fit of products. In this study, it was assumed that all products fit in each open spot. A limitation was introduced to consider the difference between block pallets and euro pallets. By assigning a fixed zone for block pallets, the level of complexity of the policy was reduced, resulting in a reduction in flexibility in the warehouse. The main impact of this assumption is a reduced capacity.

Another limitation is that in this study, is the extent to which activities other than picking and placing are considered. Value-added logistics, such as relabelling or re-stacking goods on the pallet are left out of scope. In this study, it was also assumed that there are no human or AGV errors, and equipment charging time was not included in the analysis.

A final limitation of this study is that other factors which GVCL has control over are not considered. One flexibility advantage that GVCL has is the fact that working capacity can be scaled by scheduling operators. If more workload is expected, streamlined operations can be achieved by scheduling more operators to work on busy days. Money can be saved by scheduling fewer operators on less busy days. In this research, the scope was set to achieving flexibility by introducing a storage policy, but the effects of staff scheduling were not considered. Another freedom in the GVCL decision space is dock assignment. In this study, it was assumed that each outbound order arrives on a random free dock, while in practice it is preferred to assign an outbound order to a dock close to the aisles where most pallets of that order are stored. The chosen method for selecting a suitable pick option was not extensive, as it only included the preference of picking an item from the compartment where the outbound truck is loaded.

7.4 Future research

In this section, we provide recommendations for future research based on this study. Because this study dealt with new aspects both in the practical context as well as the academic context, we provide suggestions to improve operations for GVCL and BBI, as well as suggestions for future theoretic research in academics.

7.4.1 Research suggestions for GVCL and BBI

Recall from Section 3.1 that the warehouse characteristics of GVCL justify a tailored management approach. This research primarily focused on the put-away activity, but there are other processes in which management can achieve benefits by further researching management strategies. The first suggestion for future research is to consider the scheduling of resources in the warehouse. Here, we propose two levels of detail. If a similar scope is kept, specifically Compartment C and D, the schedule of operators can be tailored to the Wormer product flow, in combination with the performance of the AGVs. Alternatively, by choosing a broader scope, for instance, the full GVCL warehouse, management can use the different process flows to dynamically schedule operators between the different compartments and process flows, and potentially reduce employee costs. Furthermore, we recommend researching the impact of dock assignment on pick times and shipping times. In this study, the decision to always dock inbound trucks alternating between the ATLS in Compartments C and D. The outbound orders are assumed to arrive randomly at a dock door. Because GVCL receives announcements for the orders, the data of the announcements might be used to determine the best location for trucks to dock. Especially on the outbound orders, this requires no additional investments, as the dock doors are already installed. Improvements can be achieved by using the information on the orders to calculate the least expensive dock assignment. For the inbound truckloads, there is less flexibility because each compartment currently has only one ATLS.

In this study, the pick selection method was simplified to choosing the item in the compartment where the outbound order is shipped from, if possible. GVCL is recommended to further research how to select good pick items under the occupationbased resource assignment. This selection method is closely related to the dock assignment.

7.4.2 Research suggestions for academics

This thesis introduced a new adaptive storage location assignment approach that is tailored to the context of a unit load warehouse with a heterogeneous picker fleet. An important gap identified was the level of detail concerning specific warehouse restrictions included in studies. In this study, the main restriction was the impact of placing an item manually or automatically on the freedom to pick an item. We recommend other researchers consider these storage constraints resulting from a hybrid pick fleet in other warehouse settings, especially in warehouses other than unit load warehouses. The impact of the storage decisions increases if storing a new product in one location generates multiple picks from that location.

Furthermore, it is suggested to assess the impact of multistage decision-making. In this research, we worked with two stages - the start of the workday, and the inbound order announcement. It can be beneficial to include more decisions at these stages, for example, the aforementioned dock assignment could be included in the decision based on the inbound order announcement. Including the task release times of the outbound orders into the first stage decision is also a research area that can further improve the performance of the pickers in a hybrid warehouse.

