MASTER THESIS INDUSTRIAL ENGINEERING AND MANAGEMENT

Redesigning the warehouse and internal logistics at Scania Production Zwolle using discrete event simulation

Author:
T.J. Looms
S2351315

Supervisors University of Twente:
Dr. L. Xie
Prof. Dr. Ir. M.R.K. MES

Supervisor Scania Production Zwolle:
K.G.J. Grit MSc

Redesigning the warehouse and internal logistics at Scania Production Zwolle using discrete event simulation

Master Thesis in Industrial Engineering and Management

Author
T.J. Looms

Home Institute
University of Twente
Drienerlolaan 5
7522 NB, Enschede

Hosting Institute
Scania Production
Zwolle B.V.
Russenweg 5
8041 AL, Zwolle

Department
Industrial Engineering and Business Information Systems (IEBIS)

Faculty
Faculty of Behavioural, Management, and Social Sciences (BMS)

Programme
MSc Industrial Engineering and Management (MSc IEM)

Specialization
Production & Logistics Management

Internal Supervisors
First supervisor: Dr. L. Xie (Lin)
Second supervisor: Prof. Dr. Ir. M.R.K. Mes (Martijn)

External Supervisor
K.G.J. Grit MSc
Logistics engineer

UNIVERSITY
OF TWENTE.

Preface

In front of you lies my Master Thesis: "*Redesigning the warehouse and internal logistics at Scania Production Zwolle using discrete event simulation*". With this thesis, I will finalize my master's program in Industrial Engineering and Management at the University of Twente with the specialization Production & Logistics Management. I conducted this thesis at Scania Production Zwolle between February and July 2024.

I would like to thank my colleagues at Scania for all the help and support during the thesis. The colleagues in my department (Logistics Engineering) were very interested in the research and helped me with practical insights on the topic. But I also need to thank all colleagues outside of my department who provided me with information and were always open to questions. Finally, I express my gratitude to my company supervisor Koen Grit who guided me greatly throughout this thesis.

Furthermore, I would like to thank my first supervisor Lin Xie for her great support during the thesis. The various rounds of feedback and her expertise in warehousing have certainly steered me in the right direction. I would also like to thank my second supervisor Martijn Mes for his support during the final phase of my thesis.

This thesis marks the end of my period following the Industrial Engineering and Management programs at the University of Twente. Looking back over the past five years following the bachelor and master programs has helped me to develop myself a lot. I look forward to applying what I have learned, both in terms of knowledge and professional skills in my future career. Finally, I would like to thank everyone who has supported me during this time, especially my friends and family.

I hope you enjoy reading my thesis.
Timo Looms

Management summary

This thesis conducted at Scania Production Zwolle, focuses on redesigning the pallet supply warehouse for a new location. The thesis has found three possible new layouts with a lower average throughput time, a smaller required area, and a lower Full Time Employee (FTE) requirement than the current situation.

Context

The largest assembly plant of Scania (a global manufacturer of trucks and busses) is located in Zwolle (Scania Production Zwolle). Within Scania Production Zwolle, the warehouse for the pallet unit supply flow is in an outdated and unconditioned building. This limits the possibilities for warehouse automation and optimization. In addition, Scania may need the location of this warehouse for other activities. Therefore, Scania is considering relocating the pallet unit supply flow warehouse to another building (building Y).

As the layout of the current warehouse is not efficient, relocating the warehouse to building Y provides an opportunity to improve its warehouse layout. Furthermore, relocating the warehouse to building Y affects the logistic flows to the production area. Therefore, this research provides Scania with an overview of the expected effects of relocating to building Y for different warehouse layouts and supply methods. Based on this Scania can make an informed decision on whether to relocate to building Y and, if so, how to design the process and the warehouse. We formulate the overall research goal of this thesis as follows:

Determine the layout and internal logistics for relocating the unit supply flow and analyze the effects this would have compared to the current situation.

Approach

To measure the performance of the layout designs and flow types, this research has set up a performance measurement system. The performance measurement system consists of KPIs in accordance with Scania's objectives. Furthermore, the method of performance measurement is determined. A literature study showed that a Discrete Event Simulation would be the most appropriate way to analyze the expected performance of the layout and flow types in this case.

The literature study also presented existing methods for warehouse design and storage allocation policies. Based on the literature study we made a selection of layouts and storage allocation policies for implementation, from which four layouts and three allocation policies are designed for the case of Scania. These include two variations of conventional layouts, a flying-v layout and a layout based on the design of a CPU (a new method introduced by this thesis). For the allocation policies, the research includes a random allocation policy, a class-based policy (ABC storage policy), and finally a combined allocation policy adapted to the CPU-based layout. For the flow types, this thesis introduces three options considered by Scania. These consist of two variants of lorry transport and one flow type using a bridge over which pallet trucks transport pallet trailers.

A Discrete Event Simulation (DES) model measures the performance of the combinations of warehouse designs, storage allocation policies, and flow types. In the DES model, the possible warehouse designs, storage allocation policies, and flow types are implemented as well as the current situation. After setting up the experiments, the simulation model runs the experiments to obtain the results of the provided options.

Results

The experiment results consist of two main parts, firstly there is the part that only concerns the internal warehouse processes. These results do not consider what happens after the pallets leave the warehouse and only focus on finding the best possible warehouse layout and allocation policy. These results show that the current warehouse design is inefficient compared to the layouts generated in this research. The best-performing warehouse designs are the two CPU-based layouts with a combined allocation policy and a conventional layout with dedicated half-euro locations using an ABC storage policy. These options achieve improvements on all the established KPIs.

For the three most promising solutions from the internal warehouse processes (described above), this thesis analyzed the effects of the adjusted logistic flows due to the relocation. The results show that if Scania uses a bridge to transport towards the production area and implements one of the three best layouts, Scania can achieve significant performance improvements at the cost of an investment. If Scania does not invest in a bridge and uses lorry transport instead, relocating to the Y-building would result in an increase of average throughput time per order but an improvement in the other KPIs. Table 1 gives an overview of the expected outcomes for Scania's options on the KPIs. Note that in the table the average order throughput time is split up in the total throughput time and the throughput time within the warehouse.

Decision	**Average order throughput time**	**Required number of FTE**	**Percentage of pallet trailers on time**	**Required space for the warehouse**
No relocation or redesign (current situation)	30:05 In warehouse: 16:25	26	98,82%	7249 m^2
Relocation without bridge conventional layout C2	53:46 (+78.68%) In warehouse: 15:12	24 (-7.69%)	100% (+1.18%)	3666 m^2 (-49.43%)
Relocation without bridge CPU-based layout alternative 1	53:28 (+77.67%) In warehouse: 14:40	24 (-7.69%)	100% (+1.18%)	4242 m^2 (-41.48%)
Relocation without bridge CPU-based layout alternative 2	53:24 (+77.49%) In warehouse: 14:56	24 (-7.69%)	100% (+1.18%)	4112 m^2 (-43.28%)
Relocation with bridge conventional layout C2	28:18 (-5.94%) In warehouse: 15:12	20 (-23.07%)	100% (+1.18%)	3666 m^2 (-49.43%)
Relocation with bridge CPU-based layout alternative 1	27:42 (-7.93%) In warehouse: 14:40	20 (-23.07%)	100% (+1.18%)	4242 m^2 (-41.48%)
Relocation with bridge CPU-based layout alternative 2	27:50 (-7.48%) In warehouse: 14:56	20 (-23.07%)	100% (+1.18%)	4112 m^2 (-43.28%)

Table 1: Overview of decision options with expected outcomes

Conclusion and recommendations

This thesis demonstrates that Scania can significantly improve its internal warehouse processes as the current layout has a large amount of required area and an inefficient layout. Relocating to the Y building presents the opportunity to redesign the warehouse. For the relocation, we recommend that Scania invests in a bridge as it reduces average throughput time, and the savings of the FTE reduction will earn back the investment over time. If Scania does not invest in a bridge, relocation still offers benefits, however at the cost of higher throughput time.

Furthermore, regarding the contribution to literature, this thesis introduces a new method for warehouse design. This research has shown that in the case of Scania, this CPU-based layout is the best-performing layout in terms of average throughput time.

Table of contents

List of Figures

List of Tables

List of equations

1 Introduction

This chapter introduces the research performed for this master thesis. It provides the reader with the necessary information on the company, the motivation for the research, and the problem solved by this research. Furthermore, it defines the scope of the research and the approach it follows.

1.1 Company Introduction

Scania is a global manufacturer of trucks and buses. Scania originates from Sweden and has approximately fifty thousand employees globally. Of these, four thousand employees work in the Netherlands and twenty-nine hundred at Scania Production Zwolle.

The corporate mission of Scania is to drive the shift towards a sustainable transport system, creating a world of mobility that is better for business, society, and the environment. To achieve this, and to be a leader in sustainable transport Scania strives for continuous improvements. Figure 1 shows the principles and methods for continuous improvement applied at Scania Production.

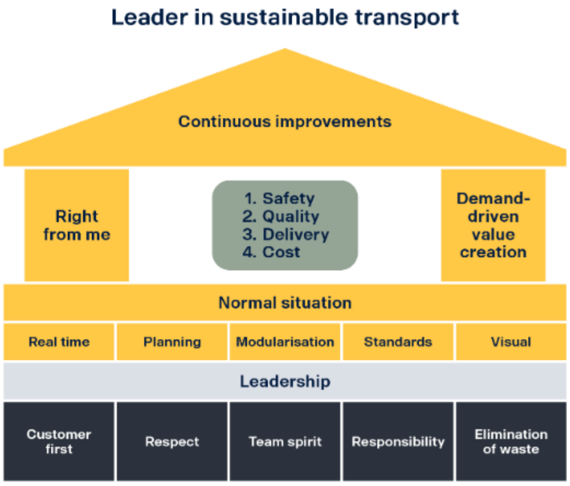

Figure 1: The Scania Production System (SPS)

Scania Production Zwolle (from now on referred to as Scania) is Scania's largest assembly plant. Within Zwolle, Scania assembles the separate parts supplied from other factories into end products (the trucks). From Zwolle Scania ships the trucks to more than eighty countries over the globe. Scania Production Zwolle accounts for about sixty percent of the total production of trucks for Scania.

1.2 Research Motivation

Currently, the pallet supply warehouse (unit supply replenishment method) for the two production lines at Scania Production Zwolle is in an outdated and unconditioned building (old building). In the current situation, Scania has limited opportunity for optimization due to the design of the current building. In addition, Scania may need the current location for future activities. Near the factory, a building (Building Y) is available for temporary storage of pallets before Scania moves the pallets to the production area.

As Scania Production Zwolle is considering moving the pallet supply to the Y building, they want to analyze layouts of the pallet storage within the Y building and assess how this would affect performance on Key Performance Indicators (KPIs) compared to the current situation. This enables Scania Production Zwolle to determine whether to move the pallet supply from the old building to the Y building.

The goal of this research is, therefore, to determine how Scania Production Zwolle can optimize the pallet supply from the Y building by analyzing the impact of several warehouse designs and other key decisions in the process. By comparing the results for building Y to the current situation this research recommends whether Scania Production Zwolle should move its warehouse to the new building and if so, how Scania should relocate to the new building.

1.3 Problem Identification

To identify the core problem the steps according to the MPSM of Heerkens and van Winden (2017) are used. Firstly, this includes making an inventory of the current problems and illustrating the causes and effects, this is done in Section 1.3.1. After this, we select the core problem, which is the basis for the research goal, this is done in Section 1.3.2.

1.3.1 Inventory of Problems

In the current situation, Scania faces multiple issues with the unit supply pallet flow from the old building. These problems cause the action problems of “low employee satisfaction” and “high pallet handling costs”.

Firstly, there is a lack of isolation and air conditioning in the old building, especially during winter times this leads to “poor working conditions” causing low employee satisfaction. In Scania's case, this also limits the possibilities for automation, leading to the problem of "no automation possible".

Secondly, the current layout of the old building is sub-optimal regarding the unit supply pallet flow. This “suboptimal warehouse design” causes “large pallet travel distances”. The large travel distances in combination with the lack of automation cause a “large number of full-time employees (FTE) needed”, but also cause a “large number of tugger trains and forklifts needed”. This leads to the action problem of “high handling costs”.

Finally, Scania is considering using the site of the old building for other purposes and thus if Scania uses the old building for the pallet unit supply “the location of the old building cannot be used for other purposes.” This leads to a “lack of expansion opportunities” for new projects.

Figure 2 provides an overview of the causes and effects of the mentioned problems in a problem cluster.

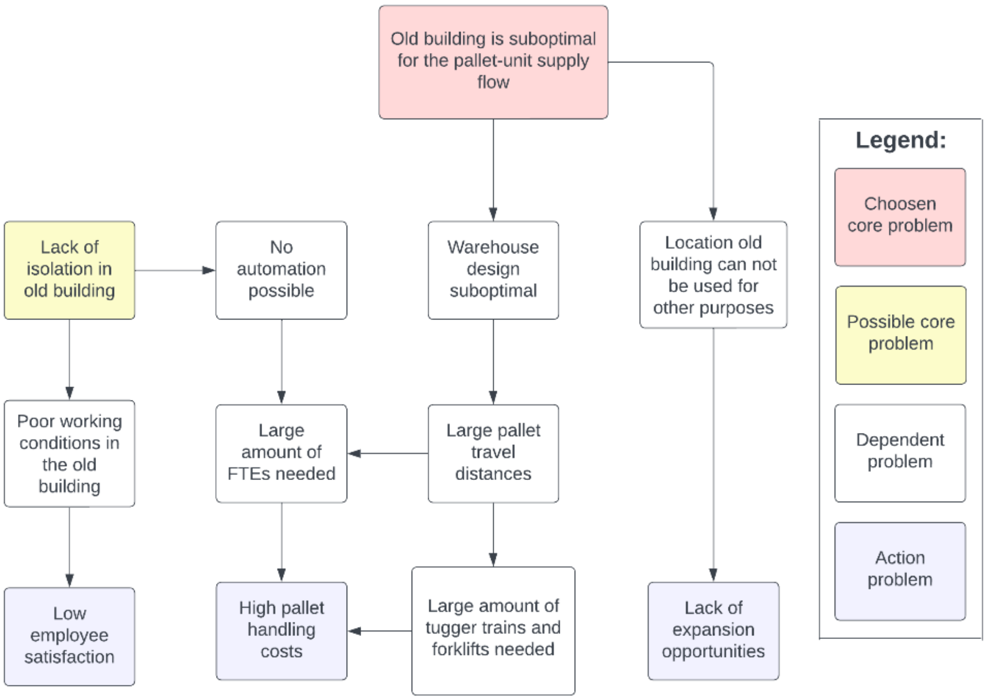

Figure 2: Problem cluster unit supply pallet flow Scania Production Zwolle

1.3.2 Core Problem and Research Goal

As the problem cluster in Figure 2 shows, one problem provided for Scania has no causes. This problem is thus the core problem and the problem this research solves. Thus, the core problem solved by this research is:

The old building is suboptimal for the pallet-unit supply flow.

Scania wants to analyze, if Scania can solve this problem by moving the pallet-unit supply flow to a different location within the facility in Zwolle. For this, the Y building is available. The research goal is to find how Scania can optimize the warehouse design and internal logistics for the Y building and to understand how this would affect the performance of their KPIs. Thus, the research goal is:

Determine the layout and internal logistics for relocation of the unit supply flow and analyze the effects this would have compared to the current situation.

1.4 Research Scope

This section defines the research aims and the intended deliverables achieved by this research.

1.4.1 Research Aims

As mentioned in Section 1.2, this research has several goals and expected benefits for Scania Production Zwolle (Scania).

Firstly, the research should give a good understanding of how Scania can optimize its warehouse and logistics for relocation. This research should produce several layouts for the new warehouse.

Secondly, the research should give Scania an indication of the effects the relocated warehouse of Scania would have on Key Performance Indicators (KPIs) relevant to Scania. To do this, this research first sets up a performance measurement system by determining the KPIs and uses this as a basis to measure the performance of the warehouses. This research measures the performance of the current warehouse and the proposed layouts found for relocation. By comparing this, the research finds the effect of the relocation on the KPIs.

In addition, the research should analyze key decisions for the internal logistics from the Y building. The Y building is situated across the road; therefore, Scania wants to analyze how the pallet supply should cross the road from the Y building (by conveyor, by bridge, or by lorry). Through the performance measurement system, we can find the impact of these decisions on the KPIs.

Finally, this research should give recommendations to Scania, on whether they should move the warehouse to the new location based on the performance measurement system. And if so, what the layout of the relocated warehouse should be.

1.4.2 Intended Deliverables

The research has the following intended deliverables based on the research aims in Section 1.4.1.

- Create a performance measurement system for warehouse design and internal logistics from pallet warehouse to production line.
- Design several warehouse layouts and designs found using several methods from the literature.
- Describe the internal logistic flows associated with the warehouse layouts and designs.
- Provide a comparison of the found layout designs of the relocated warehouse and the current warehouse according to the performance measurement system.

- Recommend to Scania, whether Scania should relocate their warehouse and if so, how they should design their warehouse in the Y building and what the corresponding logistic flows should be.

1.5 Research Design

This section illustrates the approach this research follows. It presents the research questions, which section answers the research questions, and if applicable the method used to answer the research questions.

Research question 1: How can the performance of the pallet warehouse and internal logistics be measured at Scania? Chapter 2: Current Situation and partially Chapter 3: Theoretical Background answer this research question. The sub-research questions for this research question are:

- What are key performance indicators for warehouse efficiency and internal logistics towards the production line?
- Too what extent is stochasticity involved in the process? And should these distributions be included in the performance measurement system?
- How should the performance of the warehouse layouts on the KPIs be measured? Should this be done using an analytical method, by simulation, or by another approach?
    - If we would use simulation, should this be a Discrete Event Simulation (DES) model, or would a Monte Carlo simulation be sufficient?
    - If we would use an analytical method, which analytical methods can be used to measure performance on KPIs?

Research question 2: What is the current situation regarding pallet supply from the old building? Chapter 2: Current Situation answers this research question. The sub-research questions for this research question are:

- What is the warehouse design of the old building?
- What type of storage policy does Scania currently use in the old building?
- What transportation methods does Scania use from the old building to the production line(s)?
- What are the different material flows from the old building towards the production line(s)?
- What is the performance of the current warehouse design and internal logistics according to the performance measurement system? Chapter 6: Experiment Results answers this sub-research question.

Research question 3: What are existing methods described in the literature that can be used to optimize the warehouse design? Chapter 3: Theoretical Background answers this research question, by performing a study on existing literature. The two sub-research questions for this are:

- What are the possible methods for warehouse layout design?
- What methods exist to allocate SKUs to warehouse locations?

Research question 4: What are the proposed layouts for Building Y using the methods of RQ3? And what are the corresponding logistic flows from this building to the production lines? Chapter 4: Solution Design answers this research question using the methods found in research question 3.

Research question 5: What is the performance of the proposed layouts found in RQ4 using the performance measurement system of RQ1? Chapter 6: Experiment Results answers this research question, the method to use for performance measurement is based on the findings from research question 1.

2 Current Situation

This chapter describes the current situation for Scania's unit supply pallet flow. This includes an explanation of the current warehouse layout, location, storage policy, and the general process. In addition, this chapter explains the current situation in the Y-building and introduces the Key Performance Indicators (KPIs) used in this research.

2.1 Design Pallet Unit Supply Warehouse

This section describes the current situation for pallet storage in the current warehouse. It includes a description of the warehouse layout, the type of pallet racks, how Scania stores the pallets in the pallet racks, and the method used to allocate the SKUs to the storage locations.

2.1.1 Current Warehouse Layout

The current building of Scania used for the pallet unit supply process is a manual warehouse, the warehouse is an I-shaped warehouse and is, therefore, a flow-through warehouse. Stacked pallet boxes arrive at one side of the building, after scanning the pallets the reach truck operator gets a location to store the pallet in the warehouse. The warehouse consists of three main halls each 36m wide and 84m long. Within the halls, the pallet racks are configured in a traditional layout, consisting of parallel aisles from the inbound section towards the outbound section and two traversal aisles which split each hall up into three sections. In this, the middle section is reserved for the class A SKUs. Furthermore, alongside the pallet racks, the warehouse includes ground storage locations dedicated to fast movers.

Pallet slots are reserved in the inbound zone, where a forklift operator unloads the pallets (stacks)from trucks arriving at the warehouse. The warehouse staff then picks these pallets up using reach trucks and store them in the warehouse.

The outbound zone has space reserved for trailers, here the pallet truck drivers park the empty pallet-trailers. The reach truck drivers place outbound on these trailers, which the pallet truck drivers pick up once they are full. Figure 3 illustrates the layout of the current warehouse.

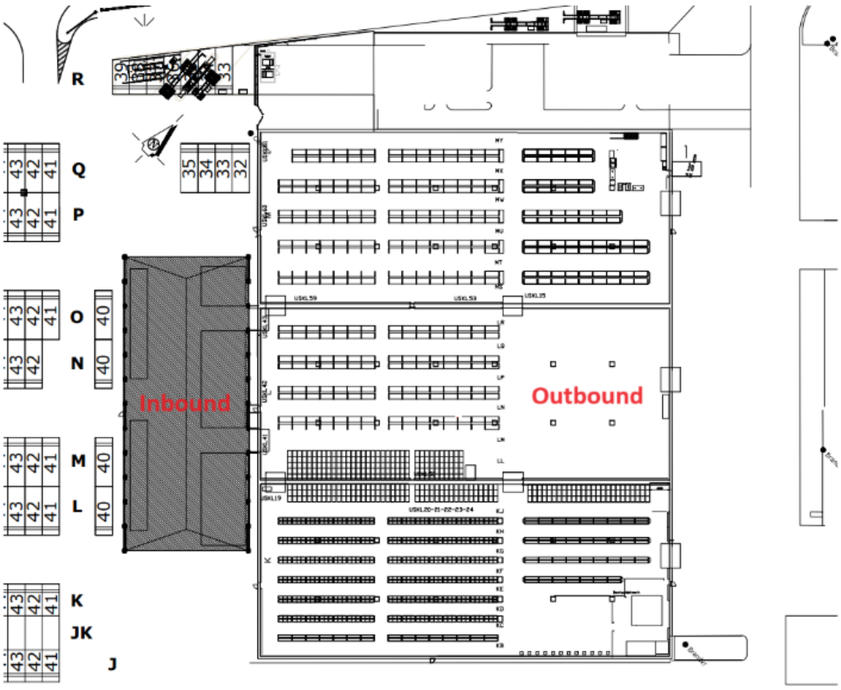

Figure 3: Map current pallet warehouse Scania

2.1.2 Pallet Rack and Storage Standards

Pallet types:

Most pallets stored in the warehouse are either Euro-pallets (0.8m × 1.2m × height) or half Euro pallets (0.8m × 0.6m × height). In addition, there some less common pallets are larger than Euro pallets and occupy multiple Euro pallet slots. The height dimension of the pallets depends on the contents stored and varies between 0.35m to 1.35m in six different height dimensions (0.35m, 0.55m, 0.75m, 0.95m, 1.15m & 1.35m). This depends on the number of collars on a pallet, a pallet with one collar has a 0.35m height, a pallet with two collars has a height of 0.55m, etc. More details on the type of pallets Scania handles will follow in Section 2.4.

Storage racks:

To store the distinct types of pallets, Scania uses two standard pallet racks within the building, pallet racks for Euro pallets or larger, and pallet racks only for half Euro pallets. Each slot within these racks is 2.7m wide and 0.6m (half Euro pallet racks) or 1.2m (Euro pallet racks) deep. These slots can accommodate three (half) Euro pallets or accommodate larger pallet types (fewer pallets per slot). Furthermore, the height of the racks is six meters, within which Scania uses different heights for the storage slots to accommodate the different pallet heights.

2.1.3 SKU Storage Policy

Currently, Scania does not store SKUs in dedicated locations; instead, Scania stores SKUs using a combination of class-based and random storage. All incoming SKUs are assigned with an A, B, or C classification. In addition, the sections in the warehouse are classified as A, B, or C locations. From this, the warehouse system generates a list of preferred locations in descending order and selects the first free location to store the SKU. Within the pallet rack, A items are stored low, and the C items are stored high.

Finally, for fast-moving items, dedicated locations next to the pallet racks at ground level are reserved. These items are only in the warehouse for a brief period and are therefore moved quickly to the production line through the floor locations.

2.2 Unit Supply Method

This section introduces the unit supply method in the current situation. Section 2.2.1 introduces the material handling equipment which Scania uses in this process. After which Section 2.2.2 introduces the unit supply process flow.

2.2.1 Material Handling Equipment

Reach trucks:

Currently, Scania uses reach trucks for pallet intake and pallet picking from the pallet racks to the pallet trailers. Each aisle within the current building can is only served by one specific reach truck, so the reach trucks only receive orders for specific aisles within the building. Each reach truck can handle multiple pallets (depending on the pallet dimensions) at the same time and has a reach height of thirteen meters. The maximum pallet stack height on the reach trucks is equal to nine pallet collars in which the pallet itself also counts as a collar. The reach trucks can travel at a speed of eight km/h. Appendix A.1. provides an illustration of the reach trucks in use.

Pallet-trailer and truck

For transport from the warehouse to the production line, the flow uses a combination of a pallet trailer and a pallet truck. Pallets are stacked on the pallet trailers, each pallet trailer has a capacity of 12.72 m^3, the number of pallets a pallet trailer can carry depends on the type of pallet. The pallet trucks can connect to the trailers to transport them toward the zones at the production line. The trucks move on a fast mode or a slow mode depending on the zone where the truck is driving. The fast mode has a speed of twenty-five km/h, and the slow mode has a speed of eleven km/h. Appendix A.2. provides an illustration of the pallet trailer and the pallet truck.

2.2.2 Unit Supply Process Flow

Pallet supply from the warehouse to the production line (also known as pallet unit supply) consists of two main transportation methods. A pallet trailer tugged by a truck (Section 2.2.1) or a pallet train transports the pallets towards the production area. This study excludes the process of moving pallets using pallet trains. As Scania expects that in the long term, pallet trailer transport will replace transport using the pallet trains for the unit supply flow, thus making this the only flow to consider. There are three separate flows of pallet trailers with one truck per flow each serving three different zones, every seventy-five minutes an order for a zone comes in. Since each pallet truck serves three zones and the orders are distributed evenly over time, every twenty-five minutes an order comes in for a pallet truck. Figure 4 illustrates a flowchart of the current process of supplying pallets to the production process using pallet trailers and pallet trucks.

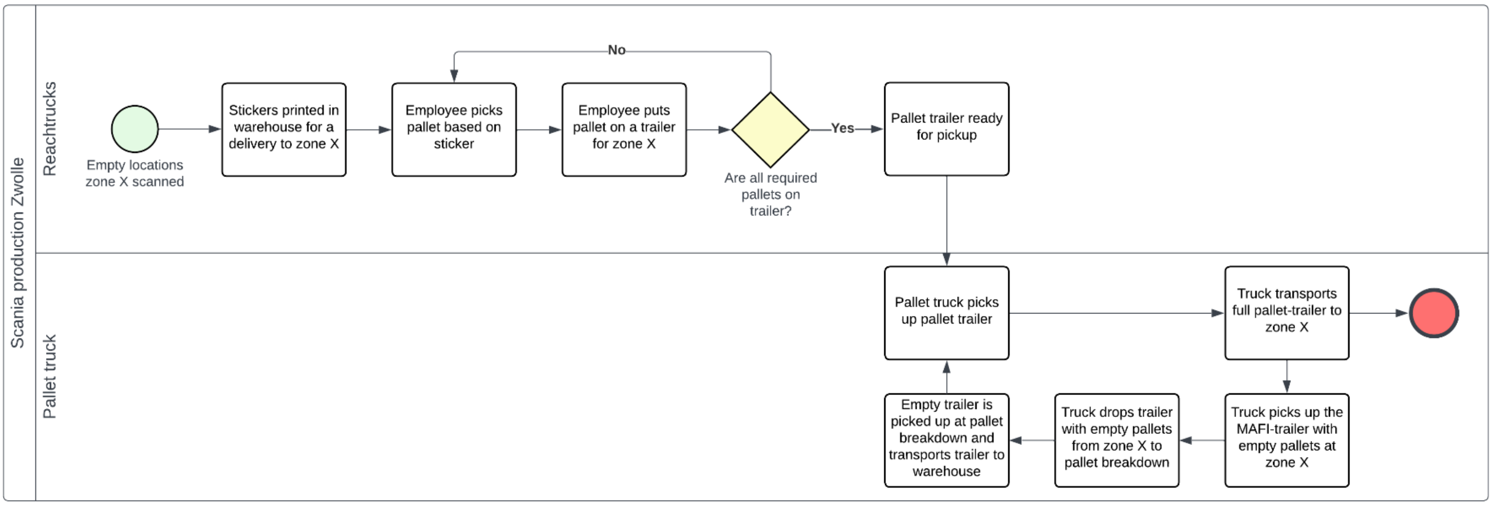

Figure 4: Flowchart process pallet trailer supply

As Figure 4 shows, the process is divided into two parts. These are the internal warehouse process of preparing pallet trailers before pickup and the process of delivering the pallet trailers to the production area (also called the line feeding process). In the line feeding process, the pallet trucks continuously travel around to pick up (full or empty) pallet trailers and deliver them to their destination, where the pallet truck should pick up a new trailer.