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A ROUTING LOGIC

A.1 Routing logic

The AGV routing is done by the Fleetcontrol of the AGVs itself. Since each unit loads is a full pallet, each item requires a separate trip, recall Figure 2.4. Storage in VNA requires and intermediate step by placing the load in a pick and drop location. When manually unloading, goods are registered as inbound at the dock. When automatically unloading with a chain conveyor, products are registered as inbound at the contour scanner. Therefore, in this overview, we do not consider manual loading or unloading of the truck a part of a trip.

A.1.1 Routing in VNAs

For the VNA forklifts, we consider three options for routing. In these examples, shown in figure A.1, the routes are shown in a green line, and the distance is equal to the length of the green line. The first one is moving from one location to another location in aisle. Here, the travel time is calculated as vehicle speed * distance between locations + the vertical difference between the locations. See example 1 in figure A.1. The second is moving from one aisle to another aisle in the same compartment. Although it looks like choice can made between changing aisles on the north or south cross aisle, this is not possible. Because of other traffic between compartments, changing aisles on the norht cross is prohibited. The travel time is calculated by adding the distance from both pick locations to the south aisle, adding the distance between the aisle * vehicle speed. See example 2.1 and 2.2 in figure A.1. Level of detail can be added by considering time to change side of the aisle (left and right), and determining cornering speed.

A VNA forklift never has to move units between compartments, it only moves units between a storage space and pick-and-drop rack.

A.1.2 Reach truck routing

For the reach trucks, we consider three options for routing. The first option is between the docks, pick and drop locations and contour scanner in the same compartment. Here, the rectilinear distance between two points is used. This is the distance in the x and the y direction added up. This distance is then multiplied by vehicle speed. This is shown as example 2 and 3 in figure A.2. The second option is movement from one of the locations mentioned before (docks, pick and drop locations and contour scanner in the same compartment) to a shuttle rack in the same compartment. The third optionis when a trip needs to be made to another compartment. We introduce a virtual I/O point. The vehicle travels to the I/O point, then to the I/O point in the other compartment. We know the fixed distance between the two I/O points. From I/O point to location we use rectilinear distance. This is shown as example 1 in figure A.2.

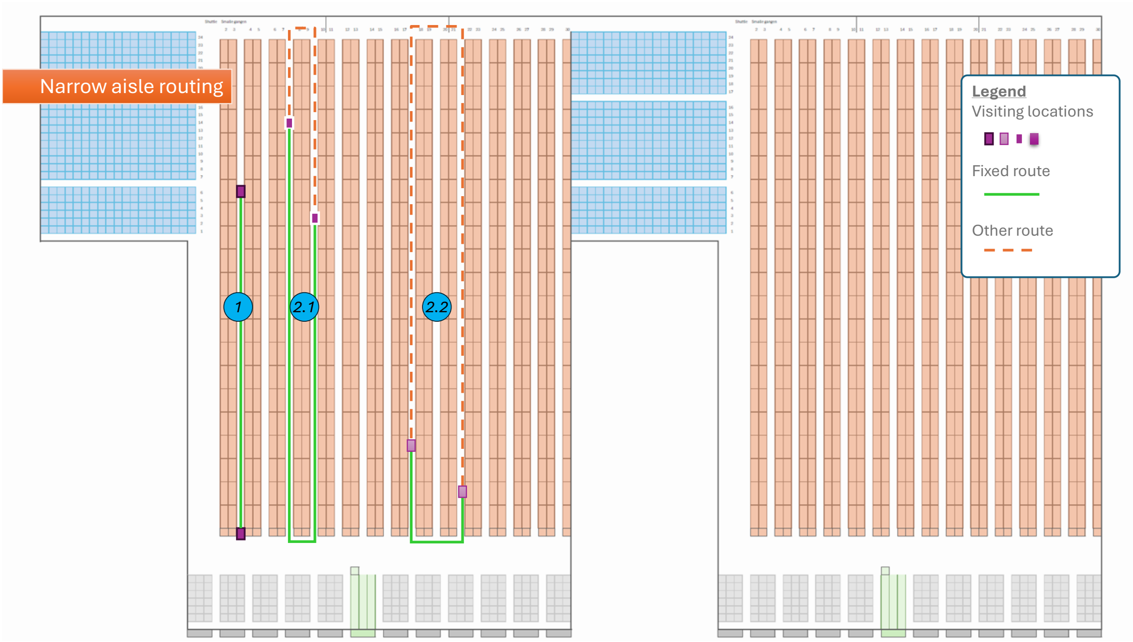


Figure A.1: VNA routing examples

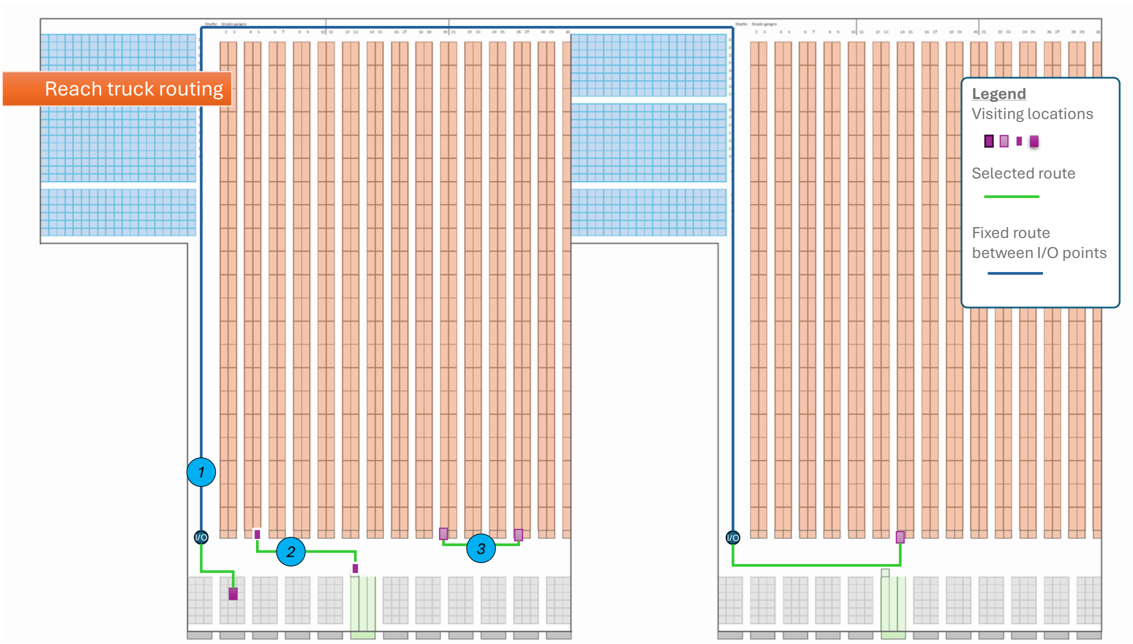


Figure A.2: Reach truck routing examples

B DATA ANALYSIS AND CALCULATIONS

This appendix provides the reader with additional information gathered and analysed in the data analysis phase, as well as other calculations used in this research.

B.1 Seasonality demand

To determine seasonality in the inbound demand, an exploratory data analysis is performed. When it was confirmed that there is seasonality depending on the weekday, a more detailed data analysis was carried out to determine the seasonal factors.

B.1.1 Exploratory data analysis

The available data is graphed to explore if there is possible seasonality present. Given that the demand fluctuates daily, simply graphing the daily demand to determine if there are patterns is insufficient. Using a seven day moving average it can be seen that the demand still fluctuates a lot, and the holiday periods become visible.

Yearly seasonality

The total demand per month per year is graphed to assess if there are patterns visible for monthly seasonality. But as can be seen, both for in- and outbound demand, there is no convincing relationship between the months throughout the years. Note that analysis is also limited by data availability, as the dataset only covers 23 months, so there are no full years to compare and draw strong conclusions from.

Conclusion: in this study, we do not consider the time of year as a factor to consider.

Weekday seasonality

The average demand per weekday per year is graphed and shows the possibility that there is more demand on some weekdays than others.

The inbound demand is highest on Monday and less throughout the week. The outbound demand is zero on Sundays. In 10% of the Saturdays, one order was observed.