Within the unit supply process flow, stochasticity is involved during several moments. As explained earlier every twenty-five minutes deterministically a new order comes in for each of the three separated pallet trailer flows. However, the number of pallets to deliver involves stochasticity. In addition, the time required to pick up the pallets by the reach trucks is stochastic and depends on the locations where the pallets are stored. Finally, the time it takes to deliver the pallet trailer to the production line, pallet breakdown, and warehouse involves stochasticity. Factors such as the traffic within the factory play a significant role in this.

2.3 Y Building

As Figure 5 shows the Y building is situated on the other side of a public road. This presents Scania with a challenge on how to cross this public road. Figure 5 also shows the old building.

In addition, Scania currently uses the Y building for temporary storage of obsolete parts and blue bins (also used in the production process). If Scania moves its unit supply pallet warehouse towards the Y building, there are other options available on what to do with this process. Therefore, this research assumes full availability of the Y-building for the recommendations.

Figure 5: Map of buildings Scania Production Zwolle

Due to the design of the Y building, the inbound and outbound zones are fixed on the different sides of the Y building. Based on this a flow-through warehouse should be used in a new situation. The maximum dimensions available for the warehouse will be 107.5m × 87.5m × 9m (L × W × H).

2.4 Introduction to the Pallet Types and Data

To determine which methods can be applied to this research, it is first necessary to introduce the available data. It is important to note that Scania defines the pallets in the warehouse by what type of packaging they are (further referred to as a pack type). From this pack type, Scania knows the storage space requirement for a certain pallet. So, the amount of (euro) pallet slots which the pallet requires, and what storage height is needed for the pallet. This thesis does not differentiate between the specific parts supplied to the production line, but only at the pack type level. So, we only classify pallets based on the space requirement to store that type of pallet. This is because, apart from the required dimensions, there is no need to differentiate between pallets in terms of handling or storage methods. Furthermore, the number of distinct parts which Scania supplies to the production area is too large to consider with the available time and resources.

For this thesis, Scania has provided data on the number of pallets ordered per day by the delivery zones within the production area. From the data provided, the mean total number of pallets ordered per day is 2039.32. Appendix B provides an overview of the different pack types and the frequency of movement of each pack type. It also provides a class for each pack type based on an ABC classification; this class is used later in the research. Figure 6 shows the Pareto distribution of the pallet types, indicating the percentage of items that represent a percentage of movements. The exact definition of class-based storage policies and specifically ABC classification follows in Section 3.2.2.

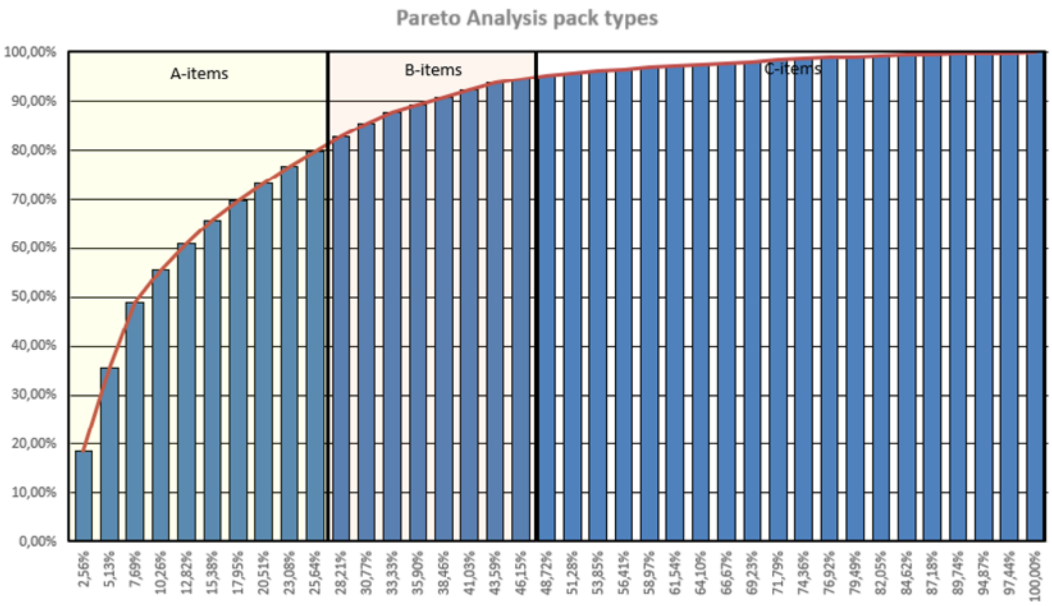

Figure 6: Pareto analysis pack types

Because the warehouse inventory levels exhibit steady-state behavior over time, this research assumes that the number of inbound pallet arrivals is equal to the number of outbound pallet departures. We need this assumption as in the real situation pallet arrivals are dependent on pallet departures, new incoming orders are done based on safety stocks and reorder points. As this thesis does not differentiate between all the distinct parts, it is not possible to incorporate the reordering policies within this thesis.

2.5 Key Performance Indicators (KPIs) Pallet Unit Supply Flow

To measure the performance of the new warehouse design(s) and compare it to the current process in the old building. Four Key Performance Indicators (KPIs) measure the efficiency of the process. Each of the KPIs is introduced in one of the subsections, followed by an overview of the KPIs including the formula and unit of measurement. Finally, this section also includes an estimation of the performance of the current situation on the KPIs.

2.5.1 Average Throughput Time Order (minutes)

For Scania orders must arrive at the production line as quickly as possible, by having low throughput time for the pallet supply Scania can ensure that there is limited downtime on the production line due to pallet supply.

Within the KPI an order is defined as the list of pallets to deliver from the pallet warehouse to a certain location on the production line. The throughput time of an order is measured by the time the order arrives (the moment the employee scans the final bar code of an empty location, and stickers are printed) to the moment the last pallet trailer of the order is placed at the location.

As explained in Section 2.2.2, this consists of a process within the warehouse, which is the preparation of pallet trailers by retrieving pallets using reach trucks. For this process new order arrives every twenty-five minutes, in the warehouse the employee should complete the order in twenty-five minutes. We define the process outside of the warehouse as picking up the pallet trailers from the warehouse using pallet trucks, delivering them to the delivery zones, returning a full pallet trailer with empty pallets to the pallet breakdown, and returning an empty pallet trailer to the warehouse. The time considered for the throughput time in this process is the time from the pallet trailer pickup at the warehouse until the time the pallet trailer delivery at the delivery zone.

2.5.2 Required Number of Full-Time Employees (#FTE)

Warehouse efficiency should limit the amount of labor required by employees. In warehousing the amount of manual labor can be reduced by for example automation, reducing travel distance, using the right equipment, and having efficient routing. By measuring the number of full-time employees (FTE) that the unit supply process would require, we can measure the warehouse's efficiency in labor.

The full-time employees considered in this research are the full-time employees on which can be differentiated between different configurations. These are the reach truck drivers, the pallet truck drivers (if the configuration uses pallet trucks), and the lorry drivers (if the configuration uses lorries to transport pallets towards the production area).

2.5.3 Percentage of Pallet Trailers prepared on time (%)

Scania works with a so-called takt time for their employees. Before this time, the employees should finish their work so the production line can continue at normal speed. In the current situation, the employees in the old warehouse who prepare the pallet trailers have a certain amount of time before the required pallets should be on the pallet trailer, so the pallet truck pick the pallet trailer up in time. For these employees, this is their Takt-time. The percentage of pallet-trailers prepared on time thus indicates how often the warehouse process could cause problems for the production process.

2.5.4 Required Space for the Warehouse (m^2)

As discussed in Section 2.3, Scania's Y-building is currently used for other purposes but still has the required space for pallet storage. As Scania Production Zwolle has limited space available and Scania could (partially) use the building for other purposes having a space-efficient warehouse with a comparatively small amount of space (m^2) required would be beneficial. This KPI only considers the area required for storage operations, as the in and outbound area size to reserve for the warehouse cannot be determined from the simulation model.

Note that this KPI used m^2 rather than m^3 because the height of the warehouse is not important as long as it fits within the building. Thus, to analyze the possibilities in the Y building, the height is a constraint rather than measured within the KPI.

2.5.5 Overview of KPIs

Table 2 provides an overview of the established KPIs, the unit of measurement, the formula, and whether the minimize or maximize the KPI.

KPI	Unit of measurement	Formula	Direction (Minimize or maximize)
Average throughput time order	Minutes (mm:ss)	$\frac{\sum_{Orders}(\text{End time order} - \text{start time order})}{\#orders}$	Minimize
Required number of FTE	Number (#)	#employees involved in process * 2 (one employee for the morning shift and one for the afternoon)	Minimize
Percentage of pallet trailers prepared on time	Percentage (%)	$\frac{\text{\#pallet trailers prepared on time}}{\text{\#orders pallet trailers}}$	Maximize
Required space for the warehouse	Squared meter (m^2)	$L_{\text{warehouse}} * W_{\text{warehouse}}$	Minimize

Table 2: Overview KPIs unit supply process

2.5.6 Performance in the Current Situation

Based on the key performance indicators found in Section 2.5, this section analyzes the performance of the current situation for the pallet unit supply flow. For the final comparisons, these values are not used as the benchmark values, instead, the outputs of the performance measurement system are used for a fair comparison. However, we use these values to validate whether the performance measurement system represents the real situation.

Average throughput time order:
There is no data available on the average throughput time per order for the internal warehouse process. However, based on the production standards at Scania, there are twenty-five minutes available to prepare the pallets within the warehouse. Furthermore, for the delivery to the production zone, four minutes and forty-five seconds is available. Based on this, the average throughput time would be around twenty-nine minutes and forty-five seconds.

Required number of FTE:
For the full-time employees to the process requires, in the current situation we only need to consider the reach truck drivers and pallet truck drivers. This is based on the employee types to consider from Section 2.5.2. At present, during the normal working hours in the process, six inbound reach truck(s) with drivers and six outbound reach truck(s) with drivers are used. In addition, the process requires three pallet trucks with drivers. The current process therefore requires sixteen full-time employees working on the process at the same time. As Scania Production Zwolle has a morning and afternoon shift this is equivalent to a thirty-two FTE requirement. Note that this number is different than the number found using the performance measurement system, Section 6.1 will explain the reason for this difference.

Percentage of pallet trailers prepared on time:
The occurrence of pallet trailers not being prepared on time is rare. Based on expert view, process supervisors have indicated that the current percentage of pallet trailers prepared on time would fall between 99% and 100%.

Required space for the warehouse:
As described in Section 2.1.1, the current warehouse consists of three halls, each measuring 36m*84m. The size of the warehouse, excluding the inbound zone would be $36 * 84 * 3 = 9072$ m^2. However, this KPI excludes the outbound zone (located in the warehouse), we need to subtract this. Furthermore, for a fair comparison, other sections such as coffee corners and offices which are not for storage are excluded. These sections are in the top and bottom right of the warehouse (See Figure 3) and are in total approximately 707 m^2. The outbound zone is approximately $36m * 31m = 1116$m^2, and thus the required space for the warehouse excluding in and outbound zones in the current situation is $9072m^2 - 1116m^2 - 707m^2 = 7249m^2$.

This chapter has provided the required information on the process in the current situation. Furthermore, this chapter introduced the available data for this research. Finally, this chapter provided the relevant KPIs for this research and an initial estimation of the current performance.

3 Theoretical Background

This chapter presents a literature study to determine which methods we can use to find a suitable warehouse design for Scania. It consists of two main research questions which are subsequently answered:

- *What are the possible methods for warehouse layout design?*
- *Which methods exist to allocate SKUs to warehouse locations?*

Moreover, this chapter addresses the question of how we can evaluate the anticipated performance of the resulting warehouse layouts with allocated SKUs. To address this, it answers the following research question:

How should the performance of the warehouse layouts on the KPIs be measured?

3.1 The Warehouse Layout Problem

This section introduces the state-of-the-art of the literature on warehousing layout problems. Furthermore, from the state-of-the-art, this section establishes methods which we can perform in the case of Scania. This section addresses the following research question: "*Which possible methods exist for warehouse layout design, which ways can pallet racks be configured?"*

3.1.1 State of the Art

In accordance with Baker and Canessa (2009) and Frazelle (2001) preparing possible warehouse layouts can be done by following the following steps:

- Space requirements planning: This involves determining the space required for each zone.
- Material flow planning: The determination of the overall flow pattern (e.g., U-shape or flow-through)
- Adjacency planning: This uses a warehouse activity relationship chart, which may form the input for computer-aided facility layout tools.
- Process location: The split of areas by low-bay and high-bay usage.
- Expansion/contraction planning: Consideration of how the facility may be changed in the future.

In accordance with the findings of Berg and Zijm (1999), three types of warehousing systems exist concerning the level of automation: manual, automated, and automatic warehousing systems. In a manual warehousing system, the order picker retrieves the articles from the racks. In the case of a pallet unit load warehouse, this would be done using for example a forklift or reach truck to retrieve pallets from pallet racks. In an automated warehousing system, the product is delivered to the picker instead of the other way around, an example of this for unit-load pallet storage would be a unit-load automated storage and retrieval system. Finally, automatic warehouses perform fully automatic order-picking operations, which are primarily utilized for the handling of small or medium-sized items. This approach is therefore not applicable in the context of Scania.

When utilizing traditional pallet racks in warehousing, several methods exist for the rack layout design. The traditional pallet rack layout in conventional warehouses comprises parallel as well as traversal aisles arranged perpendicularly. In contrast, warehouses in which the aisles are not perpendicular such as the "Flying-V" and "Fishbone" layouts, are considered to be non-orthogonal. (Saderova et al., 2020)

3.1.2 Conventional Layout

A conventional layout also referred to as a traditional layout in some literature (Cardona et al., 2015), is a type of warehousing layout characterized by the arrangement of parallel aisles orthogonal to the walls. In accordance to Gue and Meller (2009), nearly all unit load warehouses in the past used to follow a conventional layout conformed to two unspoken design rules in warehousing:

- The picking aisles must be straight, and parallel to one another.
- If present, the cross aisles must be straight, and they must meet picking aisles at right angles.

Warehouses following a conventional layout for pallet supply warehouses are space efficient as they require less space than non-orthogonal layouts having the same capacity. However, as all distances in conventional layouts from the I/O point(s) toward the storage areas are rectilinear, the travel distances for conventional layouts are inherently greater. This results in relatively lengthy pick times for unit-load pallet warehouses. (Gue & Meller, 2009)

According to the findings of Dukic and Tihomir (2014), the optimal dimensions for a warehouse to minimize the expected travel distance in a rectangular storage area with parallel aisles for unit-load warehouses can be computed numerically. Given the dimensions of a storage area (l_1 x b_1), the width of the main aisles (b_2) and the number of storage locations per layer (Q), the optimal number of aisles (n_1), optimal aisle length (L_r) and area width (B_r) can be computed. Equation 1 illustrates this model.

$$n_1 = \sqrt{\frac{Q * b_1}{2 * l_1 + b_2}}$$

$$L_r = \frac{Q * b_1}{2 * n_1}$$

$$B_r = n_1 * 2 * l_1 + n_1 * b_2$$

Equation 1: Model for optimal conventional warehouse layout (Dukic & Tihomir, 2014)

3.1.3 Non-orthogonal Layouts

Fishbone layout:

A so-called “fishbone layout” has two diagonal cross aisles and aisles in the lower zones are perpendicular to the aisles in the upper zones as illustrated in Figure 7 (Cardona et al., 2015)Figure 7. The rationale behind the fishbone layout is that it makes the distance to travel closer to the Euclidean distance instead of the rectilinear paths in a conventional layout.

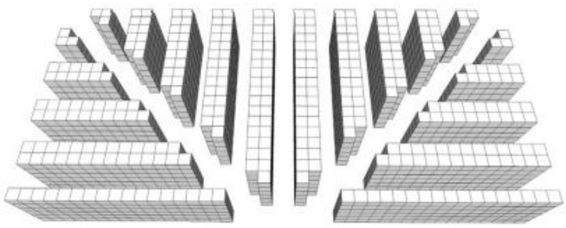

Figure 7: Detailed three-dimensional fishbone layout (Cardona et al., 2015)

Several studies have illustrated that the fishbone layout, in comparison to the traditional layout can result in reduced travel distances and thus travel times, especially for unit supply warehouses. However, fishbone layouts also require a significantly larger area for the same amount of storage locations (Dukic & Opetuk, 2008) (Cardona et al., 2015) (Gue & Meller, 2009).

Cardona, Rivera and Martínez (2012) provide a comprehensive procedure to determine the detailed dimensions of a fishbone warehouse layout.

Flying-V layout:

The flying-v layout is an adapted version of the fishbone layout. The two diagonal aisles can be curved in a flying-v layout and the upper and lower zones are no longer perpendicular as illustrated in Figure 8.

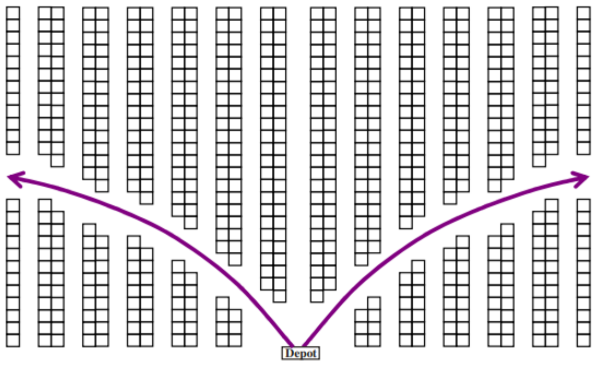

Figure 8: The flying-v warehouse layout (Roodbergen, 2011)

The flying-v layout exhibits a smaller reduction in travel distances than the fishbone layout in comparison to traditional warehouse layouts (Gue & Meller, 2009). However, the flying-v layout has also has advantages over the fishbone layout. Access into and out of the space is easier, traffic is now distributed over the bottom aisle as well, workers are better oriented due to similarities to traditional warehouses, and the more intuitive numbering of locations and existing warehouses can more easily be changed to a flying-v layout than a fishbone layout. (Gue & Meller, 2009)

<u>Other non-orthogonal layouts:</u>
Öztürkoğlu, Gue and Meller (2012) define several other non-orthogonal layouts that exist for unit-load warehouses. These could further reduce the travel distances. Table 3 provides an overview of the performance of these layout types on expected travel distances relative to the traditional layouts. In this, a lower percentage means less travel distance. However, this does come at the cost of the area required. In general, it holds that layouts with shorter travel distances require more area (Öztürkoğlu, Gue, & Meller, 2012). Thus, in this case, a clear trade-off is presented providing reduced travel distance by the implementation of different layouts, but at the expense of a larger required area.

Warehouse	*Performance (%)*
Traditional	100
Chevron	80.47
Fishbone	80.47
Leaf	78.28
Butterfly	77.48
Travel-by-flight	76.52

Table 3: Travel distance performance layouts single command unit-load warehouse from Öztürkoğlu, Gue and Meller (2012)

3.1.4 Automated Storage and Retrieval System

An automated warehouse type to consider is an Automated Storage and Retrieval System (AS/RS). The advantages of an AS/RS include the potential reduction in the number of Full Time Employees (FTE) required, higher space utilization, and more accurate picking. However, AS/RS systems require large investments and should thus have high efficiency to be worthwhile. Figure 9 illustrates the various classifications of AS/RS as determined by Roodbergen and Vis (2009). Regarding the warehouse layout problem, an AS/RS warehouse with stationary racks has a conventional layout without horizontal cross aisles in which the cranes move along the vertical aisles.

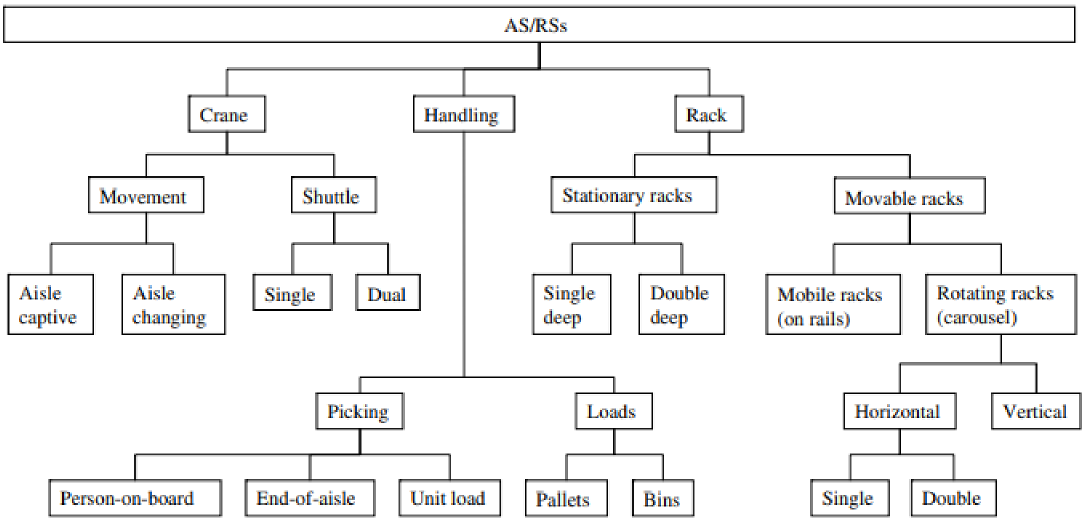

Figure 9: Classification of AS/RS system options (Roodbergen & Vis, 2009)

Singbal and Adil (2019) present a multi-aisle AS/RS warehouse design methodology and approach, which considers aspects such as storage policy, Storage and Retrieval (S/R) machine, and transfer car type.

3.2 The SKU Storage Policy

Once the layout for a warehouse is determined, the next step is to determine the method for storing SKUs in specific locations (SKU storage policy). This section analyzes the state of the art on the SKU storage policy problem and from this summarizes the methods that we could perform in the case of Scania. This section addresses the following research question: *Which methods exist to allocate SKUs to warehouse locations?*

3.2.1 Random Storage

Random storage policies are the most common storage policies used in warehouses. A random storage policy implies that items are randomly assigned to a location. Random storage ensures a uniform utilization of the warehouse and reduction of aisle congestion (Petersen, 1999). In practice, random storage is not purely random as operators tend to store or retrieve items from the closest locations in the warehouses. Furthermore, companies could prioritize locations near the outbound zone to ensure fast retrieval times from the storage locations. This is still considered random storage as there is still no reservation of specific locations for a specific (type of) SKU. The disadvantage of random storage policies is that they generally require more picking time as illustrated by Petersen and Aase (2004).

3.2.2 Class-based Storage

Class-based storage of SKUs within a warehouse defines the possible zones to store a certain SKU based on its class. The most prevalent class-based storage policy for warehouse location assignment is the ABC storage policy. This policy divides a storage area into three zones and assigns the most demanded products to the best-located zone (Silva et al., 2022). In this classification system, A items are the most demanded SKUs, C items are the least demanded SKUs and B items are what remain. ABC classification follows the 80/20 rule of Pareto, which states: that class A is the mostly valued class by having 60–80% of the total value with 10–20% of inventory; class C with a value between 5 and 15% while having 50–60% of inventory has the least significance among the classes. From 20 to 25% of items belonging to class B, values close to 30% can be achieved (Kheybari et al., 2019). In the case of a warehouse storage policy, the values are based on the percentage of movements of each item.

Class-based storage in general requires less average picking time than random storage policies as shown by Petersen and Aase (2004). This is because it ensures the best possible locations in the warehouse are only occupied by fast-moving items, which ensures a high utilization of these areas. However, as storage locations now can only be used for certain classes of SKU the utilization of locations tends to be spread less evenly, resulting in more storage slots required to fit all the inventory.

Class-based storage can have more than only three classes. However, the findings of Yu, deKoster and Guo (2015) indicate that an increase in classes does not mean better performance in average travel time. For some common demand distributions, the optimal number of classes is below 5 (Yu, deKoster, & Guo, 2015).

3.2.3 Dedicated Storage Locations / Full Turnover Policy

In a dedicated storage policy, each storage location is dedicated to a specific SKU. The benefits of a dedicated storage policy are that items are easy to find and that the most popular items can be in the most convenient locations. However, the dedicated storage policy does not efficiently utilize the available space. For assigning SKUs to their dedicated locations a cube-per-order index (COI) policy can be used to prioritize SKUs. This ranks the SKUs based on the ratio of allocated storage space to demand ratio (Equation 2). It then reserves the most convenient locations for the items with the lowest COI value. A dedicated storage policy following the COI prioritizing rule is also known as a full turnover policy (Ang & Lim, 2019).

$$COI_{item} = \frac{Storage\ space\ required_{item}}{\#Storage\ \&\ retrieval\ transactions_{item}}$$

Equation 2: Cube-per-order index

3.2.4 Mixed-shelves Storage

As described by Xie, Li and Luttmann (2023) and Rasmi, Wang and Charkhgard (2022), a mixed-shelves storage policy has been applied in large-scale facilities of e-commerce companies. This storage policy distributes items of the same SKU over the locations. This ensures that there is always an SKU of that type close by for picking. Within shelves thus items of multiple SKU types are stored for this policy. This storage policy can reduce travel distance for order-picking operations, as the chance for large travel distances is reduced through the scattered locations.

3.3 Performance Measurement of Warehouse Designs

The previous sections of the literature review establish methods to provide several warehouse designs for the new situation. The performance of each of the designs needs to be measured, while no real-time measurement of these new warehouse designs is possible. Therefore, this section provides an overview of the state of the art regarding performance measurement of the warehouse designs. By doing so, this answers the research question: *How should the performance of the warehouse layouts on the KPIs be measured?*

3.3.1 Analytical Models

The expected performance of warehouse designs can in certain cases be measured analytically, Gu, Goetschalckx and McGinnis (2010) provide an overview of performance measurement methods used in several types of warehouses. Among these, several methods from the literature are given for unit-load AS/RS or conventional multi-aisle warehouses under storage policies, which can theoretically be implemented for this research.

The mentioned methods mostly use queuing models to evaluate the performance of several warehouse designs. A queuing network can evaluate waiting times, handling times, and other performance measurement metrics assuming distributions for processes (Heragu et al., 2011).

3.3.2 Monte Carlo Simulation

According to Law (2014), in simulation, a computer is used to evaluate a model numerically, and data are gathered to estimate the true characteristics of the model. Based on this the behavior or performance of the system can be analyzed.

A Monte Carlo simulation model estimates the performance of a system under uncertainty by drawing random numbers from input distributions. Monte Carlo Simulation assesses the performance of a system based on a certain set of input parameters analytically. In Monte Carlo simulation there is no time dimension and thus a static model is in place.

A Monte Carlo simulation model can be used in travel time models to assess performance regarding warehouse designs. Such as done for an AS/RS in Azzi et al. (2011).

3.3.3 Discrete Event Simulation

Another type of simulation model that can be used to estimate the performance of warehouse designs is a Discrete event simulation model (DES). A discrete event simulation model changes state variables simultaneously at separate points in time, by the timing of events being characterized by uncertainty (Law, 2014). DES can be used to model uncertainty with the inclusion of time dimensions (dynamic model).