We follow the data analysis approach as described by Winston (2004, Chapter 3). We investigate the parameters of the trend-seasonal model, in literature referred to as the Holt-Winters. Since we use the same approach for the inbound and outbound demand, the analysis will be explained in parallel.

The trend-seasonal model is expressed as:

$$D_t = (a + bt) \cdot F_t + \epsilon_t \tag{B.1}$$

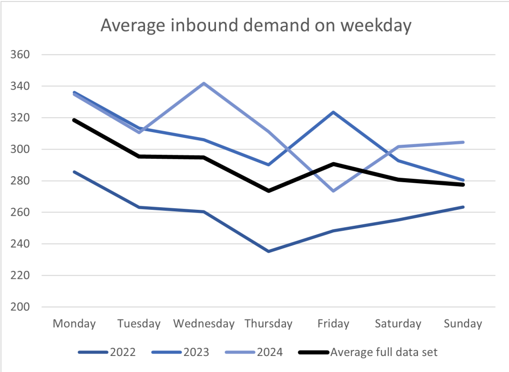


Figure B.1: Observed average inbound demand per weekday per year

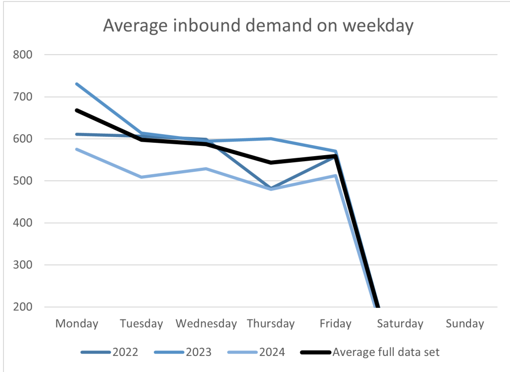


Figure B.2: Observed average outbound demand per weekday per year

where D_t represents the demand in period t, a is the demand level, b is the trend, F_t is the seasonal factor of period t and ϵ_t represents the the independent random variable.

We want to investigate the seasonality of the weekly season, so for each weekday. Therefore, we have $P = 7$ periods. To determine level a, we get a rough estimate $\tilde{a}_t$ by getting a P period moving average.

Next, the seasonal factors are estimated using:

$$F_t = \frac{D_t}{\tilde{a}_t} \tag{B.2}$$

For the outbound data, we omit saturday and sunday from the seasonal factors.

Next, the seasonal factors are normalised and used to depersonalise the available demand data. A regression of the depersonalised data with time as x-axis gives estimates for the initial level and trend.

The findings are summarized in table B.1.

To determine the distribution of the standard error ϵ_t, the demand data is transformed using the equation:

$$\text{Observed deviation} = D_t - (a_0 + bt) \cdot F_t \tag{B.3}$$

Analysis of the transformed data shows distributions that look like a normal distribution. The fitting of a normal distribution is tested with a Chi-square test. For both the inbound and outbound distribution, the test statistic is lower than the Chi-square value with 99% confidence level and 28 degrees of freedom. Therefore we can conclude that the standard error has a normal distribution with mean 0 and standard deviation shown in table B.1.

Table B.1: Overview of demand data analysis conclusions

Parameter	Inbound	Outbound
Initial level a_0	280	332
Initial trend b	0,05	-0,02
Seasonal factors [Monday...Sunday]	[1.0987; 1.0087; 0.9889; 0.9717; 0.9799; 0.9785; 0.9735]	[1,1507; 1,0036; 1,0001; 0,9174; 0,9281; 0,0000; 0,0000]
ϵ_t mean μ	13	160
ϵ_t standard deviation σ	84	196

B.2 Normalised comparison matrix for KPI weights

The normalised pairwise comparison matrices used to determine the importance of KPIs are shown in Figure B.3.

Normalised score importance of categories

	Order picker efficiency	Warehouse effectiveness	Restrictions	Practical aspects	**Final weight**
Order picker efficiency	0.230	0.193	0.484	0.389	**0.3240**
Warehouse effectiveness	0.691	0.579	0.387	0.389	**0.5115**
Restrictions	0.046	0.145	0.097	0.167	**0.1136**
Practical aspects	0.033	0.083	0.032	0.056	**0.0509**

Normalised score order picker efficiency

	Aisle changes	Store time	Retrieve time	**Final weight**
Aisle changes	0.60	0.60	0.60	**0.6000**
Store time	0.20	0.20	0.20	**0.2000**
Retrieve time	0.20	0.20	0.20	**0.2000**

Normalised score warehouse effectiveness

	dock to stock time	shipping time	Ratio of products stored automatically	Ratio of products retrieved automatically	**Final weight**
dock to stock time	0.108	0.400	0.026	0.308	**0.2106**
shipping time	0.108	0.400	0.742	0.308	**0.3894**
Ratio of products stored automatically	0.757	0.100	0.185	0.308	**0.3375**
Ratio of products retrieved automatically	0.027	0.100	0.046	0.077	**0.0626**

Normalised score practical aspects

	future data is required	state of warehouse is considered	Decision moment aisle considerations	**Final weight**
future data is required	0.250	0.250	0.250	**0.2500**
state of warehouse is considered	0.500	0.500	0.500	**0.5000**
Decision moment aisle considerations	0.250	0.250	0.250	**0.2500**

Figure B.3: Normalised pairwise comparison matrices for KPIs

B.3 Pairwise comparison matrices for qualitative KPIs

The pairwise comparison matrices used to determine the performance of policies on practical aspects are shown in Figure B.4.

Pairwise comparison matrices

Future data required:

	Baseline	Configuration 1	Configuration 2
Baseline	1	3	3
Configuration 1	1/3	1	1
Configuration 2	1/3	1	1

State of warehouse considered

	Baseline	Configuration 1	Configuration 2
Baseline	1	1/7	1/5
Configuration 1	7	1	2
Configuration 2	5	1/2	1

Decision moment aisle considerations

	Baseline	Configuration 1	Configuration 2
Baseline	1	1	1
Configuration 1	1	1	1/2
Configuration 2	1	2	1

Normalised matrices and scores

Future data required:

	Baseline	Configuration 1	Configuration 2	**Score**
Baseline	0.6	0.6	0.6	**0.6**
Configuration 1	0.2	0.2	0.2	**0.2**
Configuration 2	0.2	0.2	0.2	**0.2**

State of warehouse considered

	Baseline	Configuration 1	Configuration 2	**Score**
Baseline	0.08	0.087	0.063	**0.07546**
Configuration 1	0.54	0.609	0.625	**0.590719**
Configuration 2	0.38	0.304	0.313	**0.333821**

Decision moment aisle considerations

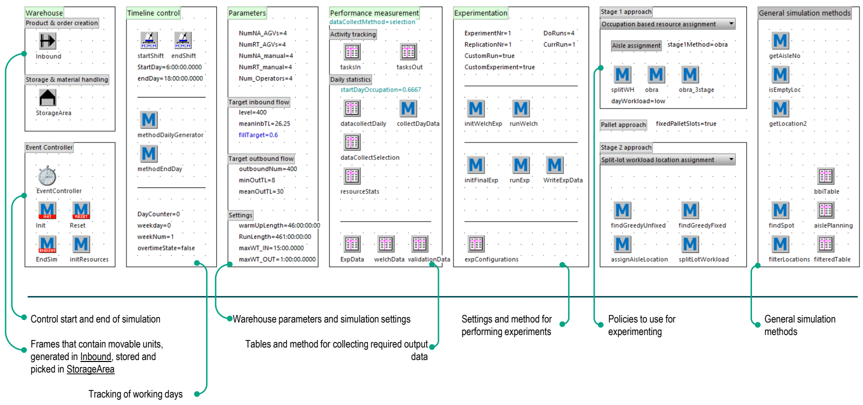
	Baseline	Configuration 1	Configuration 2	**Score**
Baseline	0.33	0.25	0.4	**0.327778**
Configuration 1	0.33	0.25	0.2	**0.261111**
Configuration 2	0.33	0.5	0.4	**0.411111**

Figure B.4: Pairwise comparison matrices and normalised scores for practical aspects