DES is frequently used to model the expected performance of warehouse design. Most research on warehouse simulation uses Discrete-event simulation to model the operations of a warehouse (Gülle & Hegmanns, 2014). Using a DES model enables performing experiments to evaluate, analyze and determine the solution parameters (Saderova et al., 2022). DES compared to Monte-Carlo simulation is different in that it enables dynamic modeling rather than a static model meaning a DES model can model the changes of the system over time.

A specific type of discrete event simulation (DES) is an agent-based simulation. In accordance with Law (2014) this is a bottom-up modeling approach driven by the smallest entities. In an agent-based simulation approach, the entities actively interact with each other and their environment. The agents in this simulation approach act without needing constant external inputs, this can be useful to simulate behavior.

3.4 Literature Gap

The theoretical background shows a broad range of literature exists on whether to use AS/RS or traditional warehouses, what layout design to use, and which SKU storage policies to use. This thesis aims to combine existing methods from literature and compare a range of combinations of warehouse type, layout, and storage policies. Using a discrete event simulation model, the combinations are compared on the performance measurement system from which recommendations are made.

Table 4 shows there is a range of existing literature that covers this topic partially for manual warehouses. This table provides an overview of the found existing literature comparing the existing methods. Some of the literature also evaluate different methods for real cases at companies. However as far as we know there is no research found that compares the performance of all the provided layouts and storage policies in a real situation using DES. This research thus differentiates by analyzing the performance of the provided options for a real problem.

Literature on manual warehouses			
Paper	Warehouse layout design	SKU storage policy	Method for performance measurement
(Derhami, Smith, & Gue, 2020)	Conventional layout	Random allocation policy	*Discrete Event Simulation (DES)*
(Saderova et al., 2020)	*Fishbone and conventional layout*	-	-
(Heragu et al., 2005)	*None only dimensioning of departments*	*Classification in four flows*	*Analytical performance measurement*
(Macro & Salmi, 2002)	*Conventional layout*	*Mixed allocation model*	*Discrete event simulation (DES)*
(Zaerpour, de Koster, & Yu, 2013)	*Conventional layout*	*Random, class-based, or full turnover-based allocation policy*	*Analytical performance measurement (Queuing network)*
(Yener & Yazgan, 2019)	*Conventional layout*	*Class based storage policy*	*Discrete event simulation (DES)*
(Pohl, Meller, & Gue, 2011)	*Flying-V, Fishbone and conventional layouts*	*Random allocation and turnover-based allocation*	*Analytical performance measurement (based on travel distance)*
(Esmero et al., 2021)	*Flying-V, Fishbone and conventional layouts*	-	*Discrete event simulation (DES)*
(Sueters, 2023)	*Conventional layout*	*Random allocation and Class based storage*	*Analytical performance measurement (based on travel distance)*
This thesis	*Conventional, Flying-V, & CPU based layout*	*Random, allocation, class-based allocation, or combined allocation policy*	*Discrete event simulation (DES)*

Table 4: Existing literature on topics covered in this thesis

Furthermore, as far as we know, the CPU-based warehouse design method, which Section 4.1.4 describes, is a new method not earlier analyzed in the literature. This research will contribute to the literature by introducing this new method and analyzing the performance of this method. Finally, this thesis differentiates from the existing literature mentioned by not only considering the performance within the warehouse, but also the supply from the warehouse towards the production area.

This chapter provided methods for warehouse design and storage allocation based on the existing literature. Furthermore, it introduces methods to evaluate the warehouse performance based on the literature. Chapter 4 and Chapter 5 uses the findings from this chapter to find the solutions and to establish the performance measurement system. Finally, this chapter also illustrated the potential value of this thesis for literature, this is done by providing the existing literature gap addressed by this research.

4 Solution Design

This chapter describes the solutions for the warehouse design problem in Scania's case. Based on the findings from the literature this chapter provides options for the warehouse layout and SKU storage policies. Additionally, this chapter describes the options for transport to the production area. Based on the described options, this chapter concludes by providing the combinations of decisions (the solutions), that the simulation model analyzes.

4.1 Options for Layout Design

From the literature in Section 3.1, there are two main layout types for manual warehouses: conventional layouts and non-orthogonal layouts. The literature review showed that the non-orthogonal layouts reduce travel distance at the cost of a larger required area. This trade-off is similar for each of the non-orthogonal layout types. Therefore, this thesis will focus on a simple implementation of a non-orthogonal layout (the flying-V layout) to indicate the expected benefits of a non-orthogonal layout. Furthermore, this thesis will analyze two conventional layout options (with or without dedicated half-euro locations) and finally introduces a layout using a new methodology for warehouse design (the CPU-based layout). Before designing the layouts firstly, the capacity requirement needs to be determined.

4.1.1 Required Capacities

The warehouse is split into three sections, to determine the required capacity in the layouts. These sections are the inbound zone, the outbound zone, and the storage area. For the capacity requirement, this thesis assumes that the current capacity available would also be the capacity in the new situation. Therefore, we use the current capacity available, as for Scania there is no need to optimize the capacity for the data available. This is due to uncertainty, regarding future demand.

Required pallet locations:

This thesis uses the base capacity of the current situation for the required pallet locations. Following the standards for pallet racks at Scania Production Zwolle, each storage location in our model is 2.8 meters wide and 1.3 meters deep. These locations can store three (half) euro pallets or a smaller number of larger pallets.

In the current situation, there is a capacity of 630 pallet rack locations per layer and there are 190 floor stacking slots for fast movers. Thus, for the capacity requirements, two cases exist, one case with pallet racks and floor stacking slots and one case with only pallet racks.

The number of pallets per layer required if only pallet racks are used given the same capacity as currently available is 756. If space for both pallet racks and floor locations should be reserved the capacity per layer to be considered would be 820.

4.1.2 Conventional Layout

To find the optimal dimensions given the required capacity in a conventional layout warehouse, the model as described in Section 3.1.2 can be used. This model minimizes travel distance by making the distance from the outbound point equal on all sides. Within the conventional layouts, there are no ground locations but only pallet racks. Furthermore, we design two distinct types of conventional layouts. Conventional layout case 1 only has pallet locations of 1.3 m deep and 2.8 m (three (half) euro pallets or a smaller number of larger pallets) wide. Conventional layout case 2 also has these pallet locations in addition to specific locations for half-euro pallets, these locations are 0.65m by 2.8 and can only fit three half-euro pallets per location.

Case 1:

The current capacity of 756 pallet slots on the base layer, needs to be adjusted to the new height dimension in the Y-building. As the pallet racks in the Y-building can be 1.5 (nine instead of six meters) times higher the storage density (per m^2) of pallet racks is also 1.5 times higher in the new situation. Thus, in the Y-building 504 pallet slots per layer are required instead of 756. By following the model in 3.1.2. we create an initial layout with sixteen aisles of sixteen slots per aisle (see Equation 3). Appendix E.1. contains a visual representation of this layout.

$$n_1 = \sqrt{\frac{Q * b_1}{2 * \ l_1 + b_2}} = \sqrt{\frac{504 * 2.8}{2 * \ 1.3 + 3}} \approx 16 \, aisles$$

$$L_r = \frac{Q * b_1}{2 * \ n_1} = \frac{504 * 2.8}{2 * \ 16} = 44.1 \ \approx 16 \, slots \, per \, aisle$$

Equation 3: model of 3.1.2 worked out to derive conventional layout

Case 2:

For the half-euro pallet slots instead of 2.6 meters per pallet rack we reserve 1.3 meters per pallet rack so one half-euro pallet fits on both sides. This option reserves space for 310 normal pallet locations and 195 half-euro pallet slots. To find the layout in case two, we consider another parameter, which is the number of half-euro racks. The new layout with dedicated slots for half-euro pallets has a total of fifteen aisles with seventeen slots per aisle, consisting of six pallet racks for half-euro pallets and nine pallet racks for the remaining pallets. This case has a reduction in the area required of 386.96 m^2 (9.64%) compared to the layout of case one. Appendix E.1 contains a visual representation of this layout.

For this layout all half euro locations are located on one side of the building. Having the half euro aisles spread over the warehouse might reduce the average travel distance to pick up pallets. However, due to convenience regarding pallet intake having half euro locations together is beneficial for Scania. The current situation also follows this logic.

4.1.3 Flying-V Layout

For the Flying-V layout this thesis only considers the case consisting of pallet locations of 1.3 m deep and 2.8 m wide. If the performance of the Flying-V layout provides significant benefits based on this thesis, Scania can further research a Flying-V layout for the second case with half-euro slots included.

For the Flying-V layout to determine the angle of the diagonal aisle, we consider the dimensions of a. As the pallet racks in a Flying-V, have an offset of one slot the angle the diagonal cross aisle follows can be calculated by $slot \, depth \, / \, slot \, width$. Using this we calculate the number of slots skipped (at which height the diagonal starts for the next rack). Calculation of the number of aisles and aisle lengths uses the same principles as in Section 4.1.2. However, now for the aisle length an additional slot width and aisle width are added. The distance between the slots needs to be an aisle width wide at any point.

Using this logic for a capacity of 504 slots and the given slot dimensions, the Flying-V layout would consist of fifteen aisles and seventeen slots per aisles. Compared to case 1 of the conventional layout an additional 791 m^2 would be required for the Flying-V layout (19.7%). However, this layout should reduce the average travel distance and thus the performance of the warehouse on average throughput. Appendix E.2. provides a visual representation of this layout.

4.1.4 CPU-based Layout

This novel method for warehouse design is inspired by the design of a central processing unit, further referred to as a CPU. A CPU consists of dedicated and shared cores. This can be translated into warehouse design as dedicated storage locations (one SKU per location) and shared space (space reserved for all SKUs), the CPU-based warehouse design follows a combination of the dedicated allocation policy and random allocation policy. This consists of allocating SKUs firstly to dedicated locations (if available) or otherwise to the shared locations. This allocation policy is further referred to as the combined allocation policy. The dedicated storage locations consist of the following types of sections:

- P-Sections (based on the P-Cores of a CPU) are sections that are specialized for performance. These sections should offer the lowest handling times. In these sections, fast-moving SKUs are stored to ensure high utilization of these sections. This will ensure fast inventory turnover at these locations.
- E-Sections (based on the E-Cores of a CPU) are the sections that are specialized for space efficiency. In these sections' slower moving SKUs are stored which are exactly fitted to a slot. This ensures high space utilization and a lower inventory turnover in these sections.

Furthermore, the shared storage is the S-Sections (based on the shared cache of a CPU). For these locations no dedicated SKUs should be allocated. Any item without a dedicated storage location is stored here and if dedicated storage is full SKUs with a dedicated storage location are also stored here.

Based on the CPU layout of the Intel Core i5 series Processor (see appendix C) the block layout as illustrated in Figure 10 was made. We chose this processor as it mimics a flow-through warehouse focused on high-performance areas near the outbound zones, which is like how the process could look in the new building. This block layout provides a basis for the warehouse layout of the CPU-based approach.

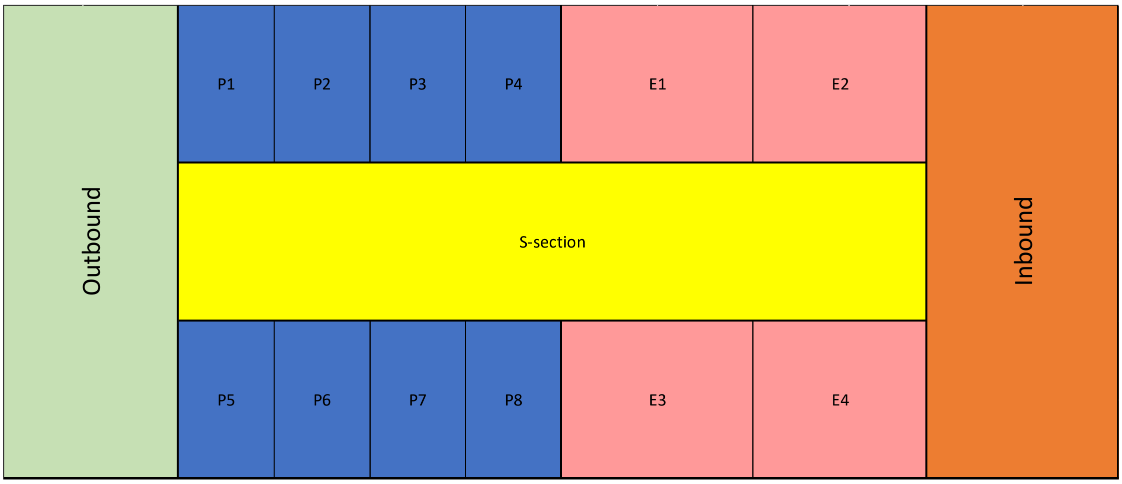

Figure 10: CPU microarchitecture-based block layout

Now we introduce the practical implementation of this new method for warehouse design in the case of Scania. As the CPU-based layout consists of three categories of storage locations, dedicated high-performance storage locations (P-sections), shared storage locations (S-sections), and space-efficient storage locations (E-sections). The movements within the warehouse are split up into their respective pack type(s) and based on the number of pallets of each type to be handled are given a class. Three flow types exist for the CPU-based layout:

- Flow 1: The item moves from inbound to the P-section if a slot is available else moves to the S-section, used for A-items.

- Flow 2: The item moves from inbound to the E-section if a slot is available for the item else moves to the S-section, used for non-A-items with a height smaller than four pallet collars.
- Flow 3: The item has no dedicated slot and always moves to the S-section, used for non-A-items with a height of minimal five pallet collars.

P-sections:
The P-sections requiring quick storage and retrieval operations, consist of ground stacking locations as these have shorter handling times. For the ground stacking locations, there is a maximum height of twenty-four pallet collars.

E-sections:
In the E-sections standard pallet racks are used, these pallet racks will be nine meters high and have an adjusted dedicated height of storage locations to the different pallet types. This way high space efficiency can be achieved in the E-sections. In the E-sections, ten to twelve pallets can are stored in a slot for one pallet in a nine-meter-high rack.

S-sections:
In the S-sections the same rack types as in the E-sections will be used, the height of the storage locations will instead be adjusted to the larger pallet types so all pallets can be stored within the S-sections if needed. Within the S-sections, six pallets per pallet slot per rack can be stored.

For the practical design of the CPU-based layout, we assume that the E-sections make up the capacity loss caused by the S-sections and thus the layout is based on the current capacity of the warehouse. The layout design follows the structure of the CPU provided in Appendix C, and thus approximately thirty-three percent of the space is reserved for each section type. The E-section consists of racks for euro pallets and half euro pallets to ensure high space utilization.

The CPU-based layout has two variants, firstly there is the variant that follows the structure of the CPU provided in Appendix C as closely as possible. The second variant has larger but fewer P-sections and E-sections. Furthermore, this option has shorter but more S-aisles. This alternative shifts the layout more towards a square and offers a reduced required area. However, the expectation is that this alternative would have higher throughput times due to the decrease in P-slots and larger travel distances to the P-sections and E-sections. Appendix E.3. provides a visual representation of the resulting layouts.

4.2 SKU Storage Policy

Based on the findings in Section 3.2, from the existing literature we identified four main methods for SKU storage allocation. These storage allocation methods are a random storage policy, a class-based storage policy, a full turnover-based storage policy, and a mixed-shelves storage policy. As at Scania, the number of distinct types of items is too large to consider a full turnover policy, a full turnover-based policy with dedicated spaces for each item would require too many item locations. Furthermore, a mixed-shelves storage policy is not applicable as unique pallets are requested at the warehouse for an order. So instead of a type of pallet, a specific pallet within the warehouse is ordered. This thesis will therefore not analyze the full turnover policy or mixed-shelves storage policy. Instead, this thesis will focus on the random and class-based storage policy. Furthermore, the CPU-based layout requires a combined allocation policy fitted to this type of layout.

4.2.1 Random Storage

A random storage policy in this case would store incoming pallets in the best slot that is available then. Upon initialization of an experiment for each slot within the warehouse, the expected time to retrieve a pallet from the slot is calculated, based on which the locations are ranked in ascending order. Once a new pallet comes in the heuristic then searches for the best available location, where the pallet fits. Appendix D.1. contains a pseudo code for the implementation of this random SKU storage policy.

4.2.2 Class-based Storage Policy

As explained in Section 2.4 our model does not need to consider all possible SKUs on item level, as there are no items requiring specific storage conditions for Scania. Our model will however differentiate items between the different pack types. The pack type in this case defines the type of pallet in which Scania stores the product. Appendix B contains an overview of the pack types for Scania.

In the class-based storage policy, first we need to classify the different pack types. For class-based storage the optimal number of classes lies below five for some common demand distributions and more classes does not mean better performance as earlier established in Section 3.2.2. Therefore, this research focuses on a simple three-class-based ABC storage policy.

The ABC classification starts by splitting up the pallets into the pack types that can arrive at the warehouse. Based on the average number of movements per pack type per day we classify these following an ABC classification. In this, pack types causing up to 80% of the movements are classified as A-items, pack types causing 15% of movements (up to 95% cumulative) are classified as B-items, and the remaining 5% is classified as C-items. Section 2.4 already illustrated the resulting Pareto distribution.

For the classification of the available slots within the warehouse, the simulation model uses the number of slots to reserve for each class as input parameters. The model then sorts (ascending) the available slots based on the expected time to retrieve a pallet from the slots. By looping over the available locations, we first add locations to class A (until the required number of A slots is reached) then to class B, and finally to class C.

The model adds the newly arriving pallets to the best possible location (shortest expected time to retrieve) in the class that corresponds with the classification of the pallet. Appendix D.2 illustrates a pseudo code for the implementation of this class-based SKU storage policy.

4.2.3 Combined Allocation Policy

The CPU-based layout uses a combined allocation policy to allocate the SKUs to the storage locations. As explained in Section 4.1.4 the CPU-based layout contains dedicated zones for either performance or space efficiency, as well as a shared space for the SKUs which cannot be stored in the dedicated sections.

The combined allocation policy first checks whether dedicated slot(s) exist for the pallet and checks whether there is enough space for the pallet in one of the slots. If this is the case the pallet it allocates the pallet to this slot. If that is not the case it allocates the pallet to the shared area.

The storage locations are classified in the combined allocation policy beforehand. Thus, for all the storage locations already has been determined whether it is a dedicated location and if so for which pack type or whether it is a shared location. The locations per type of location are ranked based on expected retrieval time in an ascending manner.

Upon arrival of a new pallet, the policy checks the type of flow assigned to the pallet. If the pallet this is a dedicated flow (assigned to a P-section or assigned to an E-section), the policy assigns the pallet to the best fit dedicated location based on expected retrieval time. If the pallet assigned flow is a shared flow or no fitting dedicated location is found, the policy assigns the pallets to the best-fit shared location. Appendix D.3. provides the pseudo-code, which provides a basis for the implementation of the combined allocation policy.

4.3 Transport Options Toward Production Area

This section provides an overview of the possible methods to transport the pallets from building Y towards the production area. Scania has provided three options, which this thesis further analyzes. These consist of one option using only pallet trucks and trailers, and two options involving lorry transport next to pallet trucks and trailers.

4.3.1 Pallet Trailers and Pallet Truck

The first option for transport towards the production area is the same transport method as in the current situation. By using a combination of pallet truck and trailer as explained in Section 2.2 pallets are transported directly to the delivery zones. To adapt this transport method for transport from building Y, Scania is considering making use of a bridge for transport towards the production building. This is a necessity as regulations do not allow the pallet truck and trailer combinations to move across the public road otherwise. This solution would require a significant investment, which this thesis will not disclose.

In this situation the pallet trucks move across the bridge toward the production area, and after delivering the full trailer, the pallet trucks pick up a trailer with empty pallets and returns this across the bridge. It then moves the trailer with empty pallets to the pallet breakdown after which it brings back a trailer without pallets to the Y-building and restarts the cycle by picking up the next full pallet trailer. Figure 11 provides a visual representation of the main movements between areas, the green symbols illustrate the flows making use of the pallet truck and trailer combinations.

Figure 11: Visual representation of new situation flow 1 pallet trucks and trailers

As there is no congestion on the bridge (at least not to the extent that it would affect travel times), the additional time required for the pallet trailer because of crossing the bridge can be calculated by $\frac{bridge\ length}{pallet\ trailer\ speed}$. This time is added for the delivery flow as well as the return flow. The bridge length would be approximately 110 meters, while the pallet truck and trailers move across the bridge at a speed of 25 km/h or 6.9444 m/s. Thus, the additional time would be $\frac{110}{6.9444} \approx$ 16 seconds.

4.3.2 Lorry Transport

The second option this thesis analyzes is to use lorries for transport towards the production areas. Scania uses this method for the items currently stored in the Y-building. This option consists of loading the items in lorries and moving them toward the production facility, where the items are unloaded and will be brought to the delivery zones using pallet trucks and trailers. The pallet trucks and trailers in this option perform their route internally within the production area. This consists of delivering full trailers towards the delivery zones, bringing the trailers with empty pallets towards the (old) pallet breakdown location, and returning an empty pallet trailer towards the arrival point of the lorries within the production area. Scania considers placing the arrival point of the lorries at two distinct locations, either close by the Y-building (flow 2a) or at the pallet breakdown (flow 2b). For the unit load pallet process, a lorry for this process has a capacity of seventy-five m^3 assuming an average fill level of 80% per lorry. Figure 12 and Figure 13 contain visual representations of the main movements between areas. In this blue represents the movement of the lorries, whereas green represents the movements of pallet trailer and truck combinations.

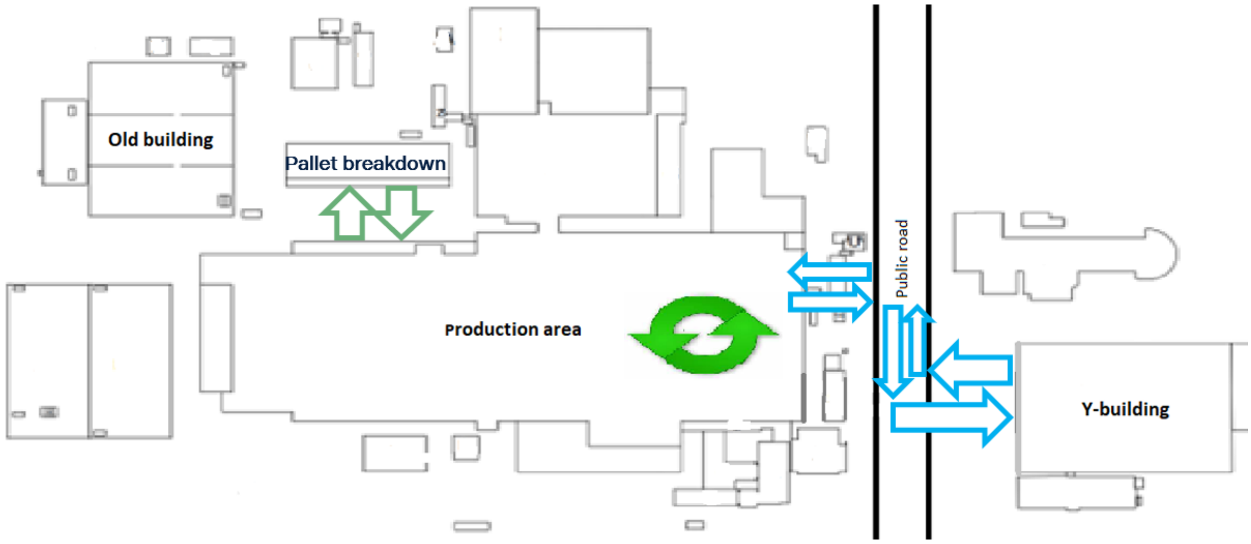

Figure 13: Visual representation of new situation flow 2a using lorry transport

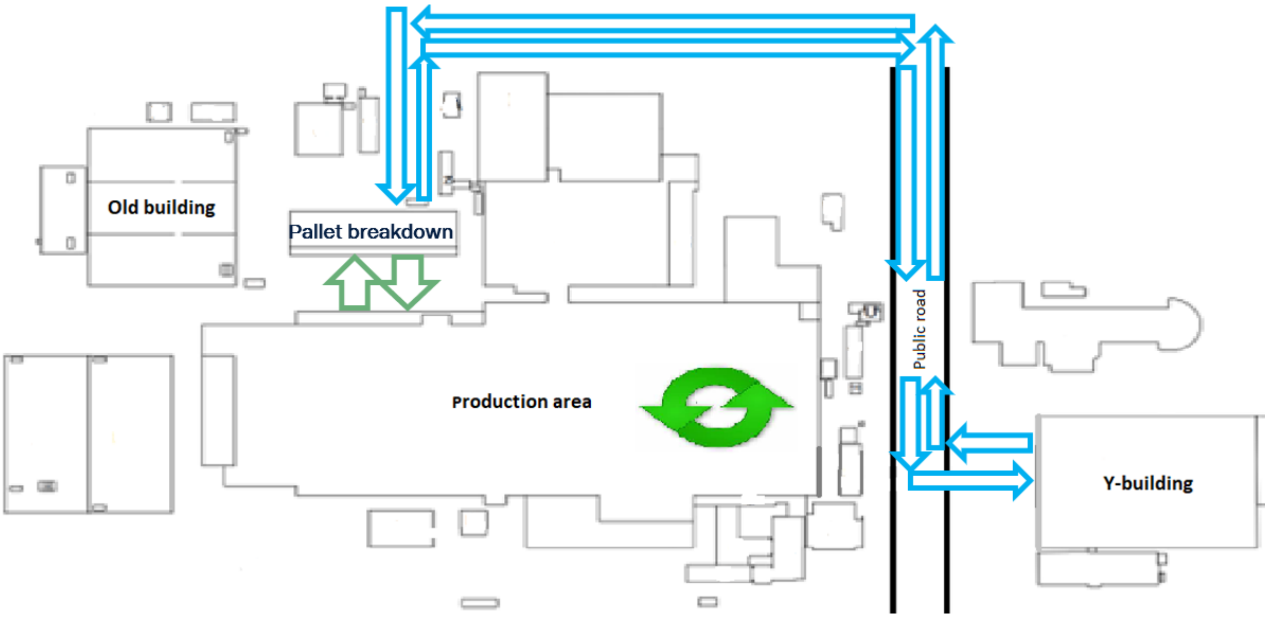

Figure 12: Visual representation of new situation flow 2b using lorry transport

4.4 Overview of Solutions

For the options within the warehouse, this thesis has found seven possible solutions. This thesis analysis these solutions as well as the current situation, to find the most promising solutions regarding the internal warehouse performance based on the KPIs. Table 5 provides an overview of the solutions analyzed for internal performance. Each solution has an assigned number and a caption describing what the solution contains.

Warehouse options		
Solution	Layout	Storage policy
1: Current situation (benchmark)	Current layout	Current allocation policy
2: CPU based approach	CPU based layout	Mixed allocation policy
5: Conventional C1 + Random	Conventional	Random storage policy
6: Conventional C1 + ABC	Conventional	Class based storage
5: Conventional C2 + Random	Conventional	Random storage policy
6: Conventional C2 + ABC	Conventional	Class based storage
7: Flying-V + Random	Flying-V layout	Random storage policy
8: Flying-V + ABC	Flying-V layout	Class based storage

Table 5: Solution options within the warehouse

After the we identify the most promising solutions for the internal warehouse decisions, for the best solutions, we implement the possible decisions concerning transport towards the production area. For each of the most promising solutions, the three different flow types described in Section 4.3 are analyzed and compared with the current situation. Figure 14 illustrates the steps followed to run all the required experiments.

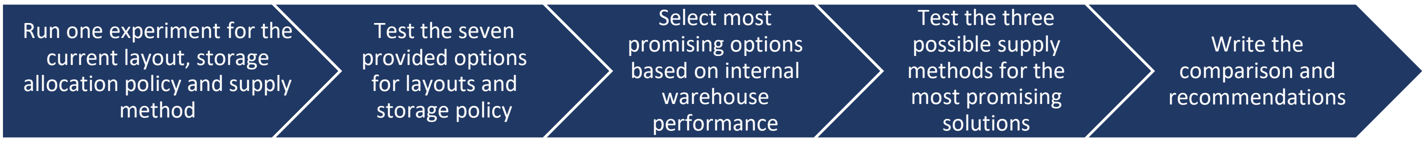

Figure 14: Experiment setup

This chapter introduced the possible solutions for warehouse design and storage policies. Furthermore, this chapter introduced the supply options from the warehouse towards the production area. The performance measurement system described in Chapter 5 will analyze the performance of these established options using the provided experiment setup in Figure 14.

5 Simulation Model

This chapter describes the simulation model used to model the real-life processes, to compare the different solutions and the current situation. It introduces the conceptual model of the processes within the simulation model, describes the in and outputs of the model, and finally validates the quality of the model by comparing the model to the real situation.

5.1 Conceptual Model

The findings in Section 3.3 illustrate three main approaches for the performance measurement of the warehouse designs from the literature. These are analytical models, Monte Carlo simulation, and discrete event simulation (DES). Due to the complexities and large scale of this problem, the warehouse design performance cannot be measured analytically. Furthermore, as the situation in the warehouse changes over time the static nature of Monte Carlo simulation makes this an unviable method. Thus, this thesis uses discrete event simulation to measure the performance of the warehouse designs.

Furthermore, within discrete event simulation, we identified a specific type of discrete event simulation which applies bottom-up modeling to model the behavior of the smallest entities. This method is called agent-based simulation. However, Agent Based simulation should in this case not be applied as behavior is not an important aspect to consider for the warehouse layout. This thesis implements the discrete event simulation model in the software Tecnomatix Plant Simulation 16.1 by Siemens.

This section introduces how the process is modeled in the software. Firstly, it identifies the model's scope to determine to which extent the processes should be modeled. Afterward for the main (sub)processes it explains the logic in which these are modeled.

5.1.1 Scope of the Model

The goal of the simulation model is to estimate the internal performance of the warehouse to find how quickly the orders of pallets can be prepared for the production process given the required number of full-time employees and the space required. Thus, the internal warehouse logistics fitted to the type of warehouse, warehouse layout, and storage policy should be simulated in detail.

Furthermore, to see how the warehouse relocation affects the performance of the supply process towards the production area. We also simulate the logistic supply processes; this requires a lower level of detail. This is because the goal is to provide an indication to support decision-making, rather than optimizing the process in detail. We simulate the possible options for the flow of the pallets toward the production area by distributions of the travel times for the flow types.

5.1.2 Simulation of the Warehouses

The generic logic the simulation model follows for the internal processes in the warehouse is similar for each of the possible warehouse layouts it analyzes. The only differences between the models are differences for the routing logic implemented. This section describes the logic of how the internal warehouse processes are implemented in the simulation model.

The inbound process:

The inbound logistics process is defined as the process from the moment pallets arrive at the warehouse until the pallets are stored in a pallet rack. In the current situation, pallets arrive at the warehouse in trailers, after the trailers arrive the pallets need to be unloaded by reach trucks, this takes up some processing time. In the simulation model, a source generates pack types based on an interarrival time following the distributions of the pack types.

After the pallets are unloaded, they need to be moved towards a storage location. To do so it uses one of the SKU storage policies described in Section 4.4 to assign the pallets to a storage location. In the warehouses reach trucks transport the pallets toward the pallet racks, the reach trucks first route toward the pallet pick-up point, to pick up an inbound pallet. If there is a larger queue of inbound pallets, the reach truck picks up as many pallets as it can based on the capacity of nine pallet collars. The model is three-dimensional, and the fork of the reach truck moves to the correct height to drop off pallets. This process thus considers the handling and movement times of the process. After dropping off the pallet the reach truck brings the next pallet to the assigned destination of the pallet. If the reach truck is empty, it returns to the pick-up point to pick up the next pallet(s). For all movements, the reach trucks always take the fastest allowed route. Figure 15 illustrates the logic the inbound reach trucks follow upon arrival at a destination.

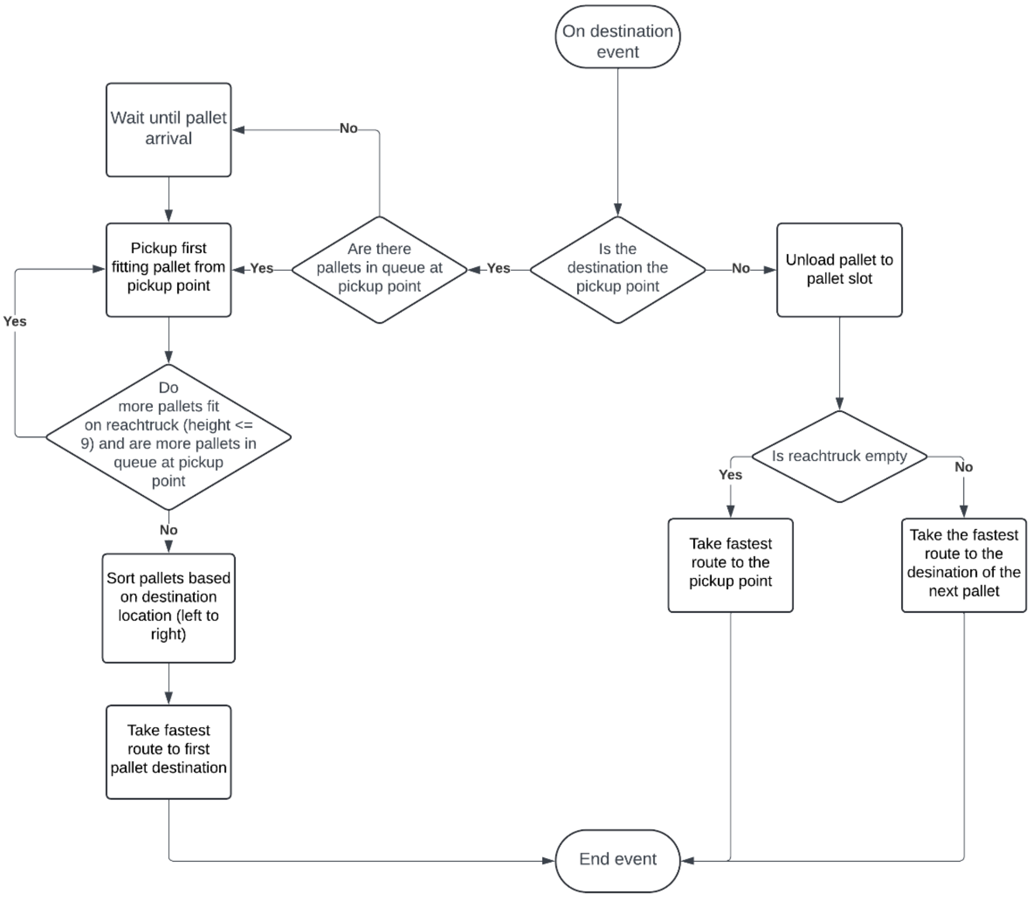

Figure 15: inbound reach truck on destination event

The outbound process:

For the outbound process, every twenty-five minutes an order for a delivery zone arrives in the warehouse for an X number of pallets. In the simulation model, the number of pallets follows a normal distribution. To determine which pallets, need to be retrieved the simulation model generates this random from the inventory at that moment. For this, the probability of generation of each pallet depends on the pack type frequencies as provided in Appendix B.

Reach trucks also retrieve the pallets from storage locations in this process, there are dedicated reach trucks for the outbound process which are not used in the inbound process. After moving a pallet to the outbound location, a reach truck either starts picking the next pallet of that order, moves on to the next order, or waits until a new order arrives. Upon arrival at the outbound zone the next route is already determined. It routes the fastest route to retrieve the first pallet from storage, upon arrival at the storage location the fork moves to the correct height to pick up the pallet, after returning the fork to floor level the forklift routes back to the outbound location if no more pallets are to be picked up in that route. If still pallets remain to be picked up within the route, the reach truck moves towards the next nearby pallet to pick this pallet up. Figure 16 illustrates the logic a reach truck follows upon arrival at a destination.

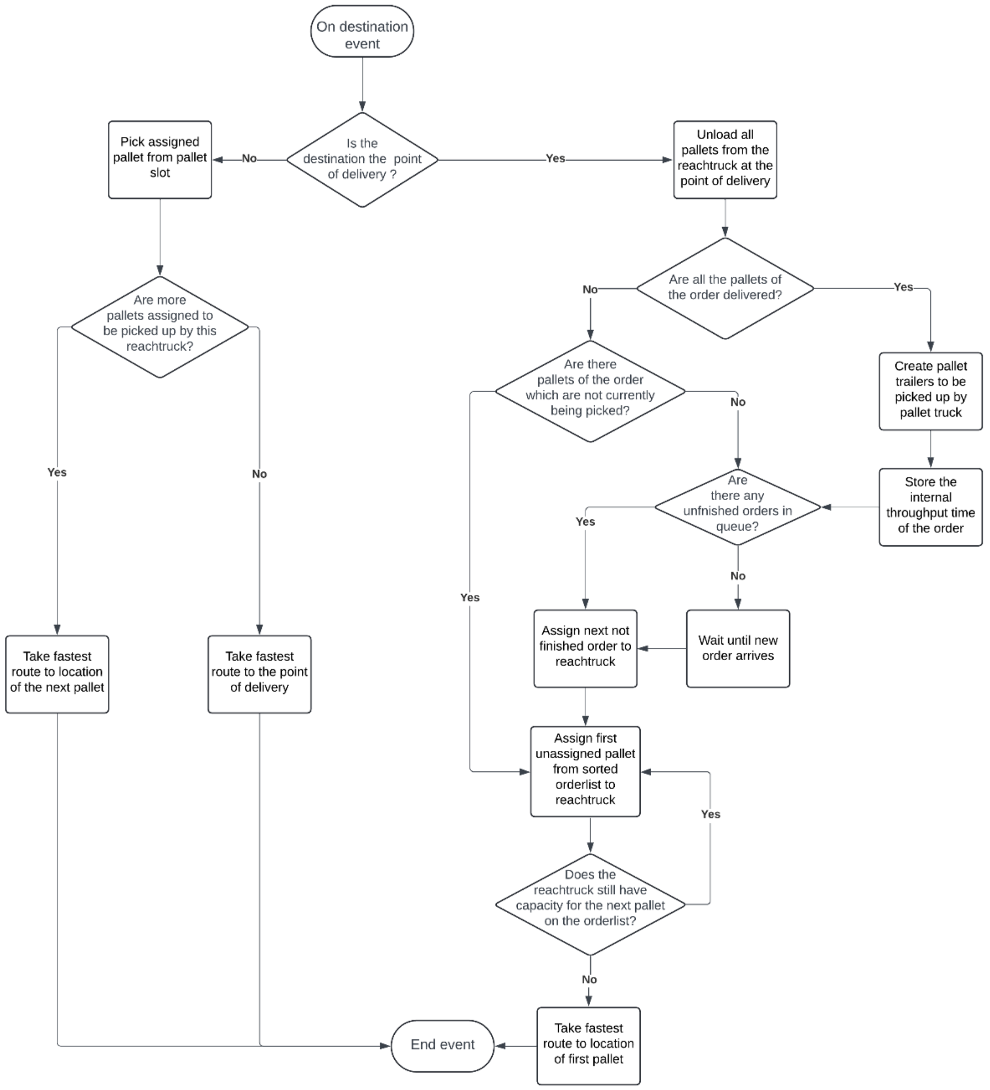

Figure 16: outbound reach truck on destination even

<u>*Routing Logic:*</u>

To determine the order in which the pallets are delivered to the storage locations or retrieved from the storage locations, the pallets are sorted based on the storage location of the pallet. This sorts the pallets based on their position within the warehouse so reach trucks pick up/deliver the pallets from left to right. After dropping off or picking up a pallet, it calculates which route is the fastest towards the next destination and thus always takes the shortest possible route towards the destination.

Figure 17 provides a snapshot of the visual 3-dimensional model in action. As this figure shows, the warehouse is filled with pallets, the outbound reach trucks (in blue) retrieve these pallets from the warehouse. The inbound reach trucks (in orange) bring the pallets into the warehouse.

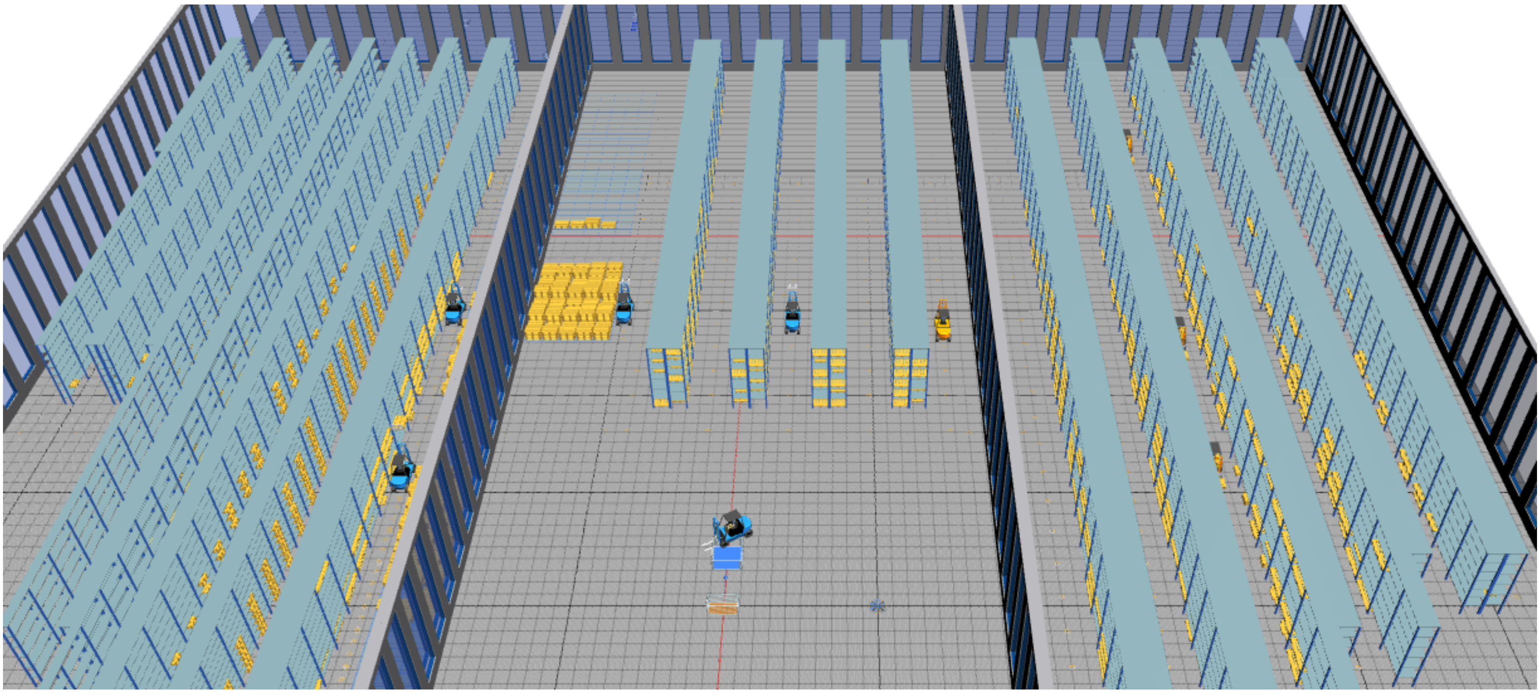

Figure 17: Snapshot of the 3D simulation model for the current situation in Tecnomatix Plant Simulation

5.1.3 Simulation of the Pallet Supply Process

Section 4.3 introduced the possible transport options from building Y towards the production area. Within these options, we can identify two process types. This section explains how the simulation model simulates these processes.

Pallet truck and trailer flow:

The current situation, as well as each of the proposed transport options in Section 4.3 uses the pallet truck and trailer transport method. Within the simulation model, this process is modeled by three sub-processes. Firstly, there is the process of the pallet truck delivering the pallet trailers to production, after finishing this process, the model registers the end time to measure the throughput time KPI. The second process is the flow of moving a trailer with empty pallets toward the pallet breakdown. After this, the third process can start, which moves an empty pallet trailer from the pallet breakdown toward the warehouse. This results in the return of a pallet trailer and the availability of the pallet truck for a new delivery. If no delivery is prepared yet, the pallet truck will wait until one is available to start the process again. The time required for these processes is randomly distributed following a triangular distribution as further explained in Section 5.2.1. For the current situation and solution 2a (see Figure 12) the base distribution is used, for the case with a bridge (solution 1 see Figure 11) the base distribution is used with an additional time for crossing the bridge. Solution option 2b (see Figure 13) combines visiting the pallet breakdown and returning an empty trailer (as the location of the empty trailer drop-off and the pallet breakdown is the same) thus one step is removed from the return process, meaning that the empty pallets can be returned immediately after delivering the full pallet trailer.

Lorry transport flows:

For each of the lorry transport flows defined in Section 4.3.2, the process consists of three steps. The loading process (done at the warehouse level and incorporated within the simulation model of the warehouse), the transport process and unloading process at the production facility, and the return flows. After the finishing, the first two steps, a list of pallet trailers is ready for pickup by the pallet trucks. Within the simulation model, the steps are modeled as simple processes with a given distribution (again triangular distribution see Section 5.2.1.) for the duration of the process step. For the transport and return flow step, the model differentiates between the two possible options in Section 4.3.2.

5.1.4 Other Model Assumptions

The model assumes constant reach truck driving speed without acceleration. Furthermore the model does not include traffic interactions, meaning that reach trucks do not need to have to wait for any traffic within the warehouse and can always take the fastest route to their (next) destination.

Reach trucks within the warehouse handle incoming pallets first in first out. Also, incoming orders are handled first in first out, once a reach truck has finished its part of an order it checks whether there are still pallets to be picked up for that order, and if not, it moves on / waits until the next order. Within an order a reach truck starts with the first pallet on the list, it then checks whether it can pick up the next pallet of the order within the capacity left. If it fits the pallet is added to the list of pallets to be picked up by that reach truck, it does this until the reach truck cannot pick up more pallets. Most of the time, a reach truck can pick up one to three pallets depending on the pallet dimensions.

5.2 Inputs for the Simulation Model

This section gives an overview of the inputs of the simulation model. This section separates the inputs in inputs for the processes modeled from the real situation as well as input parameters for the solutions analyzed.

5.2.1 Input Distributions

This section introduces how the simulation model models the main processes (which follow stochasticity). For this, we consider the pallet arrivals, the pallet orders from the production lines, the handling time of pallets and the supply deliver times.

Pallet arrivals:

Regarding pallet inflow of the current warehouse (old building), the number of pallet arrivals and departures over a day is used to derive the interarrival times. Several statistical distributions for the interarrival times are tested and compared to the measured values. The best fitting distribution of the distributions we tested for the pallet arrival and departures from the warehouse is a Log-normal distribution (see appendix F.1)

A Chi-Square test checks whether a Log-normal distribution is a fitting distribution for the data. As seen in Appendix F.2 the test statistic (X^2) is smaller than the Chi-Square value for a 95% confidence level and fifteen degrees of freedom. Thus, on a 95% confidence level, we cannot reject the null hypothesis (H_0), so we assume a Log-normal distribution for the pallet in and outflow.

Pallet orders:

For each pallet truck, pallet orders come in at a deterministic interarrival time of twenty-five minutes, this is because every seventy-five minutes an employee scans all empty locations for a production zone to determine the order from the pallet warehouse. Each truck consists of three locations for which orders the pallet truck handles the order. Thus, an order arrives at the warehouse for the three pallet trucks every twenty-five minutes. For this, we assume no interruption in the downstream process of pallet consumption at production and the scanning process. For the number of pallets within the order, we assume a normal distribution based on previous findings from Scania.

Pallet handling times (internal warehouse process):

For pallet retrievals from storage by reach truck, there are some handling times to consider. For these handling times, this thesis uses real-time measurements to determine these values. A few steps that have handling times are picking up a pallet from the inbound zone, moving the pallet in/out of the pallet rack, checking the pallet label, and loading a pallet on a pallet trailer. For these steps, we assume constant handling times within the model which are different for floor storage locations and pallet racks. The steps of moving the reach truck fork up/down are not included as this is modeled based on the height change and fork speed within the simulation model.

Delivery times pallet supply process:

As for the pallet delivery process, there is a lack of available data, the approach followed is to use expert opinion. In accordance with Law (2014) and Standridge (2013) in case there is a lack of data available for some process steps in simulation a triangular approach can be used. This requires the minimum, maximum, and modus (most common value), from which we implement a triangular distribution in the simulation model. Thus, for the delivery times of the pallet supply process steps, we asked the corresponding supervisors (who assumingly have the most knowledge of the subject) what based on their expertise the minimum time required, the maximum time required, and the most occurring approximate duration for that situation would be. The simulation model uses these values as the input values of the triangular distributions.

5.2.2 Input Parameters

Besides the layout generated and the corresponding pallet supply process chosen the following input parameters are also determined.

Number of reach trucks:

The simulation model enables adjustment of the number of in and outbound reach trucks, this directly affects the KPI required number of FTE.

If the number of inbound reach trucks is too low pallets overflow the inbound warehouse, the model then stops running and the solution is thus infeasible. As the number of inbound reach trucks does not influence the other KPIs, we chose the minimum number of reach trucks for a feasible solution.

An increase in outbound reach trucks affects the warehouse throughput time. More outbound reach trucks mean orders are finished quicker at the cost of a larger amount of FTE required. The model tests the performance of the warehouse against six different options for the number of outbound reach trucks. This illustrates the trade-off between FTE requirement and throughput time for a warehouse layout.

Height configurations per pallet rack:

To determine which pallet types can be stored in which slot, all pallet slots have a maximum allowed height for pallets. In the simulation model to simulate the current situation, each aisle has a height configuration that approximates the real situation with the pallet slots in that aisle.

The goal of this thesis is not to optimize the exact height configurations of each slot. Thus, the proposed layouts have one standard height configuration. Each aisle (consisting of two pallet racks) has the same configuration, in which for the left and right racks a different slot height per store level is determined. This standard configuration is based on the pallet frequencies and is different for hallways that consist of euro slots and half-euro slots.

Percentage of slots reserved per class type:

In the case of a class-based allocation policy, the input parameters *Percentage A-slots* and *Percentage B-slots* determine which percentage of storage locations to reserve for each class. From this, the model derives the number of storage locations of each class type, the initialization procedure of a class-based allocation policy uses these values (as seen in Appendix D).

The percentage of slots to reserve for each class affects the performance of the warehouse for a class-based policy. If too many slots are reserved for A and B-class items, the warehouse lacks flexibility as lower-class items can be stored in less available locations. However, if too few slots are reserved for A and B class items, this mitigates the benefits of a class-based storage policy on expected retrieval distance.

5.3 Outputs for the Simulation Model

The outputs of the simulation model are the Key Performance Indicators as determined in Section 2.5. This subsection explains how the simulation model retrieves these KPIs as outputs.

Average throughput time order (minutes):
For the average throughput time of orders, the simulation model considers the entire process, for the start time of an order it uses the moment of generation of the order in the warehouse. For the end time of the order, the model uses the time all pallets within the order are delivered to the delivery zone. At the end of the simulation run the average it takes the average over all orders finished.

Note that the average order throughput time can be split into a few parts. Firstly, there is the internal warehouse throughput time, this is the time from when the orders come in until the time all pallets are prepared in the warehouse. This can measure the internal warehouse efficiency. To compare the layouts, before analyzing the effects of the supply method we only use this value. Secondly, there might be a slight waiting time for the pallet trailers until the pallet trucks can pick them up. The pallet truck first completes its route before it can pick up trailers for the next order. Finally, there is the time from the moment the pallet trailer is picked up until the pallet trailer arrives at the production area. This time follows the provided triangular distribution (see Section 5.2.1).

Required number of Full Time Employees (#FTE):
The required number of FTE is calculated at the warehouse level as well as in the unit supply process. Based on the definition of the number of FTE to consider within the process as defined in Section 2.5.2 within the warehouse only the in and outbound reach truck drivers are considered. At the end of the simulation, the number of reach trucks used in the warehouse is calculated.

For the process outside of the warehouse, dependent on the flow type chosen to transport the pallets toward the production area there is a predetermined number of FTE required. This number is based on the number of lorries required (one FTE per lorry) and number of pallet trucks required (one FTE per pallet truck).

Percentage of pallet trailers prepared on time (%):
The model calculates the percentage of pallet trailers prepared on time within the warehouse frame. The simulation model calculates this at the end of the simulation by counting the number of orders for which the measured warehouse throughput is below twenty-five minutes and dividing this by the total number of orders handled within the warehouse.

Required space for the warehouse (m^2):
The model calculates the required space for the warehouse within the warehouse frame. The simulation model calculates this by taking the length of the warehouse and the width of the warehouse (using the coordinates of the aisles) and multiplying this. As the model is scaled this provides the correct area requirement. For the current situation, the required space for the warehouse is equal to the value found in Section 2.5.6.

5.4 Verification and Validation of the Simulation Model

To ensure that the results of the simulation model provide a realistic estimate of reality, we need to verify and validate the simulation model. In accordance with Law (2014) in simulation, verification ensures that the model performs the processes as described in the conceptual model correctly. Whereas validation ensures that the simulation model provides an accurate representation of reality.

The verification and validation process uses the model of the current situation. This is because, for the current situation, there is knowledge of the process available at Scania which we can use in the validation process.

5.4.1 Model Verification

To verify the model, we debug and check the processes in the Tecnomatix Plant Simulation model step by step. The model consists of several different objects, which combined perform the processes as described in the conceptual model. This step is essential to ensure we followed the described logic.

Inbound process:

For the inbound process, the verification consists of checking that the pallet arrivals follow the correct distribution as provided in Section 5.2.1. Furthermore, we check each of the SKU allocation policies to ensure that SKUs are allocated to the correct destination location. Finally, we check the logic for the inbound reach trucks to ensure the routing is implemented correctly and the processes have the correct processing times.

Outbound process:

For the outbound process, the order generation process is checked, this follows the correct logic and generates an order for each pallet truck every twenty-five minutes. Furthermore, the reach trucks follow the correct logic by handling the first pallet within an order suitable for that specific reach truck, if no pallet is available, they start with or wait until the next order. Finally, we verify that the routing logic of the outbound reach truck is correct.

Pallet supply process:

As the pallet supply process has a lower level of detail, verification of the process is simple in comparison to the verification of the internal warehouse processes. For each of the steps included in this process, dependent on which flow is used for the process, the duration of the steps is verified, and whether the step is started during the correct time.

5.4.2 Model Validation

The model verification confirmed that the simulation model performs the processes described in the conceptual model correctly. After this, validation ensures that the model also gives a representation of reality.

Internal warehouse process:

To validate the model there is a lack of data available for these process steps, therefore according to the techniques of Law (2014) for this, the outcomes of the simulation model are validated by using the expert view of the experts of the process. For this, the model is checked with colleagues with an understanding of the processes. As the simulation model is three-dimensionally animated, the experts can easily judge whether it gives an appropriate view of the real situation. By running through each of the process steps with the corresponding colleague of that process step each of the model's components is validated (white box validation). Finally, black box validation ensures realistic outcomes by checking whether the outcomes are realistic given the inputs. After incorporating feedback and advice to make the model more accurate, the validation has confirmed that the simulation model for the internal warehouse process has the required level of accuracy to be used for recommendations in this thesis.

Pallet supply process:
The pallet supply process has a lower level of detail is lower than the internal warehouse process, therefore validation of this step indicates whether the level of detail is sufficient for this process. For this black box validation is used in which using expert opinion it is checked whether the outputs are realistic given the inputs of the model. So, in this case, whether the throughput times based on the flow types and warehouse throughputs provide a realistic view of reality.

This chapter provided a description of the performance measurement system used to measure the performance of the solutions from Chapter 4. This performance measurement system is a discrete event simulation model for which the logic followed is explained in this chapter.

6 Experiments and Results

This chapter discusses the outcomes of running the experiments. It starts by describing the setup of the experiments. This also includes the settings the simulation model uses to run the experiments, such as the warmup period length, run length, and number of replications. Furthermore, it concludes by providing the results per experiment.