C SIMULATION OVERVIEW

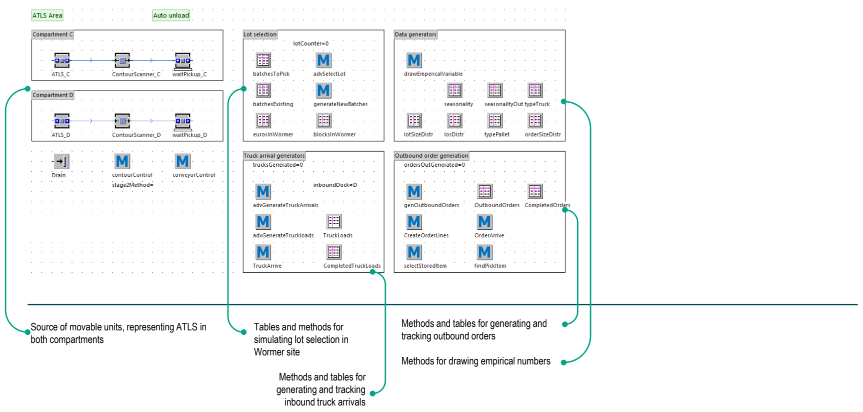
The model is created in object oriented programming software Siemens Plant Simulation. Frames are used to separate different functions of the warehouse and simulation settings. An overview of the frames is shown in Figure C.1. One frame represents the inbound area, the ATLS and contour scanner. Objects representing the incoming products are generated here. One frame represents the warehouse storage area. This is also the working area. Resources are modeled here as static objects. The travel time empty travel time is registered as set-up time of stations, and the loaded travel time is registered as working time of the stations. There are stations representing the AGVs, and stations representing the manual equipment. The overall warehouse control is also developed in this frame: tables containing each storage area, methods to distribute the work among the resources, and methods to register the acitivies such that KPIs can be tracked.

Frame: ControlPanel



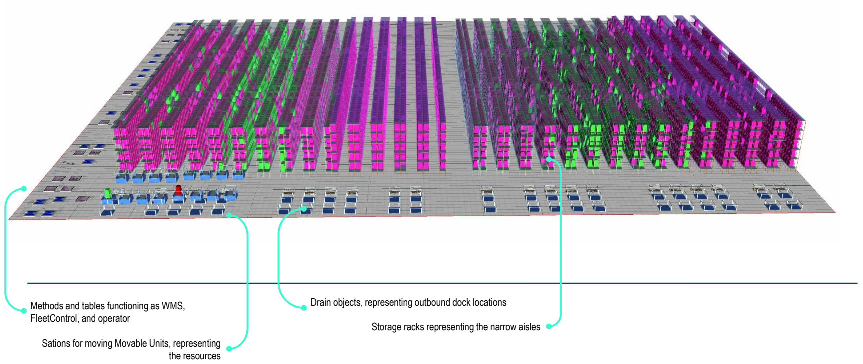
(a)

Frame: Inbound



(b)

Frame: StorageArea



(c)

Figure C.1: Overview of simulation: (a) Control panel (b) Frame Inbound, where in- and outbound orders are generated (c) Snapshot of simulation frame StorageArea in 3D view during an experiment

D SIMULATION OUTPUTS AND CALCULATIONS

D.1 Calculation required number of replications

In Section 6.2.2 we formulated how to determine the number of replications. For each KPI, the confidence interval half-width is determined using calculations in Excel. A copy of the sheet is shown in Figure D.1. The moment the CIHW is lower than the value $\gamma' = 0.0476...$ as calculated in Section 6.2.2. Note that for the KPI 'ratio of traffic faults' is not included, because the reference policy splits the warehouse completely, and the observed ratio is always 0. Since for all other seven KPIs, the CIHW is acceptable after four replications, it is assumed that for the last KPI, this will also be the case.

D.2 Simulation output exploration results

Table D.1 shows the output for each efficiency KPI per exploration replication.

D.2.1 Exploration experiments results

Table D.1 shows the output for each replication of the policy exploration experiments.