6.1 Experiment Design

To make a comparison between the several solutions established in Chapter 4, firstly for each of the solutions, some input parameters should be provided. These are the parameters: number of inbound reach trucks, number of outbound reach trucks, and percentage of slots to reserve per class type (in case of a class-based allocation policy).

In the simulation model, the number of inbound reach trucks does not affect the performance of the warehouse, as this is solely based on the retrieval times by the outbound reach trucks. However, if there are too few inbound reach trucks, the inbound buffer overflows, meaning the model cannot reach a steady state. The optimal number of inbound reach trucks on our KPIs is equal to the minimum number of inbound reach trucks for which the model reaches a steady state, as this minimizes the number of FTE and does not affect the other KPIs. For each of the solution options the minimum required number of inbound reach trucks for which the model reaches a steady state is equal to four. This can be explained by the fact that the demand for the inbound reach trucks is equal in each of the solutions, and the slight difference in travel distances is not significant enough to reduce the required inbound reach trucks by one unit. Therefore, each of the solutions options has, the number of inbound reach trucks set to four.

In contrast, the number of outbound reach trucks does affect the performance of the solutions. More outbound reach trucks lower the average (internal warehouse) throughput time and can result in a higher percentage of trailers prepared on time. As this presents a trade-off between the number of FTE required (two per additional outbound reach truck) and throughput time, there is no optimal number of outbound reach trucks. Instead for each of the solutions, we use several values for the number of outbound reach trucks to find the efficient frontier on this trade-off for each solution. The range considered for this is between three and eight outbound reach trucks. Three is the minimum of this range as this is the minimum amount for a viable solution, as with less than three outbound reach trucks orders cannot be handled in time causing lists of backorders. Eight is the maximum of the considered range, as more reach trucks within the warehouse would not be desirable in the potential situation within the new warehouse of Scania due to an overflow of traffic. For the current situation, the model only considers the option with six outbound reach trucks as this corresponds to the real situation.

If a solution makes use of a class-based allocation policy, in the model an input parameter indicates what percentage of slots to reserve for class A-items and what percentage of slots to reserve for class B-items. Based on this the model computes the number of slots to reserve per class type, the initialization of the class-based allocation policy uses this number (see Appendix D.2.). To determine the fraction per class we run experiments for several configurations of these options, from which we select the option with the lowest average throughput time. For finding this the model assumes four outbound reach trucks with the current pallet supply approach. Table 6 shows the best configurations found and Appendix G illustrates the experiment results on which the best configurations are based.

Input parameters class-based allocation	Conventional Layout C1	Conventional layout C2 (with half-euro slots)	Flying-V layout
Percentage A slots	*9 %*	*7 %*	*9 %*
Percentage B slots	*20 %*	*11 %*	*12 %*

Table 6: Input parameters class-based allocation

Besides these input parameters, there are also some input parameters regarding the simulation model which need to be defined. These are the warmup period, the run length, the number of replications, and the random number streams.

6.1.1 Warmup Period

For each of the solutions the warehouse starts empty, to fill up the warehouse to a reasonable fill rate at first the simulation model runs twenty-four production hours without orders coming in. This will ensure that the warehouse is filled up to a reasonable fill rate. After orders start coming in, the system still needs time before the outputs reach a steady state. Thus, a warmup period needs to be included so the first values can be deleted in the final outputs.

To find the warmup period we simulate the current situation, which consists of the current warehouse layout with six in and outbound reach trucks. Furthermore, for the unit supply process, we use the base distributions for the pallet truck and trailer combination. To find the warmup period we consider the KPI average order throughput time, as this is the main output KPI which changes over time in the simulation model. According to Law (2014), Welch's graphical approach can be used to determine the warm-up period. For this, the model simulated ten independent runs of fifty days (1200 production hours) for which it measures the output variable *order throughput time* for each order. Figure 18 illustrates that the graph of the moving average throughput time becomes smooth for W = 1000, based on this graph, the system becomes stable around order 1250. As every eight minutes an order comes in, there is a warmup period of 1250*8 = 10000 minutes (166 hours and 40 minutes) after the orders start arriving. However, as the first order arrives after twenty-four hours the total warmup period is thus 190 hours and 40 minutes.

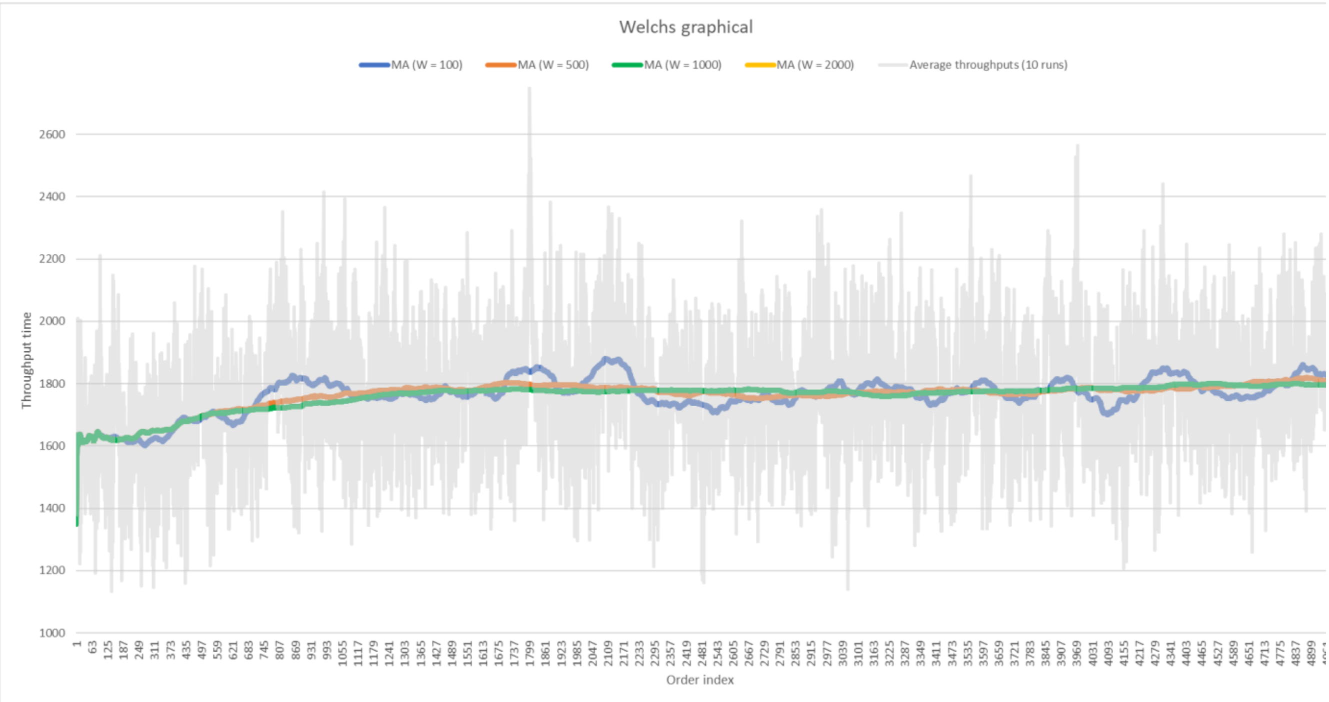

Figure 18: Welch's graphical procedure for warmup period

This is a relatively long warmup period for a simulation model. However, as the warehouse firstly needs to be filled up before it could reach a steady state for this case such a long warmup period is a necessity.

6.1.2 Run Length and Number of Replications

The replication/deletion approach in accordance with Law (2014) is used, this means the simulation is performed for several runs in which for each run the warm-up period is not considered in performance measurement. Based on the rule of thumb by Law (2014) the run length should be larger than ten times the warm-up period. Our simulation model thus uses a run length of eighty days as this is marginally larger than ten times the warmup period.

To find the required number of replications given the run length and warmup period, again we use the base model for the current situation. For this, the simulation model runs ten independent runs, with different random number seed values. This determines the minimum required amount of runs to have a confidence level of 95% for the output. After each replication, we calculate the half-width of the 95% confidence interval. If this is smaller than 0.05 of the mean, our model has enough replications in accordance with Law (2014). Table 7 and Table 8 illustrate the required calculations for both main outputs, as can be seen for our simulation model two replications per experiment already achieve the required relative error. Therefore, the simulation model performs two runs of eighty days for each to find the outputs.

Run	Average throughput time	Mean	Var	Tvalue (95% level of confidence)	CIHW	Error
1	1799,852493					
2	1800,760412	1800,306	0,412159	12,70620474	5,768103754	0,003204
3	1769,276481	1789,963	321,1591	4,30265273	44,51801643	0,024871
4	1807,897737	1794,447	294,5186	3,182446305	27,30784804	0,015218
5	1823,012261	1800,16	384,0863	2,776445105	24,3342801	0,013518
6	1770,411671	1795,202	454,7617	2,570581836	22,37936378	0,012466
7	1796,412434	1795,375	379,1774	2,446911851	18,00903899	0,010031
8	1794,642458	1795,283	325,0763	2,364624252	15,07334954	0,008396
9	1782,106498	1793,819	303,7336	2,306004135	13,39631107	0,007468
10	1818,161103	1796,253	329,2384	2,262157163	12,98009953	0,007226

Table 7: Number of replications based on throughput time

Run	Percentage trailers on time	Mean	Var	Tvalue (95% level of confidence)	CIHW	Error
1	98,97605418					
2	98,66967669	98,82286544	0,046933583	12,70620474	1,946447553	0,019696328
3	98,51648795	98,72073961	0,054755847	4,30265273	0,581287411	0,0058882
4	98,78255261	98,73619286	0,03745911	3,182446305	0,307970994	0,00311913
5	98,83899057	98,7567524	0,030207806	2,776445105	0,215806083	0,002185229
6	98,71805208	98,75030235	0,024415864	2,570581836	0,163980368	0,001660556
7	98,72611465	98,74684696	0,020430131	2,446911851	0,132191911	0,001338695
8	98,91961622	98,76844312	0,021242693	2,364624252	0,12184899	0,001233683
9	98,68580182	98,75926075	0,019346199	2,306004135	0,106914511	0,001082577
10	98,72611465	98,75594614	0,017306488	2,262157163	0,094108152	0,000952937

Table 8: Number of replications based on trailers prepared on time

Note that usually a discrete event simulation model requires more than two replications to achieve the required confidence level, as two replications will result in large confidence intervals. Most literature therefore suggests using at least five replications. However, as the run length is quite large because of the long warmup period, in this case two replications would still have a sufficient level of confidence.

6.1.3 Random Number Generation

In Tecnomatix plant simulation random number generation depends on the seed values of the processes. The seed values provide a fixed stream of random numbers, meaning the same results are reproducible by using the same seed values. The simulation model makes use of the technique of common random numbers. This technique ensures the same random number streams are used when comparing different input settings. By doing so it ensures that the difference in outputs is solely based on the difference between inputs of the solutions. In Tecnomatix plant simulation we achieve this by setting the random number variant to the run number. This means that for each experiment consisting of two runs (as found in Section 6.1.2) all first runs have the same random number streams and all second runs have the same random number streams.

6.2 Experiment Results Internal Warehouse Performance

For each of the layout types in the Tecnomatix plant simulation model, we run an experiment for each combination of the number of outbound reach trucks and the allocated storage policies for that layout. As there are six options for the number of outbound reach trucks to consider, there are twelve options for the conventional layouts and flying-V layout as these consist of two different storage policies. Whereas for the CPU-based layouts, which only have one option for the storage policy, there are six experiments to perform. This means in total there are $12 * 3 + 6 * 2 = 48$ experiments to run for the found solutions, and one benchmark experiment for the current situation. All these experiments only consider the internal warehouse throughput time of the warehouse to identify the most promising solutions. After identifying the most promising solutions from this, we analyze the supply methods for these solutions in Section 6.3.

6.2.1 Current Situation

To provide a benchmark on the Key Performance Indicators first the performance of the current situation is analyzed. For the current situation with four inbound reach trucks, six outbound reach trucks, and the current allocation policy two runs are performed to find the outputs based on the simulation model. Table 9 provides an overview of the performance of the current situation on the KPIs based on our simulation model.

	Current situation				
	Throughput time (min)	Internal throughput time (min)	Required FTEs (#)	Percentage Trailers on	Required space (m^2)
Mean	30:05	16:25	26	98,82%	7249
95% CI lower bound	29:59	16:09		96,07%	
95% CI upper bound	30:12	16:41		100,00%	

Table 9: Benchmark performance current situation on KPIs

6.2.2 Conventional Layout(s)

For the conventional layouts, there are four options to consider as there are two layout types and two storage allocation policies to consider. Conventional layout C1 only consists of storage locations for euro pallets, whereas conventional layout C2 also has slots dedicated to half-euro pallets. Furthermore, both layouts have a random allocation policy and a class-based allocation policy, which are both analyzed. Appendix H.1 illustrates the results of each experiment.

As seen from the results for all the experiments the percentage of pallet trailers on time is 100%, this illustrates that the target outputs are achieved given the input data for these warehouses assuming the current supply process. Furthermore, the space requirement for conventional layout C1 (approximately 4023 m^2) is 9.75% more than the space required for conventional layout C2 (approximately 3666 m^2).

Figure 19 illustrates the trade-off between the number of full-time employees required in the process and the average internal throughput time for the conventional layouts. By increasing the number of outbound reach trucks the required number of FTE increases, as it requires additional employees to handle the reach trucks. However, by increasing the number of outbound reach trucks orders are handled quicker and thus the internal throughput time decreases, as depicted in Figure 19. From the figure and the results can also be concluded that conventional layout C2 with class-based storage Pareto dominates the other solutions for all settings regarding the number of outbound reach trucks as this option is the best across all KPI dimensions. Figure 19 shows that this option has the lowest average internal throughput time per order, for all options which corresponds to the number of

FTE required in the process. Furthermore, all solutions score the same on the percentage of pallet trailers prepared on time (100%) and this solution has the minimum space requirement of the solutions analyzed.

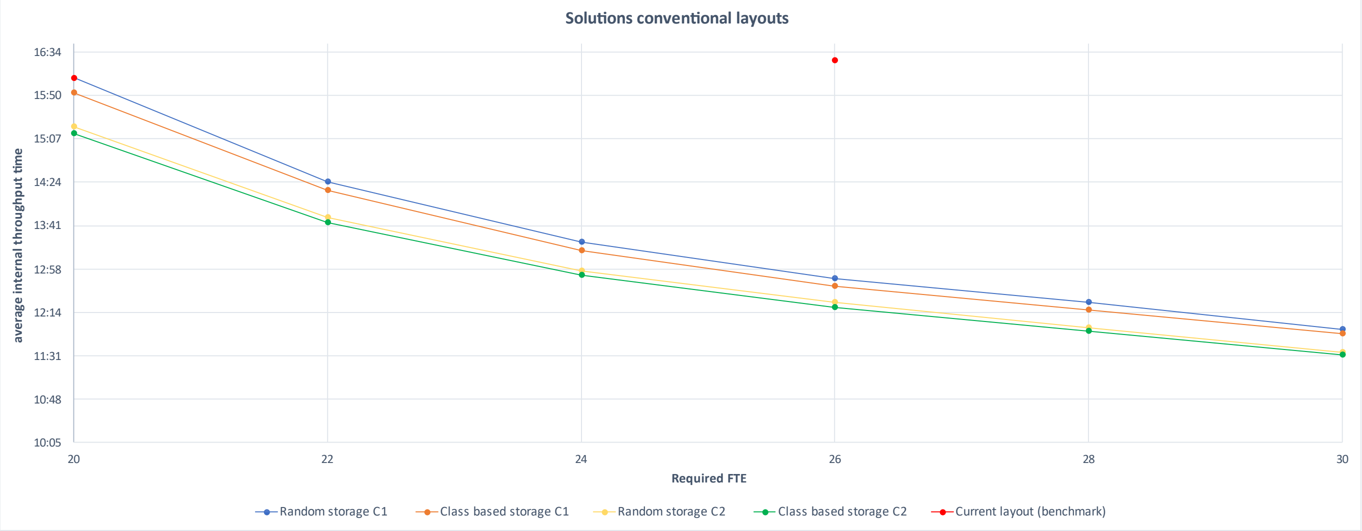

Figure 19: Solution comparison of conventional layouts

Due to this Pareto dominance of the conventional layout C2 with class-based storage, the other conventional options are dropped as a Pareto improvement is always achievable by switching to this option. Thus, Section 6.3 only contains this option for further analysis in the comparison. So, the options for conventional layout C1 and the random storage policy for conventional layout C2 will not be further considered.

Conventional layout C2 provides an improvement as the layout is denser and thus offers shorter travel distances. A potential downside of conventional layout C2 in comparison to conventional layout C1 is that it offers less storage flexibility for euro pallets, as there are now fewer locations available for these. However, the established KPIs do not reflect this flexibility.

The class-based storage policy provides a reduction in average internal throughput time as now it stores only fast-moving items in the best possible slots. This ensures that within the best slots, it does not store items that are in storage for a long time, this causes fast inventory turnover at the best possible locations ensuring good utilization of the best possible slots. Appendix H.3. provides a heatmap based on the number of movements towards each zone (averaged over two runs) for the solutions. The heatmaps for the conventional layouts illustrate the principle of the class-based policy, by a higher number of interactions near the outbound location (centrally located in the outbound zone).

6.2.3 Flying-V Layout

In the Flying-V layout also both the class-based allocation policy and the random allocation policy are considered. Appendix H.1. illustrates the results of the experiments of this layout. For this layout, the required area is 4477 m^2, compared to the conventional layout C2 this is a 22.1% increase. Furthermore, for all experiments performed the percentage of pallet trailers prepared on time was once again 100%. Figure 20 illustrates the trade-off between the number of FTE required in the process and the average internal throughput time. As can be seen from Figure 20 the class-based storage policy Pareto dominates the random storage policy on the KPIs as it has a lower internal throughput time for all possible numbers of required FTE, while performing as well on the other KPIs.

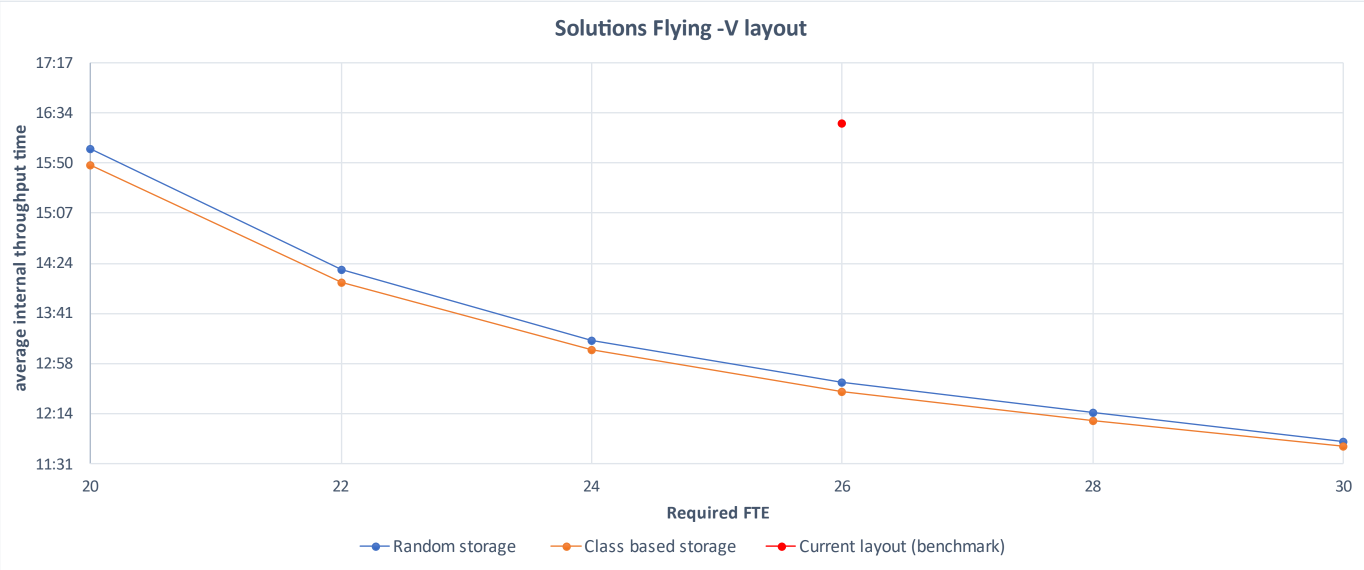

Figure 20: Solution comparison Flying-V layout

The Flying-V layout designed in Section 4.1.3, only makes use of euro locations and does not have dedicated locations for half euro pallets. As shown in Section 6.2.2, using dedicated half-euro locations can improve performance on internal throughput time, while also reducing the required space for the warehouse. Thus, for a fair comparison to the conventional layouts, the Flying-V layout is compared with conventional layout C1. Figure 21 provides a comparison between the Flying-V and the conventional layouts assuming a class-based storage policy.

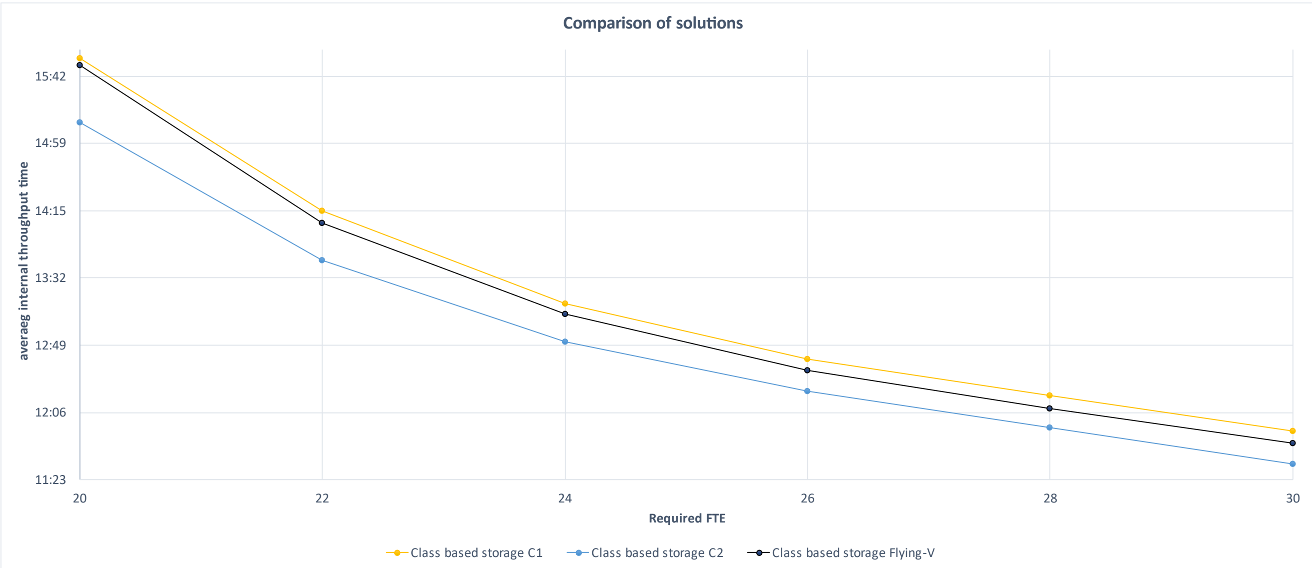

Figure 21: Performance comparison of Flying-V layout and conventional layouts

As seen the Flying-V layout compared to conventional layout C1 can offer a reduction in internal throughput time at the cost of additional space required. However, as this research did not consider the conventional layout with half euro locations the Flying-V layout is Pareto dominated by conventional layout C2. Therefore, the analysis of the supply process will not include this layout.

6.2.4 CPU-based Layout

For the CPU-based layout only the combined allocation policy as described in Section 4.2.3 is considered, the results for the experiments of this layout can be found in Appendix H.1. For this experiment the two alternatives as described in Section 4.1.4 and illustrated in Appendix E.3. are considered. The required area for alternative 1 of this layout is approximately 4242 m^2, this is 15.7% more than the conventional layout C2. The required area for alternative 2 of this layout is approximately 4112 m2, which is 12.2% more than conventional layout C2. Similarly, to the previously found solutions, the percentage of pallet trailers prepared on time for all experiments of both alternatives of this solution is equal to 100%. Figure 22 illustrates the trade-off between the number of FTEs required and order throughput of both alternatives compared to conventional layout C2.

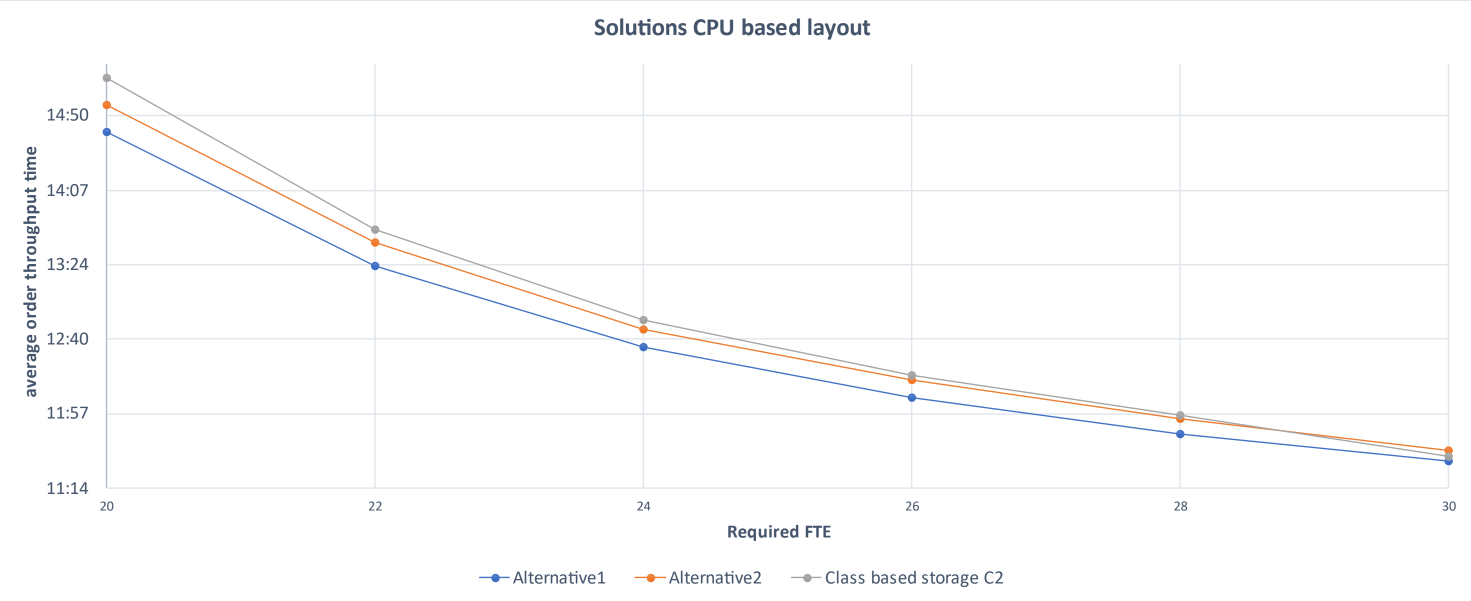

Figure 22: Solution comparison CPU-based layout

As can be seen from Figure 22 for both alternatives the CPU-based layout has a lower internal average order throughput time in comparison to the currently best-found solution the conventional layout C2 with class-based allocation.

There is no Pareto dominance of conventional layout C2 with class-based allocation over the CPU-based layouts as the CPU-based layouts offer lower average throughput given the number of required FTE. Furthermore, there is also no Pareto dominance of the CPU-based layout over conventional layout C2 as the required area is larger. Therefore, these options are both considered in the analysis of the supply process.

Table 10 provides an overview of the internal warehouse performance of all the solutions given the minimum number of outbound reach trucks selected, as well as the current situation. Based on this we select the two most promising solutions: conventional layout C2 with class-based allocation and CPU-based layout with combined allocation for further consideration.

Decision	Average internal throughput time order	Required number of FTE	Percentage of pallet trailers on time	Required space for the warehouse
No relocation or redesign (current situation)	16:25	26	98,82%	7249 m^2
Conventional layout C1 with random allocation	16:08 (-1.73%)	20 (-23.07%)	100% (+1.18%)	4023 m^2 (-44.5%)
Conventional layout C1 with class-based allocation	15:53 (-3.25%)	20 (-23.07%)	100% (+1.18%)	4023 m^2 (-44.5%)
Conventional layout C2 with random allocation	15:20 (-6.67%)	20 (-23.07%)	100% (+1.18%)	3666 m^2 (-49.4%)
Conventional layout C2 with class-based allocation	15:12 (-7.41%)	20 (-23.07%)	100% (+1.18%)	3666 m^2 (-49.4%)
Flying-V layout with random allocation	16:03 (-2.27%)	20 (-23.07%)	100% (+1.18%)	4477 m^2 (-38.2%)
Flying-V layout with class-based allocation	15:49 (-3.67%)	20 (-23.07%)	100% (+1.18%)	4477 m^2 (-38.2%)
CPU-based layout alternative 1 with combined allocation policy	14:40 (-10.65%)	20 (-23.07%)	100% (+1.18%)	4242 m^2 (-41.5%)
CPU-based layout alternative 2 with combined allocation policy	14:56 (-9.01%)	20 (-23.07%)	100% (+1.18%)	4112 m^2 (-43.28%)

Table 10: Internal warehouse performance of all solutions

6.3 Experiment Results Supply Process

To measure the performance of the most promising solutions from Section 6.2, we also consider the flow towards the production area. To do so the options from Section 4.3 are implemented in the simulation model by the approach described in Section 5.1.3.

6.3.1 Solutions Bridge Flow

The two alternatives for the CPU-based layout with a combined allocation policy and the conventional layout C2 with class-based allocation policy are tested for the bridge flow supply method. Appendix H.2 illustrates the results of the experiments for three to eight outbound reach trucks.

Compared to the results of 6.2, the findings for the KPIs percentage pallet trailers on time (100% in all experiments) and required area (3666 m^2 for conventional layout C2, 4242 m^2 for the CPU-based layout alternative 1 and 4112 m^2 for the CPU-based layout alternative 2) remain the same. For the FTE requirement of the bridge flow, there is the same requirement as in Section 6.2 with the only variable being the number of outbound reach trucks. Now for the order throughput, the model will consider the time until the pallet reaches the delivery zone at the production line, instead of when the trailers are prepared. Figure 23 provides an overview of the performance of the bridge flow on the number of required FTE and average order throughput time for a given number of outbound reach trucks.

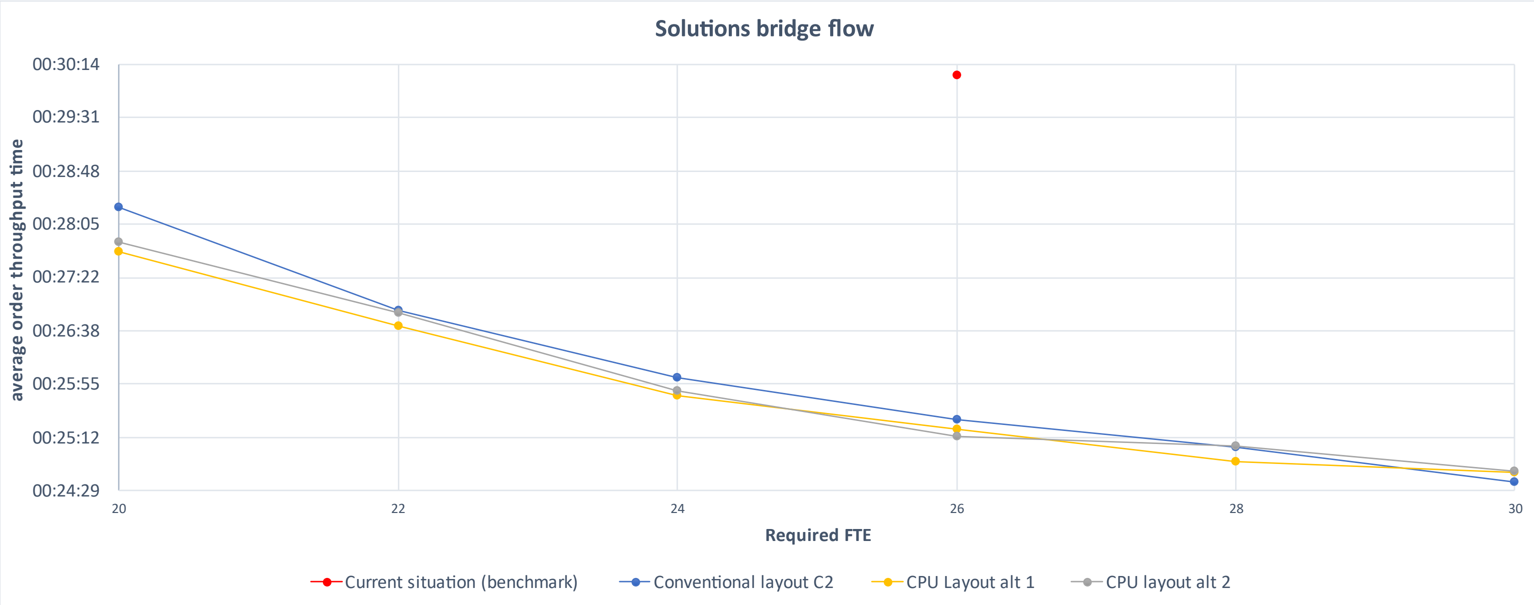

Figure 23: Solution comparison of bridge flow

As the results show, by relocating to the Y-building and investing in a bridge to enable the same supply method a Pareto improvement compared to the current situation is achievable. Table 11 illustrates an overview of the achievable changes in the Key Performance Indicators.

KPI	Old value	New Value	Percentage change
Average throughput time order	30:05	Conventional layout C2: 24:36 – 28:18 CPU-based layout alt 1: 24:43 – 27:42 CPU-based layout alt 2: 24:45 – 27:50	Dependent on the number of outbound reach trucks Conventional layout between -18.25% and -5.94% CPU-based layout alt 1 between -17.84% and -7.93% CPU-based layout alt 2 between -17.77% and -7.48%
Required number of FTE	26	All layouts: 20 – 30	Dependent on the number of outbound reach trucks between -23.07% and +15.39%
Percentage of pallet trailers prepared on time	98,82%	All layouts: 100%	Both layouts: +1.18%
Required space for the warehouse	7249 m^2	Conventional layout C2: 3666 m^2 CPU-based layout alt 1: 4242 m^2 CPU-based layout alt 2: 4112 m^2	Conventional layout C2: -49.43% CPU-based layout alt 1: -41.48% CPU-based layout alt 2 -43.28%

Table 11: Overview of KPI change relocation Y-building (bridge flow)

6.3.2 Solutions Lorry Transport

Similarly, as done in Section 6.3.1, both the CPU-based layouts with the combined allocation policy and conventional layout C2 with class-based allocation policy are tested for the two options of lorry transport. Appendix H.2. provides the results of the experiments for three to eight outbound reach trucks. The KPIs percentage of pallet trailers on time and required space for the warehouse remain the same compared to Section 6.3.1. However, the trade-off between FTE requirement and average throughput time changes significantly. Figure 24 illustrates this, in this figure LF1 represents flow type 2a and LF2 represents flow type 2b.

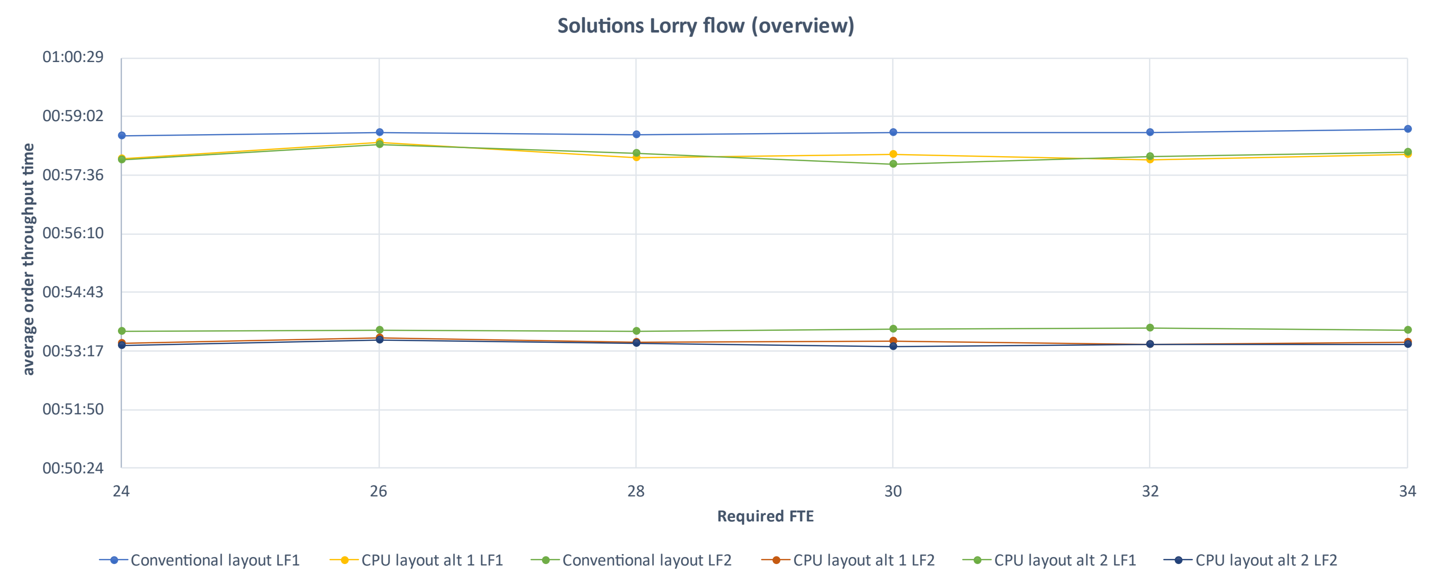

Figure 24: Solution comparison lorry flow options

As Figure 24 shows, flow type 2b has significantly lower throughput time and Pareto dominates flow type 2a. This makes sense as if moving the lorry toward the pallet breakdown, the return flow of pallet trailers within the production area only consists of one visit (to pallet breakdown) instead of two visits. Figure 24 also illustrates that the CPU-based layouts slightly outperform the conventional layout on average order throughput time at the cost of a larger required area. Finally, Figure 24 depicts that in the case of lorry transport, there is no benefit of increasing the number of outbound reach trucks over the minimal level of three. This is most likely because the time before the lorry returns to the warehouse to pick up the pallets is mostly longer than the time before the order is prepared. Meaning a slightly lower warehouse throughput does not improve overall order throughput.

To compare the lorry flow to the bridge flow and current situations, this thesis only further considers the layouts for flow type 2 as these layouts are not Pareto-dominated. As seen in Figure 25, the lorry flow has higher average throughput times, compared to the current situation and the options making use of a bridge flow. Furthermore, the minimum number of required FTE in this process also is higher than the bridge flow solutions.

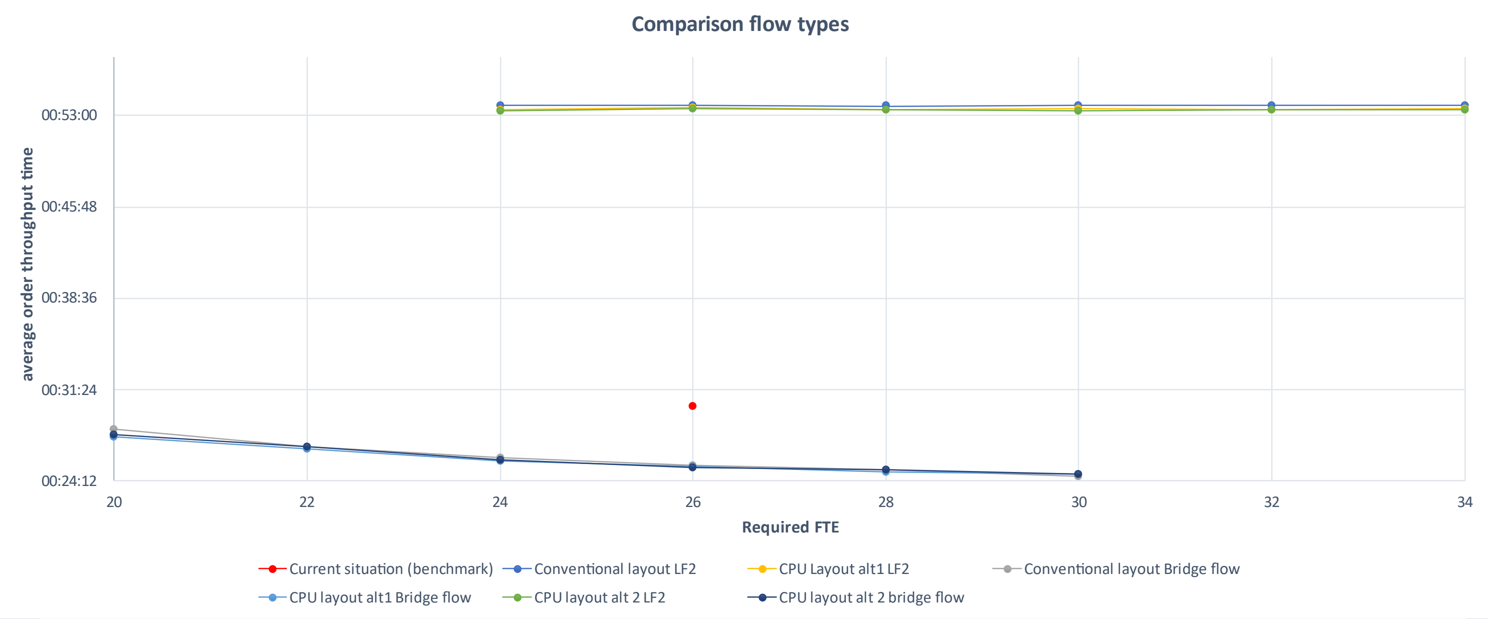

Figure 25: Comparison of lorry flow, bridge flow, and current situation

If Scania does not invest in enabling the bridge flow, relocating the warehouse to the Y-building does have advantages as it can improve the internal warehouse performance. A higher percentage of pallet trailers can be prepared on time, a lower required number of FTE, and higher space efficiency can be achieved by the improved layout. However, due to the additional lorry transport, the average order throughput time goes up compared to the current situation. Table 12 shows an overview of the KPI changes compared to the current situation. For these results, the number of outbound reach trucks is set to three as a further increase would not improve the performance on the KPIs.

KPI	Old value	New Value	Percentage change
Average throughput time order	30:05	Conventional layout C2: 53:46 CPU-based layout alt 1: 53:28 CPU-based layout alt 2: 53:24	Conventional layout C2: +78.68% CPU-based layout alt 1: +77.67% CPU-based layout alt 2: +77.49%
Required number of FTE	26	All layouts: 24	All layouts: -7.69%
Percentage of pallet trailers prepared on time	98,82%	All layouts: 100%	All layouts: +1.18%
Required space for the warehouse	7249 m^2	Conventional layout C2: 3666 m^2 CPU-based layout alt 1: 4242 m^2 CPU-based layout alt 2: 4112 m^2	Conventional layout C2: -49.43% CPU-based layout alt 1: -41.48% CPU-based layout alt 2: -43.28%

Table 12: Overview of KPI change relocation to Y-building (lorry flow)

This chapter illustrated the expected measured performance on the Key Performance Indicators from the different layouts and supply methods using the discrete event simulation model. The outcomes listed within this chapter are used to draw the conclusions and provide recommendations.

7 Conclusions and Recommendations

To finalize this thesis this chapter contains the conclusions and recommendations which can be made based on this research. This consists of the conclusions which discuss the main findings of our research, it then discusses the contribution to literature and the recommendations to Scania. Finally, it discusses the limitations of the research to consider and what could be researched in the future based on the findings.

7.1 Conclusions

Reflecting on the research questions described in Section 1.5, this research has provided the answers to all five research questions (RQs).

Firstly, for RQ1: *How can the performance of the pallet warehouse and internal logistics be measured at Scania?* By analyzing the current situation, this thesis has established a performance measurement system consisting of four KPIs. Furthermore, the theoretical background showed that for this situation a Discrete Event Simulation model can be used to measure the expected performance of a warehouse.

For RQ2: *What is the current situation regarding pallet supply from the old building?* Chapter 2 provides an extensive analysis of the current situation. Furthermore, Chapter 2 also includes an estimation of the performance of the current situation on the KPIs from RQ1.

For RQ3: *What are the existing methods described in the literature that can be used to optimize the warehouse design?* Chapter 3 provides several existing methods from the literature. For warehouse design, it found conventional layouts and non-orthogonal layout options. Furthermore, for the storage policy to determine where in the warehouse parts should be allocated, we established four main options. These are random storage, class-based storage, dedicated storage, and mixed-shelves storage.

Based on the findings from RQ3, chapter 4 describes some proposed layouts for the situation of Scania. Furthermore, chapter 4 also describes the supply options towards the production area. This answers RQ4: *What are the proposed layouts for Building Y using the methods of RQ3? And what are the corresponding logistic flows from this building to the production lines?* For the warehouse layout problem, four possible options are designed. This consists of two conventional layouts, a Flying-V layout, and two alternatives of a CPU-based layout. Furthermore, Chapter 4 describes three possible options for the logistic flows towards the production area: one flow making use of pallet trailers and pallet trucks and two options making use of lorries.

Based on all the options found from RQ4 using a Discrete Event Simulation model Chapter 6 compares the options for warehouse design and supply options. This also includes a comparison with the current situation. This answers RQ5: What is the performance of the proposed layouts and supply options found in RQ4 using the performance measurement system of RQ1? This chapter discusses the main findings from this comparison below. The findings consist of two parts: findings concerning the warehouse design and findings concerning the relocation to the Y-building.

7.1.1 Warehouse Design

This section only considers the internal warehouse processes, so it excludes the delivery towards the production area by pallet trucks and pallet trailers. This means that the order throughput time, in this case, would be the time until the order is prepared at the warehouse.

Compared to the current layout an improvement in efficiency on all KPIs for warehouse design is achievable. The current layout is split into three halls making it inefficient due to a large amount of travel distance. This can be reduced significantly by using a different layout. The large amount of travel distance causes high internal order throughput times and a high number of required FTE. Furthermore, the current layout has low space efficiency and a comparatively low percentage of pallet trailers prepared on time. The simulation model indicates that the layouts' conventional layout with half-euro locations and the two alternatives of the CPU-based layout perform the best out of the found warehouse layouts.

For the Flying-V layout and conventional layouts, both a random storage policy and a class-based policy are evaluated. This has shown that for these layouts and all experiment settings, the class-based storage reduces the average internal order throughput time compared to the random storage policies. This illustrates that in the case of Scania, reserving the best possible slots for fast movers can improve order throughput times. As all other KPIs remain the same between the policies, the class-based storage policy Pareto dominates the random storage policy. Thus, the remainder of the conclusion will not contain the random storage policy and instead includes only the results of the class-based policy or the combined allocation policy (CPU-based layout).

The conventional layout with half euro locations (conventional layout C2) has the minimum required area of the found solutions of 3666 m^2. This would reduce the required area by 49.43% compared to the current situation (7249 m^2). Furthermore, the simulation model found that all pallet trailers were prepared on time during the simulation runs. The layout would thus provide a 100% performance on the KPI percentage of pallet trailers prepared on time. This is a 1.18% improvement from the current situation (98.82%). The improvement in the internal order throughput time and FTE reduction depends on the decision on how many outbound reach trucks to use. Assuming the minimal number of outbound reach trucks (three) that would be able to handle the orders in time, the average internal order throughput time would be 15:12. This is a 7.41% reduction of average order throughput time compared to the current situation (16:25). Finally, the FTE reduction when using the minimal number of outbound reach trucks would be six concerning the internal warehouse processes.

The CPU based layout requires 4242 m^2 space or 4112 m^2 depending on which alternative. This is more than the conventional layout C2 however still reduces the required area by 41.48% or 43.28% compared to the current situation. Similarly, to conventional layout C2, the CPU-based layouts also have a 100% performance on the KPI percentage pallet trailers on time. However, compared to the conventional layout C2 the CPU-based layout has a lower average order throughput time. Assuming the minimal number of outbound reach trucks (three), for the CPU-based layout the average internal order throughput would be 14:40 for alternative 1. This is a 10.65% reduction compared to the current situation and a 3.5% reduction compared to the performance of conventional layout C2. For alternative 2 of the CPU-based layout the internal order throughput time would be 14:56. This is a 9.01% reduction compared to the current situation and a 1.73% reduction compared to the performance of convention layout C2.

For the Flying-V layout, the model showed that a reduction in average internal order throughput time can be achieved in comparison to conventional layout C1 (only slot euro pallets). This is as expected, as the diagonal cross aisles reduce the average travel distance. However, as the Flying-V layout only consists of euro slots and no dedicated half euro locations, conventional layout C2 still outperforms this layout on both the required space and average order throughput.

7.1.2 Relocation to Y-building

This thesis has analyzed two main transport methods towards the production area, for the relocation to the Y building. The first option is to invest in a bridge to cross the road from building Y towards the production area. This makes use of the current transport method towards the production area, which consists of pallet trucks and trailers. This option requires a large (undisclosed) investment, but this would make the supply process simple. The second option is to use a lorry to transport the pallets towards the production area, at the production area pallet trucks and trailers would then further transport the pallets. This lorry transport option consists of two different possible logistic flows analyzed.

The results from the simulation model show that if Scania does not invest in a bridge, but instead uses lorry transport the average order throughput time would be higher than in the current situation. This is mostly due to the additional loading and unloading steps required to perform the transport and the waiting times until the trailer starts transport towards the production area. The lorries would in the best scenario transport pallet trailers towards the location for the pallet breakdown. If Scania uses lorry transport, the benefits of the low internal throughput times of the new warehouse layouts are negated by the lorry transport. Assuming the minimum required number of outbound reach trucks are used, the average order throughput time would be 53:46 (78.68% higher than the current situation) for conventional layout C2, 53:28 (77.67% higher than the current situation) for the CPU-based layout alternative 1 and 53:24 (77.49% higher than the current situation) for the CPU-based layout alternative 2. The total FTE requirement in the process would be two lower than the current situation (six FTE reduction in the warehouse internally, but four FTE more for lorry transport).

If Scania decides to invest in the bridge, enabling pallet truck and trailer transport directly towards the production area, this will achieve Pareto improvements compared to the current situation. The average order throughput time would be 28:18 (5.94% lower than the current situation) for conventional layout C2, 27:42 (7.93% lower than the current situation) for the CPU-based layout alternative 1 and 27:50 (7.48% lower than the current situation) for the CPU-based layout alternative 2. Furthermore, the FTE requirement would be six lower than the current situation. This assumes using the minimum number of outbound reach trucks (three).

7.2 Recommendations to Scania Production Zwolle

This section discusses the recommendations that can be made to Scania Production Zwolle based on the findings discussed in the conclusion.

Regarding warehouse design based on the options analyzed, Scania should implement conventional layout C2 or one of the alternatives of the CPU-based layout if they relocate to building Y. As discussed in section 7.1.1 these options offer an improvement compared to the current situation on the KPIs and are the only layouts, not Pareto dominated by other layouts. The CPU-based layout alternative 1 performs the best on average order throughput time, whereas the conventional layout C2 has the lowest space required. The CPU based layout alternative 2 has slightly higher order throughput time than alternative 1 but with a smaller area requirement. Which one to choose out of these three options depends on which KPI Scania prioritizes. For the fastest possible handling of orders, Scania should choose the CPU-based layout alternative 1. However, if Scania wants to minimize the space requirement, Scania should choose the conventional layout C2.

Depending on which layout Scania chooses, they should implement a corresponding storage policy. For conventional layout C2, Scania should implement a class-based policy. This policy offers lower average throughput times than a random storage policy. For the CPU-based layouts, Scania should implement the combined allocation policy specifically for the CPU-based layout. Section 4.2 describes these storage policies.

Regarding the logistic flow towards the production area when relocating to the Y-building, if Scania decides to invest in a bridge significantly lower average order times is achievable. Furthermore, this requires four less FTE compared to lorry transport. The employee cost savings would in the long term earn back the investment required for the bridge. Based on this research, Scania should invest in the bridge as this investment would earn itself back and has lower throughput times compared to the lorry transport. However, this decision is more complicated and depends on more than only the performance of the unit-supply process. If Scania decides not to invest in the bridge, they can (for the time being) use lorry transport for this process at the cost of performance for the unit supply process.

When Scania does not invest in a bridge to enable pallet trailer transport, the average throughput time goes up significantly compared to the current situation due to lorry transport. Scania should analyze the impact this has on the overall production time, to support this decision.

This thesis has shown that a redesign of the warehouse can provide improvements compared to the current situation for the internal warehouse processes. However, relocating the warehouse to building Y would require significant investment in a bridge or would complexify the supply process using lorries. Based on this, the decision to relocate to building Y depends on external forces. This depends on the importance of freeing up the old building for other purposes and the overall need for relocation. Table 13 provides an overview of the expected outcomes of the possible decisions, assuming the minimum outbound reach trucks (three) will be used. Note that in the table the average order throughput time is split up in the total throughput time and the throughput time within the warehouse. This provides Scania with the necessary information regarding the final decision options.

Decision	**Average order throughput time**	**Required number of FTE**	**Percentage of pallet trailers on time**	**Required space for the warehouse**
No relocation or redesign (current situation)	30:05 In warehouse: 16:25	26	98,82%	7249 m^2
Relocation without bridge conventional layout C2	53:46 (+78.68%) In warehouse: 15:12	24 (-7.69%)	100% (+1.18%)	3666 m^2 (-49.43%)
Relocation without bridge CPU-based layout alternative 1	53:28 (+77.67%) In warehouse: 14:40	24 (-7.69%)	100% (+1.18%)	4242 m^2 (-41.48%)
Relocation without bridge CPU-based layout alternative 2	53:24 (+77.49%) In warehouse: 14:56	24 (-7.69%)	100% (+1.18%)	4112 (-43.28%)
Relocation with bridge conventional layout C2	28:18 (-5.94%) In warehouse: 15:12	20 (-23.07%)	100% (+1.18%)	3666 m^2 (-49.43%)
Relocation with bridge CPU-based layout alternative 1	27:42 (-7.93%) In warehouse: 14:40	20 (-23.07%)	100% (+1.18%)	4242 m^2 (-41.48%)
Relocation with bridge CPU-based layout alternative 2	27:50 (-7.48%) In warehouse: 14:56	20 (-23.07%)	100% (+1.18%)	4112 (-43.28%)

Table 13: Overall decision expected outcomes

7.3 Contributions to Literature

This research contributes to the existing literature in multiple ways. Firstly, this thesis compares existing layout design options and storage allocation policies using DES. This is not necessarily a novel approach; however, the literature review has not found research that compares the given options for a practical case. Furthermore, this practical case differentiates from other case studies as it consists of a unique differentiation between the pallet dimensions on which the warehouse design needs to be adapted.

Secondly, as far as known from the existing literature analyzed, the CPU-based layout described in Section 4.1.4 is a new method for warehouse design. As discussed in Section 7.2 the CPU-based layout alternative 1 is the best out of the layouts analyzed on average throughput time, which comes at the cost of a larger area than a conventional layout. This research has the academic contribution that it introduces a novel approach to warehouse design. This method can is applicable when in a warehouse, differentiation between high-performance locations, space-efficient locations, and shared locations can be done.

Finally, most existing literature on warehouse design only considers the process until the SKU leaves the warehouse. This thesis differentiates from this as it also compares different transport methods towards the production area. Using the DES model, this thesis analyzes both the impact of warehouse design and storage allocation as well as the outbound logistics from the warehouse.

7.4 Limitations of Research

The research has limitations to consider before acting on the conclusions and recommendations. The limitations are a necessity due to the complexity of the case.

Firstly, the level of detail for the analysis of the different supply methods toward the production area is lower than the level of detail for the internal warehouse processes in the simulation model. The supply methods have been analyzed using simple distributions based on expert views to indicate the expected performance of these options. This means that, to some extent, the real situation might be different from the simulated model.