Table D.1: Summary statistics exploration experiments aisle division

Exploration	Replication	RatioAisleCh	AvgStoreT	AvgRetrieveT
1	1	0.20	834.03	265.61
1	2	0.21	800.36	264.49
1	3	0.20	831.42	269.51
1	4	0.19	797.02	259.81
2	1	0.19	834.70	302.17
2	2	0.21	849.75	310.77
2	3	0.20	817.42	307.00
2	4	0.20	827.33	303.87
3	1	0.22	882.75	345.33
3	2	0.22	878.60	347.42
3	3	0.22	851.04	334.55
3	4	0.21	877.02	343.13
4	1	0.21	843.62	280.08
4	2	0.20	819.06	276.14
4	3	0.21	837.15	279.97
4	4	0.21	830.63	272.58

n	KPI ratioAC	mean	var	t value	CIHW
1	0,236578045				
2	0,231578784	0,234078414	1,24963E-05	12,70620474	0,135684516
3	0,232269351	0,233475393	7,33906E-06	4,30265273	0,028824025
4	0,233397488	0,233455917	4,89422E-06	3,182446305	0,015078842

n	avgStoreT	mean	var	t value	CIHW
1	911,8462721				
2	905,7332805	908,7897763	18,68433336	12,70620474	0,042734263
3	919,0814507	912,2203344	44,64835401	4,30265273	0,018196114
4	926,6184002	915,8198509	81,59164386	3,182446305	0,01569437

n	avgRetrieveT	mean	var	t value	CIHW
1	309,5917514				
2	314,4518421	312,0217968	11,81024087	12,70620474	0,098956721
3	302,8417932	308,9617956	33,99594207	4,30265273	0,046879657
4	304,5000629	307,8463624	27,64072601	3,182446305	0,02717514

n	avgDockToStockT	mean	var	t value	CIHW
1	1664,563129				
2	1671,346506	1667,954817	23,00710189	12,70620474	0,025837324
3	1694,553931	1676,821189	247,3411741	4,30265273	0,023298992
4	1706,957344	1684,355228	391,9410791	3,182446305	0,01870285

n	avgShippingT	mean	var	t value	CIHW
1	1457,394952				
2	1539,060192	1498,227572	3334,605701	12,70620474	0,346294274
3	1513,541143	1503,332096	1745,471338	4,30265273	0,069036235
4	1518,195397	1507,047921	1218,876989	3,182446305	0,03686243

n	ratioStoreAuto	mean	var	t value	CIHW
1	0,475070817				
2	0,498704517	0,486887667	0,000279276	12,70620474	0,308381848
3	0,474692352	0,482822562	0,000189213	4,30265273	0,070772381
4	0,48965765	0,484531334	0,000137822	3,182446305	0,038553878

n	ratioPickAuto	mean	var	t value	CIHW
1	0,476267871				
2	0,501548674	0,488908272	0,00031956	12,70620474	0,328510564
3	0,475589346	0,48446863	0,000218911	4,30265273	0,075865411
4	0,490251212	0,485914276	0,0001543	3,182446305	0,040677545

Figure D.1: Confidence interval half-width calculations for KPIs

D.2.2 Policy evaluation results

Table D.2 shows the output for each replication of the policy evaulation study.

Table D.2: Summary statistics comparison experiments aisle division

Exploration	Replication	RatioAisleCh	AvgStoreT	AvgRetrieveT	AvgDockToStockT	AvgShippingT	RatioStoreAuto	RatioPickAuto	RatioTrafficFault
Baseline	1	0.231	931.933	313.234	1696.639	1769.113	0.497	0.497	0.000
Baseline	2	0.225	929.214	294.556	1682.078	2533.517	0.455	0.458	0.000
Baseline	3	0.233	952.273	320.028	1746.460	1814.689	0.496	0.497	0.000
Baseline	4	0.222	918.685	285.111	1637.857	2450.921	0.447	0.451	0.000
Configuration 1	1	0.207	827.137	253.000	1531.563	2220.107	0.922	0.398	0.018
Configuration 1	2	0.199	783.815	252.067	1407.979	2576.870	0.926	0.385	0.020
Configuration 1	3	0.207	829.970	259.807	1532.102	2634.625	0.929	0.415	0.020
Configuration 1	4	0.205	827.413	252.335	1508.301	1889.264	0.927	0.404	0.020