The simulation model fully separates the in and outbound processes for this research. This means the distribution of the inbound pallets is separated from the outbound orders. Whereas, in the real situation, the inbound pallet arrivals depend on the outbound demand. In the real situation, inbound pallet orders are ordered when the inventory reaches a reorder point. As the average number of outgoing pallets equals approximately the average number of inbound pallets, the simulation model still has a steady inventory level after some period and provides a similar fill rate level as the real situation. However, the model could be more accurate if inbound orders depend on the consumption of pallets from the production area.

Traffic potentially has a large influence on the performance of the warehouse layouts. A layout could have short travel distances, but if the reach trucks wait a lot for other reach trucks to pass, the layout is still not efficient. The simulation model currently does not consider traffic within the warehouse; thus, the results might have a positive bias regarding the performance of the layouts.

Finally, this research does not consider human error and inefficient handling. The simulation model assumes no deviation from the so-called “normal situation”. This could also give a positive bias to the performance of the layouts, as in the real situation human errors do happen, affecting the efficiency of the process. However, as human error can happen for all layouts, this would most likely not affect the results of the research.

7.5 Future Research

This section contains some topics which could be further analyzed based on this research. This is split up into two parts. Firstly, there are future research directions for Scania that can be researched to make a more thorough decision on the relocation of the warehouse. Secondly, some research topics could be investigated by other academics based on this research.

7.5.1 Future Research for Scania

As concluded in Section 7.1.1, the Flying-V layout provides an improvement in average throughput time in comparison with the conventional layout with only euro locations. As also discussed in Section 7.1.1, including dedicated locations for half-euro pallets, can improve the performance of the warehouse. Thus, for a fair comparison to the other layouts, Scania should research a Flying-V layout with dedicated half-euro locations to find how this would affect the performance of the warehouse. If this would have a lower average order throughput time than the conventional layout C2 and the CPU-based layout it might be a better warehouse design for the case of Scania than the other layouts. In addition to this Scania can also research the other possible types of non-orthogonal layouts as mentioned in Section 3.1.3 (such as Chevron layout and Fishbone layout) which can further reduce the average throughput time per order at the expense of a larger required area.

This research has found that the CPU-based layout can achieve the lowest order throughput times out of the layouts analyzed. The CPU-based layout has P-sections, consisting of floor locations for fast-moving items, this enables quick handling of pallets. For Scania, it could be interesting to research how the other layouts, such as the conventional and flying-V layouts perform if floor locations are included within these layouts. This might result in even better performance than the CPU-based layout on order throughput time.

As explained in Section 7.4 traffic can play a significant role in the performance of the warehouse layouts. Before making a final decision, Scania should research how large the impact of traffic on the layouts would be. For example, based on the warehouse heatmap in Appendix H.3. the CPU-based layout has more traffic toward the outbound zone of the warehouse. By researching how this would affect the warehouse performance, a better-informed decision on the layout choice can be made.

Finally, one of the options for warehouse design Scania considers implementing would be an automated storage and retrieval system (ASRS see Section 3.1.4). For this option, Scania could use a conveyor (bridge) to handle the transport towards the production area. This would mean a lower number of FTE would be required in the process, providing cost savings at the cost of a significant investment. This thesis does not include the analysis of an ASRS, as the performance of an ASRS depends on the specifications from the supplier, thus the expected benefits of considering this in our thesis are low. Scania should investigate whether an automated storage and retrieval system could be a viable investment.

7.5.2 Future Academic Research

This thesis has shown that the CPU-based warehouse design would be an appropriate solution for the case of Scania. From the layouts analyzed in this thesis, the CPU-based layout performs the best concerning the average order throughput time. This should encourage other academics, to analyze the impact of a CPU-based warehouse layout for other cases. This would illustrate if this type of layout also works for different cases and not only for the case of Scania. For this implementation of the CPU-based layout, it is a necessity that within the warehouse differentiation is possible between fast-performance locations, space-efficient locations, and shared (flexible) storage.

Appendix C provides the CPU processor used as inspiration for the CPU-based layout. Other academics could research how layouts inspired by other (newer generation) CPU processors would perform in other cases.

Bibliography

Ang, M., & Lim, Y. F. (2019). How to optimize storage classes in a unit-load warehouse. *European Journal of Operational Research*, *278*(1), 186-201. https://doi.org/10.1016/j.ejor.2019.03.046

Azzi, A., Battini, D., Faccio, M., Persona, A., & Sgarbossa, F. (2011). Innovative travel time model for dual-shuttle automated storage/retrieval systems. *Computers & Industrial Engineering*, *61*(3), 600-607. https://doi.org/10.1016/j.cie.2011.04.015

Baker, P., & Canessa, M. (2009). Warehouse design: A structured approach. *European Journal of Operational Research*, *193*(2), 425-436. https://doi.org/10.1016/j.ejor.2007.11.045

Berg, J. P. v. d., & Zijm, W. H. M. (1999). Models for warehouse management: Classification and examples. *International Journal of Production Economics*, *59*(1), 519-528. https://doi.org/https://doi.org/10.1016/S0925-5273(98)00114-5

Cardona, L. F., Rivera, L., & Martínez, H. J. (2012). Analytical study of the Fishbone Warehouse layout. *International Journal of Logistics Research and Applications*, *15*(6), 365-388. https://doi.org/10.1080/13675567.2012.743981

Cardona, L. F., Soto, D. F., Rivera, L., & Martínez, H. J. (2015). Detailed design of fishbone warehouse layouts with vertical travel. *International Journal of Production Economics*, *170*, 825-837. https://doi.org/10.1016/j.ijpe.2015.03.006

Derhami, S., Smith, J. S., & Gue, K. R. (2020). A simulation-based optimization approach to design optimal layouts for block stacking warehouses. *International Journal of Production Economics*, *223*, Article 107525. https://doi.org/10.1016/j.ijpe.2019.107525

Dukic, G., & Opetuk, T. (2008, Mar 09-15). Analysis of order-picking in warehouses with fishbone layout. [International conference on industrial logistics (icil 2008): Logistics in a flat world: Strategy, management and operations]. International Conference on Industrial Logistics, Tel Aviv, ISRAEL.

Dukic, G., & Tihomir, O. (2014). Warehouse Layouts. *Warehousing in the Global Supply Chain: Advanced Models, Tools and Applications for Storage Systems*, 55-69. https://doi.org/10.1007/978-1-4471-2274-6_3

Elektrische trekker P250 | Serie 127-05 | Motrac. (2024). Motrac. https://www.motrac.be/linde/nl/producten/magazijntrucks/trekkers-platformwagens/p250

Esmero, A. T., Branzuela, Q. R. S., Paypa, J. T., Rojo, S. M. S., Sacay, E. S., Selerio, E. F., & Ocampo, L. A. (2021). Heuristic comparative assessment of non-conventional warehouse designs. *Engineering Management in Production and Services*, *13*(1), 89-103. https://doi.org/doi:10.2478/emj-2021-0007

Frazelle, E. H. (2001). *World-Class Warehousing and Material Handling*. McGraw Hill LLC. https://books.google.nl/books?id=mK_Pf9DkOX0C

Gu, J. X., Goetschalckx, M., & McGinnis, L. F. (2010). Research on warehouse design and performance evaluation: A comprehensive review. *European Journal of Operational Research*, *203*(3), 539-549. https://doi.org/10.1016/j.ejor.2009.07.031

Gue, K. R., & Meller, R. D. (2009). Aisle configurations for unit-load warehouses. *Iie Transactions*, *41*(3), 171-182. https://doi.org/10.1080/07408170802112726

Gülle, M., & Hegmanns, T. (2014, Apr 28-30). Simulation-Based Performance Analysis of a Miniload Multishuttle Order Picking System.*Procedia CIRP* [Variety management in manufacturing: Proceedings of the 47th cirp conference on manufacturing systems]. 47th CIRP Conference on Manufacturing Systems, Univ Windsor, Windsor, CANADA.

Heerkens, H., & van Winden, A. (2017). *Solving Managerial Problems Systematically*. Noordhoff Uitgevers.

Heragu, S. S., Cai, X., Krishnamurthy, A., & Malmborg, C. J. (2011). Analytical models for analysis of automated warehouse material handling systems. *International Journal of Production Research*, *49*(22), 6833-6861. https://doi.org/10.1080/00207543.2010.518994

Heragu, S. S., Du, L., Mantel, R. J., & Schuur, P. C. (2005). Mathematical model for warehouse design and product allocation. *International Journal of Production Research*, *43*(2), 327-338. https://doi.org/10.1080/00207540412331285841
Intel Core i5-13600K. (2022). TechPowerUp. https://www.techpowerup.com/review/intel-core-i5-13600k/2.html
Kheybari, S., Naji, S. A., Rezaie, F. M., & Salehpour, R. (2019). ABC classification according to Pareto's principle: a hybrid methodology. *Opsearch*, *56*(2), 539-562. https://doi.org/10.1007/s12597-019-00365-4
Law, A. M. (2014). *Simulation modeling and analysis* (5th edition. ed.). McGraw-Hill Education.
Macro, J. G., & Salmi, R. E. (2002, Dec 08-11). A simulation tool to determine warehouse efficiencies and storage allocations. [Proceedings of the 2002 winter simulation conference, vols 1 and 2]. 35th Winter Simulation Conference, San Diego, Ca.
Öztürkoğlu, Ö., Gue, K. R., & Meller, R. D. (2012). Optimal unit-load warehouse designs for single-command operations. *Iie Transactions*, *44*(6), 459-475. https://doi.org/10.1080/0740817X.2011.636793
Petersen, C. G. (1999). The impact of routing and storage policies on warehouse efficiency. *International Journal of Operations & Production Management*, *19*(9-10), 1053-1064. https://doi.org/10.1108/01443579910287073
Petersen, C. G., & Aase, G. R. (2004). A comparison of picking, storage, and routing policies in manual order picking. *International Journal of Production Economics*, *92*, 11-19.
Pohl, L. M., Meller, R. D., & Gue, K. R. (2011). Turnover-based storage in non-traditional unit-load warehouse designs. *Iie Transactions*, *43*(10), 703-720. https://doi.org/10.1080/0740817X.2010.549098
Rasmi, S. A. B., Wang, Y., & Charkhgard, H. (2022). Wave order picking under the mixed-shelves storage strategy: A solution method and advantages. *Computers & Operations Research*, *137*, 105556. https://doi.org/https://doi.org/10.1016/j.cor.2021.105556
Roodbergen, K. J. (2011). *An explanation of some rack layout concepts*

for warehouses.
Roodbergen, K. J., & Vis, I. F. A. (2009). A survey of literature on automated storage and retrieval systems. *European Journal of Operational Research*, *194*(2), 343-362. https://doi.org/10.1016/j.ejor.2008.01.038
Saderova, J., Rosova, A., Behunova, A., Behun, M., Sofranko, M., & Khouri, S. (2022). Case study: the simulation modelling of selected activity in a warehouse operation. *Wireless Networks*, *28*(1), 431-440. https://doi.org/10.1007/s11276-021-02574-6
Saderova, J. J., Saderova, J., Poplawski, L., Balog, M., Jr., Michalkova, S., & Cvoliga, M. (2020). LAYOUT DESIGN OPTIONS FOR WAREHOUSE MANAGEMENT. *POLISH JOURNAL OF MANAGEMENT STUDIES*, *22*(2), 443-455.
Silva, A., Roodbergen, K. J., Coelho, L. C., & Darvish, M. (2022). Estimating optimal ABC zone sizes in manual warehouses. *International Journal of Production Economics*, *252*, Article 108579. https://doi.org/10.1016/j.ijpe.2022.108579
Singbal, V., & Adil, G. K. (2019). A flexible approach to designing a single crane, multi-aisle automated storage/retrieval system considering storage policies, transport equipment and demand skew. *International Journal of Computer Integrated Manufacturing*, *32*(11), 1053-1066. https://doi.org/10.1080/0951192x.2019.1686169
Standridge, C. R. (2013). Beyond Lean: Simulation in Practice.
Sueters, M. L. (2023). Reducing the total travelling distance of order picking in a warehouse by introducing class-based storage. In: University of Twente.
Toyota Reflex RRE140/160/180/200/250H Reach Forklift. (2022). Toyota Material Handling Australia. https://www.toyotamaterialhandling.com.au/products/reach-forklifts/toyota-reflex-rre140-160-180-200-250h-reach-forklift/

Xie, L., Li, H., & Luttmann, L. (2023). Formulating and solving integrated order batching and routing in multi-depot AGV-assisted mixed-shelves warehouses. *European Journal of Operational Research*, *307*(2), 713-730. https://doi.org/https://doi.org/10.1016/j.ejor.2022.08.047

Yener, F., & Yazgan, H. R. (2019). Optimal warehouse design: Literature review and case study application. *Computers & Industrial Engineering*, *129*, 1-13. https://doi.org/https://doi.org/10.1016/j.cie.2019.01.006

Yu, Y., deKoster, R. B. M., & Guo, X. (2015). Class-Based Storage with a Finite Number of Items: Using More Classes is not Always Better. *Production and Operations Management*, *24*(8), 1235-1247. https://doi.org/10.1111/poms.12334

Zaerpour, N., de Koster, R. B. M., & Yu, Y. G. (2013). Storage policies and optimal shape of a storage system. *International Journal of Production Research*, *51*(23-24), 6891-6899. https://doi.org/10.1080/00207543.2013.774502

Appendices

A Material Handling

This appendix illustrates the material handling methods (as described in Subsection 2.2.1) of the current process of the pallet unit supply method from the old building.

A.1 Reach Trucks

Figure 26: Reach trucks in current building (Toyota Reflex RRE140/160/180/200/250H Reach

A.2 Pallet Trailers and Trucks

Figure 27: Pallet-truck (Elektrische trekker P250 | Serie 127-05 | Motrac, 2024)

Figure 28: Pallet Trailers

B. Introduction Pack Types and Pareto Analysis

This appendix illustrates the information used to determine the ABC classifications using a Pareto analysis.

Packtype	Dimensions	% of movements	Cumulative % of movements	Class
13	0,80 X 1,20 X 0,75	18,50%	18,50%	A
14	0,80 X 1,20 X 0,95	17,06%	35,56%	A
12	0,80 X 1,20 X 0,55	13,50%	49,05%	A
3	1,60 X 1,20 X 0,75	6,67%	55,73%	A
22	0,80 X 0,60 X 0,55	5,36%	61,09%	A
21	0,80 X 0,60 X 0,35	4,59%	65,68%	A
94	2,50 X 1,20 X 0,95	4,15%	69,83%	A
T4	0,80 X 1,60 X 0,95	3,57%	73,40%	A
X4	2,65 X 1,20 X 0,95	3,30%	76,70%	A
4	1,60 X 1,20 X 0,95	3,17%	79,88%	A
53	0,80 X 1,20 X 0,75	2,81%	82,69%	B
5	1,60 X 1,20 X 1,15	2,79%	85,48%	B
T5	0,80 X 1,60 X 1,15	2,42%	87,90%	B
93	2,50 X 1,20 X 0,75	1,51%	89,41%	B
11	0,80 X 1,20 X 0,35	1,48%	90,89%	B
X3	2,65 X 1,20 X 0,75	1,44%	92,33%	B
T6	0,80 X 1,60 X 1,35	1,39%	93,72%	B
X7	2,65 X 1,20 X 1,55	0,93%	94,65%	B
T3	0,80 X 1,60 X 0,75	0,61%	95,26%	C
42	2,20 X 0,80 X 0,55	0,57%	95,82%	C
41	2,20 X 0,80 X 0,35	0,42%	96,24%	C
96	2,50 X 1,20 X 1,35	0,37%	96,61%	C
54	0,80 X 1,20 X 0,95	0,37%	96,99%	C
D2	0,80 X 0,60 X 0,55	0,35%	97,33%	C
45	2,20 X 0,80 X 1,15	0,30%	97,64%	C
23	0,80 X 0,60 X 0,75	0,30%	97,94%	C
X6	2,65 X 1,20 X 1,35	0,30%	98,23%	C
T2	0,80 X 1,60 X 0,55	0,27%	98,51%	C
X2	2,65 X 1,20 X 0,55	0,25%	98,76%	C
J2	0,80 X 0,60 X 0,60	0,25%	99,01%	C
43	2,20 X 0,80 X 0,75	0,19%	99,20%	C
D3	0,80 X 0,60 X 0,75	0,18%	99,38%	C
E3	0,80 X 1,20 X 0,75	0,16%	99,54%	C
D4	0,80 X 0,60 X 0,95	0,15%	99,69%	C
X1	2,65 X 1,20 X 0,35	0,14%	99,83%	C
16	0,80 X 1,20 X 1,35	0,08%	99,90%	C
T1	0,80 X 1,60 X 0,35	0,06%	99,97%	C
J3	0,80 X 0,60 X 0,81	0,03%	100,00%	C

Table 14: Overview of Pack Types

C. CPU Microarchitecture Design

This appendix illustrates the CPU processor on which the new CPU-based warehouse design approach as introduced in Section 4.1.4 is based.

Figure 29: Intel core Raptor Lake CPU microarchitecture (Intel Core i5-13600K, 2022)

D. SKU Allocation Methods

This appendix contains the SKU allocation methods used within the simulation model.

D.1. Random Allocation Policy

Algorithm 1 Random allocation policy initialization

```
for Location in Warehouse.locations do
    Location.ExpectedRetrievalTime ← CalculatePalletRetrievalTime(Location)
end for
Warehouse.locations.Sort on ExpectedRetrievalTime Ascending
```

Algorithm 2 Random allocation policy new pallet arrival

```
SlotsRequired ← Pallet.requiredslots
for location in Warehouse.locations do
    if location.SpaceRemaining ≥ SlotsRequired then
        Pallet.move(location)
        Location.SpaceRemainig ← Location.SpaceRemaining − SlotsRequired
        ExitForLoop
    end if
end for
```

D.2. Class based allocation policy

Algorithm 3 Class based allocation policy initialization

```
for Location in Warehouse.locations do
    NrLocations ← NrLocations + 1
    Location.ExpectedRetrievalTime ← CalculatePalletRetrievalTime(Location)
end for
Warehouse.locations.Sort on ExpectedRetrievalTime Ascending
NrLocations ← 0
for Location in Warehouse.locations do
    NrLocations ← NrLocations + 1
    if NrLocations ≤ NrSlotsA then
        Location.Class ← A
        Else if NrLocations ≤ NrSlotsB
        Location.Class ← B
        Else
        Location.Class ← C
    end if
end for
```

Algorithm 4 Class based allocation policy new pallet arrival

```
SlotsRequired ← Pallet.requiredslots
for location in Warehouse.locations do
    if location.SpaceRemaining ≥ SlotsRequired & Pallet.class = location.class then
        Pallet.move(location)
        Location.SpaceRemainig ← Location.SpaceRemaining − SlotsRequired
        ExitForLoop
    end if
end for
```

D.3. Combined allocation policy

Algorithm 5 Mixed allocation policy initialization

```
for Location in Warehouse.Plocations do
    Location.ExpectedRetrievalTime ← CalculatePalletRetrievalTime(Location)
end for
Warehouse.Plocations.Sort on ExpectedRetrievalTime Ascending
for Location in Warehouse.Elocations do
    Location.ExpectedRetrievalTime ← CalculatePalletRetrievalTime(Location)
end for
Warehouse.Elocations.Sort on ExpectedRetrievalTime Ascending
for Location in Warehouse.Slocations do
    Location.ExpectedRetrievalTime ← CalculatePalletRetrievalTime(Location)
end for
Warehouse.Slocations.Sort on ExpectedRetrievalTime Ascending
```

SCANIA

Algorithm 6 Mixed allocation policy new pallet arrival

```
SlotsRequired ← Pallet.requiredslots
FlowType ← Pallet.flowtype
Locationfound ← false
if location.FlowType = P-Flow then
    for location in Warehouse.Plocations do
        if location.SpaceRemaining ≥ SlotsRequired then
            Pallet.move(location)
            Location.SpaceRemaining ← Location.SpaceRemaining − SlotsRequired
            Locationfound ← true
            ExitForLoop
        end if
    end for
else if location.FlowType = E-Flow then
    for location in Warehouse.Elocations do
        if location.SpaceRemaining ≥ SlotsRequired then
            Pallet.move(location)
            Location.SpaceRemaining ← Location.SpaceRemaining − SlotsRequired
            Locationfound ← true
            ExitForLoop
        end if
    end for
else
    for location in Warehouse.Slocations do
        if location.SpaceRemaining ≥ SlotsRequired then
            Pallet.move(location)
            Location.SpaceRemaining ← Location.SpaceRemaining − SlotsRequired
            Locationfound ← true
            ExitForLoop
        end if
    end for
end if
if LocationFound = false then
    for location in Warehouse.Slocations do
        if location.SpaceRemaining ≥ SlotsRequired then
            Pallet.move(location)
            Location.SpaceRemaining ← Location.SpaceRemaining − SlotsRequired
            ExitForLoop
        end if
    end for
```

E. Visual Representation Layouts

This appendix illustrates the visual representations of the generated layouts created in Tecnomatix Plant Simulation. Within all images the inbound zone is located on the top side of the image and the outbound zone on the bottom side of the image.

E.1. Conventional Layout(s)

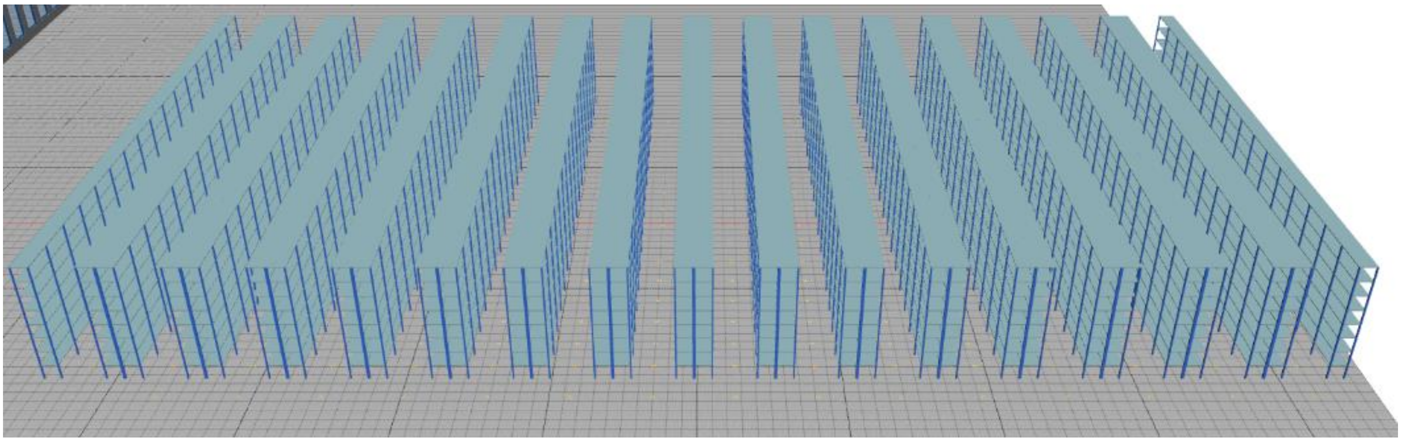

Figure 31: Visual representation of conventional layout case 1 generated in Tecnomatix plant simulation

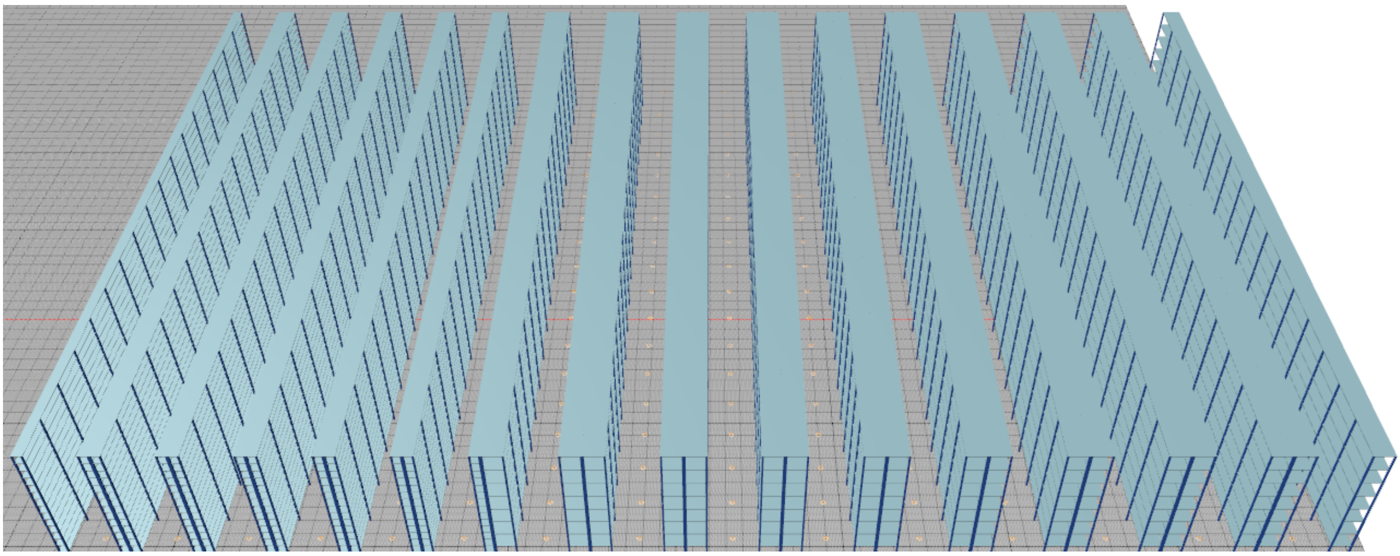

Figure 30: Visual representation of conventional layout case 2 generated in Tecnomatix Plant Simulation

E.2. Flying-V Layout

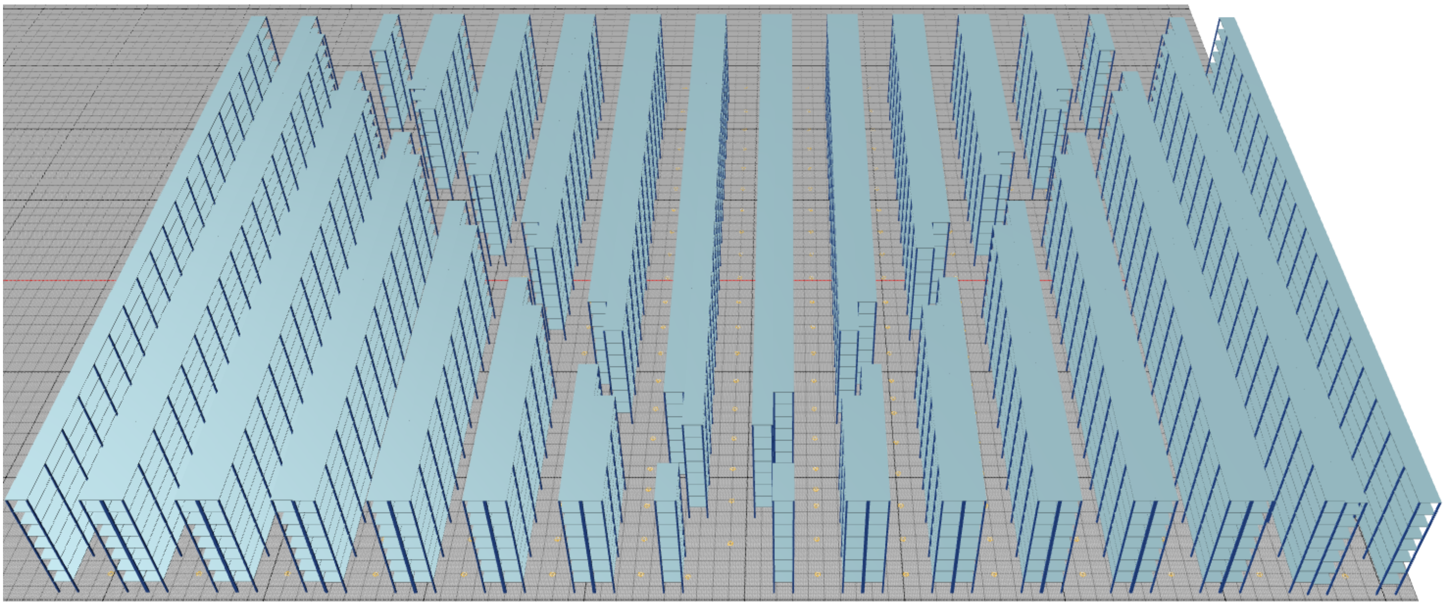

Figure 32: Visual representation of Flying-V layout generated in Tecnomatix plant simulation

E.3. CPU-Based Layout

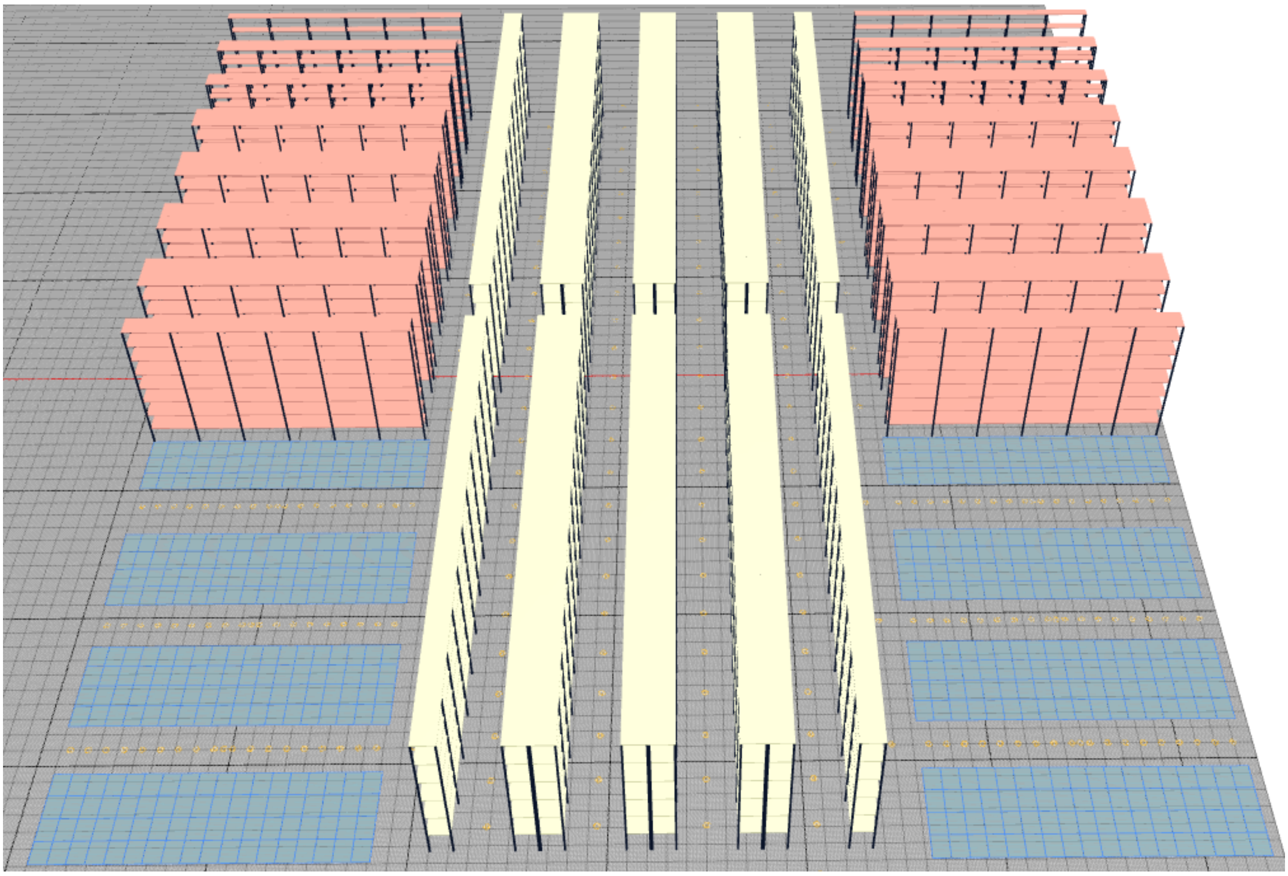

Figure 33: Visual representation of CPU-based layout (alternative 1) generated in Tecnomatic plant simulation (P-sections in blue, S-sections in yellow, and E-sections in red)

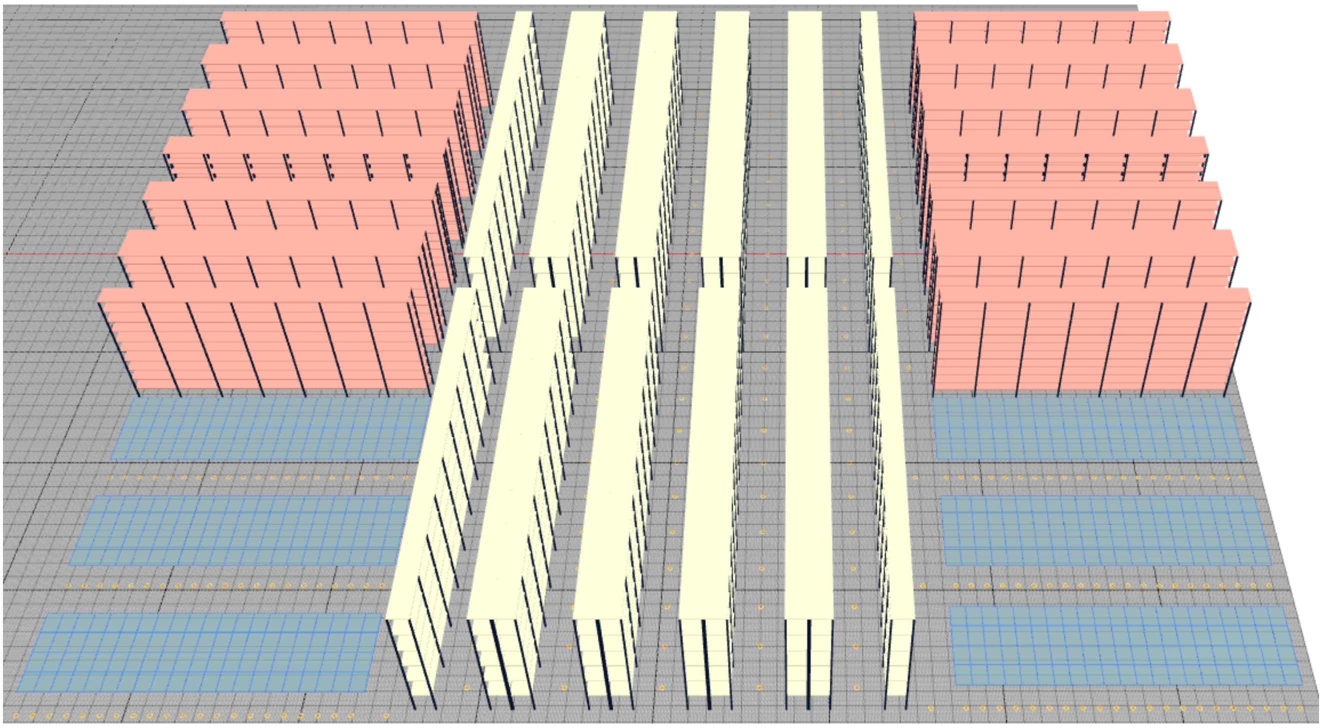

Figure 34: Visual representation of CPU-based layout (alternative 2) generated in Tecnomatic plant simulation (P-sections in blue, S-sections in yellow, and E-sections in red)

F. Pallet Flow Distributions

This appendix contains the support for our assumption to use a Log-normal distribution for the pallet in and outflow from the warehouse.

F.1 Histogram Overplot Log-normal Distribution

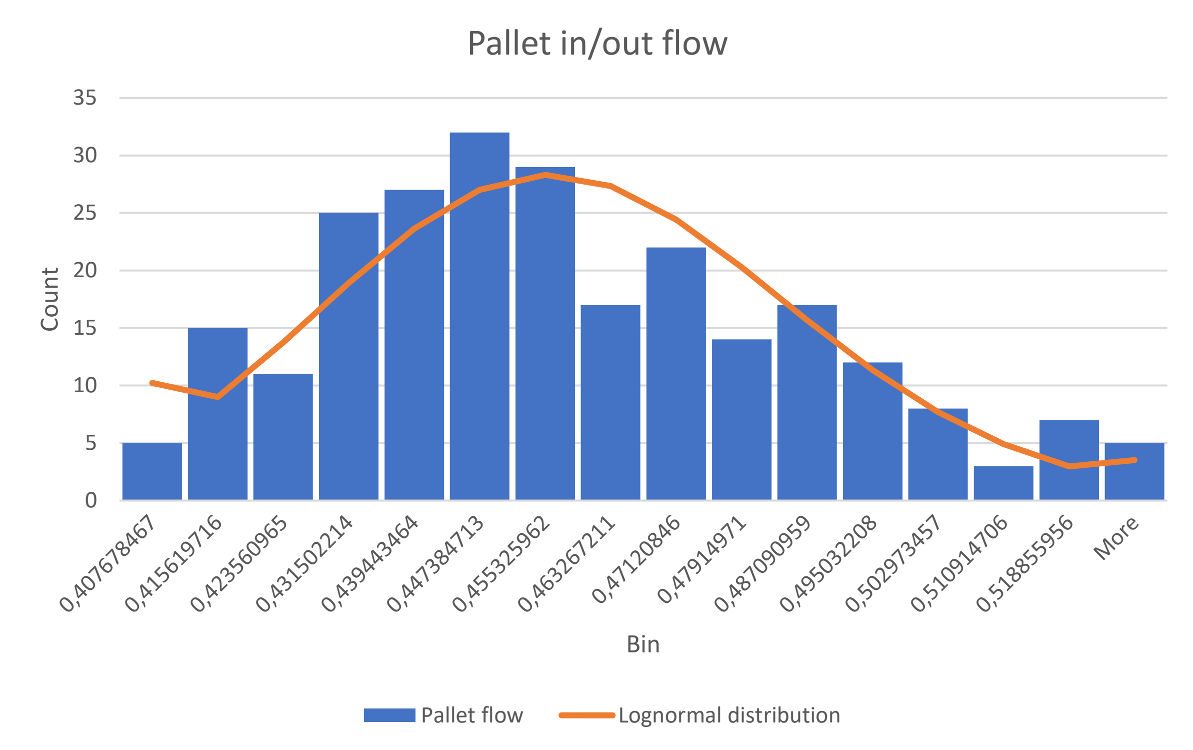

Figure 35: Lognormal distribution over plot Pallet flow

F.2 Chi-Square Test Log-normal Distribution

Bin Number	Lower Bound	Upper Bound	Count	Count Log-normal	Chi-Square Error
1	Less	0,407678467	5	10,22482432	2,669854104
2	0,40767847	0,415619716	15	9,007532486	3,986626411
3	0,41561972	0,423560965	11	13,72713769	0,541793938
4	0,42356097	0,431502214	25	18,90414706	1,965675729
5	0,43150221	0,439443464	27	23,65152398	0,474062122
6	0,43944346	0,447384713	32	27,01840723	0,918494799
7	0,44738471	0,455325962	29	28,31364265	0,016638142
8	0,45532596	0,463267211	17	27,33868612	3,909786674
9	0,46326721	0,47120846	22	24,42300669	0,240386512
10	0,47120846	0,47914971	14	20,2649624	1,936828359
11	0,47914971	0,487090959	17	15,67483696	0,112030326
12	0,48709096	0,495032208	12	11,34130924	0,038256035
13	0,49503221	0,502973457	8	7,700736475	0,011629882
14	0,50297346	0,510914706	3	4,921934976	0,750484122
15	0,51091471	0,518855956	7	2,969783924	5,46930081
16	0,51885596	More	5	3,517527814	0,624792155
Test statistic (X^2)			23,66664012		
Chi-square value CL = 95% & DF = 15			**24,99579014**		

Table 15: Chi-square test Log-normal distribution pallet in and outflow

G. Finding Input Parameters Class-based Policy

This appendix contains the experiment results on which the input parameters for the class-based policy are based. Note that more values than the values mentioned are tested but deemed worse than the found solutions.

G.1. Conventional Layout Case 1

Experiment	root.PercentageASlots	root.PercentageBslots	root.AverageThroughput
Exp 01	0.05	0.08	26:10.1835
Exp 02	0.05	0.12	26:16.8994
Exp 03	0.05	0.16	26:06.9763
Exp 04	0.05	0.2	26:13.3249
Exp 05	0.09	0.08	26:15.6995
Exp 06	0.09	0.12	26:11.1821
Exp 07	0.09	0.16	26:12.6443
Exp 08	0.09	0.2	25:54.3440
Exp 09	0.13	0.08	26:07.2984
Exp 10	0.13	0.12	26:09.7214
Exp 11	0.13	0.16	25:59.2156
Exp 12	0.13	0.2	26:06.8711

Table 16: Experiment results 1 conventional layout C1 input parameters slots

Experiment	root.PercentageASlots	root.PercentageBslots	root.AverageThroughput
Exp 1	0.08	0.18	25:59.7683
Exp 2	0.08	0.2	25:58.4877
Exp 3	0.08	0.22	26:10.6789
Exp 4	0.09	0.18	26:06.7541
Exp 5	0.09	0.2	25:54.3440
Exp 6	0.09	0.22	26:06.2932
Exp 7	0.1	0.18	26:05.9200
Exp 8	0.1	0.2	26:05.5055
Exp 9	0.1	0.22	25:58.1051

Table 17: Experiment results 2 conventional layout C1 input parameters slots

G.2. Conventional Layout Case 2

Experiment	root.PercentageASlots	root.PercentageBslots	root.AverageThroughput
Exp 01	0.05	0.08	26:46.2057
Exp 02	0.05	0.09	26:49.9192
Exp 03	0.05	0.1	26:46.9726
Exp 04	0.05	0.11	26:43.7429
Exp 05	0.06	0.08	26:48.7328
Exp 06	0.06	0.09	26:44.7311
Exp 07	0.06	0.1	26:39.4825
Exp 08	0.06	0.11	26:42.9607
Exp 09	0.07	0.08	26:38.3623
Exp 10	0.07	0.09	26:53.1389
Exp 11	0.07	0.1	26:47.5277
Exp 12	0.07	0.11	26:37.1062

Table 18: Experiment results conventional layout C2 input parameters slots

G.3. Flying-V Layout

Experiment	root.PercentageASlots	root.PercentageBslots	root.AverageThroughput
Exp 01	0.05	0.08	28:09.8320
Exp 02	0.05	0.12	27:35.5701
Exp 03	0.05	0.16	27:22.9048
Exp 04	0.05	0.2	27:25.1523
Exp 05	0.07	0.08	27:11.4789
Exp 06	0.07	0.12	27:22.8290
Exp 07	0.07	0.16	27:29.7905
Exp 08	0.07	0.2	27:25.5193
Exp 09	0.09	0.08	27:23.0167
Exp 10	0.09	0.12	27:08.8561
Exp 11	0.09	0.16	27:22.7047
Exp 12	0.09	0.2	27:26.6058
Exp 13	0.11	0.08	28:10.2988
Exp 14	0.11	0.12	28:18.5423
Exp 15	0.11	0.16	27:24.6350
Exp 16	0.11	0.2	27:15.6567

Table 20: Experiment results 1 Flying-V layout input parameters slots

Experiment	root.PercentageASlots	root.PercentageBslots	root.AverageThroughput
Exp 1	0.08	0.11	27:20.0667
Exp 2	0.08	0.12	27:17.7235
Exp 3	0.08	0.13	27:30.7015
Exp 4	0.09	0.11	27:14.7041
Exp 5	0.09	0.12	27:08.8561
Exp 6	0.09	0.13	27:16.2662
Exp 7	0.1	0.11	27:20.4651
Exp 8	0.1	0.12	27:17.6613
Exp 9	0.1	0.13	27:17.4228

Table 19: Experiment results 2 Flying-V layout input parameters slots

SCANIA

H. Experiment Outputs

This appendix contains all the experiment outputs from the simulation model on which the findings described in Chapter 6 are based.

H.1. Internal Warehouse Performance

Conventional layout C1:

Experiment	Inputs		Outputs					
	Storage policy	Outbound reachtrucks	Average throughput time (min)	LB throughput time (min)	UB throughput time (min)	Required FTE (#)	Percentage trailers on time (%)	Required space (m^2)
1	Random	3	16:08	16:00	16:17	20	100	4023,039898
2	Random	4	14:24	14:21	14:28	22	100	4023,039898
3	Random	5	13:25	13:21	13:28	24	100	4023,039898
4	Random	6	12:48	12:44	12:53	26	100	4023,039898
5	Random	7	12:24	12:22	12:26	28	100	4023,039898
6	Random	8	11:57	11:48	12:06	30	100	4023,039898
7	Class based	3	15:53	15:52	15:54	20	100	4023,039898
8	Class based	4	14:16	14:12	14:19	22	100	4023,039898
9	Class based	5	13:16	13:12	13:19	24	100	4023,039898
10	Class based	6	12:40	12:38	12:42	26	100	4023,039898
11	Class based	7	12:17	12:11	12:23	28	100	4023,039898
12	Class based	8	11:54	11:53	11:54	30	100	4023,039898

Table 21: Experiment outputs of conventional layout C1

Conventional Layout C2:

Experiment	Inputs		Outputs					
	Storage policy	Outbound reachtrucks	Average throughput time (min)	LB throughput time (min)	UB throughput time (min)	Required FTE (#)	Percentage trailers on time (%)	Required space (m^2)
1	Random	3	15:20	15:14	15:25	20	100	3665,745176
2	Random	4	13:49	13:45	13:53	22	100	3665,745176
3	Random	5	12:56	12:50	13:01	24	100	3665,745176
4	Random	6	12:24	12:20	12:29	26	100	3665,745176
5	Random	7	11:59	11:58	12:01	28	100	3665,745176
6	Random	8	11:35	11:35	11:35	30	100	3665,745176
7	Class based	3	15:12	15:06	15:18	20	100	3665,745176
8	Class based	4	13:44	13:37	13:51	22	100	3665,745176
9	Class based	5	12:51	12:43	12:59	24	100	3665,745176
10	Class based	6	12:20	12:17	12:22	26	100	3665,745176
11	Class based	7	11:56	11:54	11:58	28	100	3665,745176
12	Class based	8	11:32	11:29	11:35	30	100	3665,745176

Table 22: Experiment outputs of conventional layout C2

Flying-V layout:

Experiment	Inputs		Outputs					
	Storage policy	Outbound reachtrucks	Average throughput time (min)	LB throughput time (min)	UB throughput time (min)	Required FTE (#)	Percentage trailers on time (%)	Required space (m^2)
1	Random	3	16:03	15:54	16:12	20	100	4477,2
2	Random	4	14:18	14:15	14:21	22	100	4477,2
3	Random	5	13:18	13:10	13:25	24	100	4477,2
4	Random	6	12:41	12:33	12:49	26	100	4477,2
5	Random	7	12:15	12:10	12:19	28	100	4477,2
6	Random	8	11:51	11:49	11:52	30	100	4477,2
7	Class based	3	15:49	15:46	15:52	20	100	4477,2
8	Class based	4	14:08	13:57	14:18	22	100	4477,2
9	Class based	5	13:09	13:08	13:10	24	100	4477,2
10	Class based	6	12:33	12:26	12:39	26	100	4477,2
11	Class based	7	12:08	12:06	12:10	28	100	4477,2
12	Class based	8	11:46	11:44	11:49	30	100	4477,2

Table 23: Experiment outputs of Flying-V layout

CPU based layouts:

Experiment	Inputs		Outputs					
	Storage policy	Outbound reachtrucks	Average throughput time (min)	LB throughput time (min)	UB throughput time (min)	Required FTE (#)	Percentage trailers on time (%)	Required space (m^2)
1	Combined allocation policy	3	14:40	14:34	14:46	20	100	4241,64
2	Combined allocation policy	4	13:23	13:21	13:25	22	100	4241,64
3	Combined allocation policy	5	12:36	12:30	12:42	24	100	4241,64
4	Combined allocation policy	6	12:07	12:02	12:11	26	100	4241,64
5	Combined allocation policy	7	11:45	11:43	11:48	28	100	4241,64
6	Combined allocation policy	8	11:29	11:23	11:36	30	100	4241,64

Table 24: Experiment outputs CPU-based layout alternative 1

Experiment	Inputs		Outputs					
	Storage policy	Outbound reachtrucks	Average throughput time (min)	LB throughput time (min)	UB throughput time (min)	Required FTE (#)	Percentage trailers on time (%)	Required space (m^2)
1	Combined allocation policy	3	14:56	14:50	15:03	20	100	4111.875075
2	Combined allocation policy	4	13:36	13:08	14:04	22	100	4111.875075
3	Combined allocation policy	5	12:46	12:44	12:48	24	100	4111.875075
4	Combined allocation policy	6	12:16	12:13	12:19	26	100	4111.875075
5	Combined allocation policy	7	11:54	11:52	11:56	28	100	4111.875075
6	Combined allocation policy	8	11:36	11:32	11:40	30	100	4111.875075

Table 25: Experiment outputs CPU-based layout alternative 2

H.2. Experiment Results Full Supply Process

Bridge flow:

Exp	Inputs				Outputs					
	Layout	Storage policy	Outbound reachtrucks	Flowtype	Average throughput time	LB throughput time	UB throughput time	Required FTE	Percentage trailers on time	Required space
1	Conventional layout C2	Class based storage	3	Bridge	28:18	24:58	31:39	20	100	3665.745176
2	Conventional layout C2	Class based storage	4	Bridge	26:55	25:56	27:55	22	100	3665.745176
3	Conventional layout C2	Class based storage	5	Bridge	26:00	25:13	26:47	24	100	3665.745176
4	Conventional layout C2	Class based storage	6	Bridge	25:26	24:42	26:10	26	100	3665.745176
5	Conventional layout C2	Class based storage	7	Bridge	25:04	24:18	25:49	28	100	3665.745176
6	Conventional layout C2	Class based storage	8	Bridge	24:36	24:14	24:58	30	100	3665.745176
7	CPU layout alt 1	Combined allocation policy	3	Bridge	27:42	27:33	27:52	20	100	4241.64
8	CPU layout alt 1	Combined allocation policy	4	Bridge	26:42	25:59	27:25	22	100	4241.64
9	CPU layout alt 1	Combined allocation policy	5	Bridge	25:46	25:17	26:14	24	100	4241.64
10	CPU layout alt 1	Combined allocation policy	6	Bridge	25:19	24:57	25:41	26	100	4241.64
11	CPU layout alt 1	Combined allocation policy	7	Bridge	24:52	24:32	25:13	28	100	4241.64
12	CPU layout alt 1	Combined allocation policy	8	Bridge	24:43	24:24	25:03	30	100	4241.64
13	CPU layout alt 2	Combined allocation policy	3	Bridge	27:50	27:49	27:51	20	100	4111.875075
14	CPU layout alt 2	Combined allocation policy	4	Bridge	26:53	26:15	27:30	22	100	4111.875075
15	CPU layout alt 2	Combined allocation policy	5	Bridge	25:49	25:12	26:26	24	100	4111.875075
16	CPU layout alt 2	Combined allocation policy	6	Bridge	25:13	25:08	25:18	26	100	4111.875075
17	CPU layout alt 2	Combined allocation policy	7	Bridge	25:05	24:39	25:31	28	100	4111.875075
18	CPU layout alt 2	Combined allocation policy	8	Bridge	24:45	21:55	27:34	30	100	4111.875075

Table 26: Experiment results with bridge supply flow

Lorry flow (2a):

Exp	Inputs				Outputs					
	Layout	Storage policy	Outbound reachtrucks	Flowtype	Average throughput time	LB throughput time	UB throughput time	Required FTE	Percentage trailers on time	Required space
1	Conventional layout C2	Class based storage	3	Lorry flow1	58:35	55:49	1:01:20	24	100	3665.745176
2	Conventional layout C2	Class based storage	4	Lorry flow1	58:39	56:15	1:01:02	26	100	3665.745176
3	Conventional layout C2	Class based storage	5	Lorry flow1	58:35	58:11	58:58	28	100	3665.745176
4	Conventional layout C2	Class based storage	6	Lorry flow1	58:39	57:01	1:00:17	30	100	3665.745176
5	Conventional layout C2	Class based storage	7	Lorry flow1	58:39	56:34	1:00:44	32	100	3665.745176
6	Conventional layout C2	Class based storage	8	Lorry flow1	58:43	58:14	59:11	34	100	3665.745176
7	CPU layout alt 1	Combined allocation policy	3	Lorry flow1	58:00	57:17	58:43	24	100	4241.64
8	CPU layout alt 1	Combined allocation policy	4	Lorry flow1	58:24	56:02	1:00:45	26	100	4241.64
9	CPU layout alt 1	Combined allocation policy	5	Lorry flow1	58:01	57:32	58:30	28	100	4241.64
10	CPU layout alt 1	Combined allocation policy	6	Lorry flow1	58:06	56:15	59:57	30	100	4241.64
11	CPU layout alt 1	Combined allocation policy	7	Lorry flow1	57:58	57:56	58:01	32	100	4241.64
12	CPU layout alt 1	Combined allocation policy	8	Lorry flow1	58:06	55:51	00:21	34	100	4241.64
13	CPU layout alt 2	Combined allocation policy	3	Lorry flow1	57:58	57:30	58:26	24	100	4111.875075
14	CPU layout alt 2	Combined allocation policy	4	Lorry flow1	58:21	55:41	1:01:00	26	100	4111.875075
15	CPU layout alt 2	Combined allocation policy	5	Lorry flow1	58:07	57:05	59:10	28	100	4111.875075
16	CPU layout alt 2	Combined allocation policy	6	Lorry flow1	57:52	57:18	58:25	30	100	4111.875075
17	CPU layout alt 2	Combined allocation policy	7	Lorry flow1	58:03	58:01	58:05	32	100	4111.875075
18	CPU layout alt 2	Combined allocation policy	8	Lorry flow1	58:10	55:54	00:26	34	100	4111.875075

Table 27: Experiment results with lorry flow (2a)

Lorry flow (2b):

Exp	Inputs				Outputs					
	Layout	Storage policy	Outbound reachtrucks	Flowtype	Average throughput time	LB throughput time	UB throughput time	Required FTE	Percentage trailers on time	Required space
1	Conventional layout C2	Class based storage	3	Lorry flow 2	53:46	51:48	55:44	24	100	3665.745176
2	Conventional layout C2	Class based storage	4	Lorry flow 2	53:47	53:17	54:17	26	100	3665.745176
3	Conventional layout C2	Class based storage	5	Lorry flow 2	53:46	52:40	54:52	28	100	3665.745176
4	Conventional layout C2	Class based storage	6	Lorry flow 2	53:48	52:04	55:33	30	100	3665.745176
5	Conventional layout C2	Class based storage	7	Lorry flow 2	53:50	52:01	55:39	32	100	3665.745176
6	Conventional layout C2	Class based storage	8	Lorry flow 2	53:48	52:55	54:40	34	100	3665.745176
7	CPU layout alt 1	Combined allocation policy	3	Lorry flow 2	53:28	52:45	54:10	24	100	4241.64
8	CPU layout alt 1	Combined allocation policy	4	Lorry flow 2	53:36	52:14	54:57	26	100	4241.64
9	CPU layout alt 1	Combined allocation policy	5	Lorry flow 2	53:29	52:43	54:16	28	100	4241.64
10	CPU layout alt 1	Combined allocation policy	6	Lorry flow 2	53:30	53:03	53:58	30	100	4241.64
11	CPU layout alt 1	Combined allocation policy	7	Lorry flow 2	53:27	53:14	53:39	32	100	4241.64
12	CPU layout alt 1	Combined allocation policy	8	Lorry flow 2	53:30	53:01	53:59	34	100	4241.64
13	CPU layout alt 2	Combined allocation policy	3	Lorry flow 2	53:24	53:07	53:42	24	100	4111.875075
14	CPU layout alt 2	Combined allocation policy	4	Lorry flow 2	53:33	52:20	54:45	26	100	4111.875075
15	CPU layout alt 2	Combined allocation policy	5	Lorry flow 2	53:28	52:45	54:10	28	100	4111.875075
16	CPU layout alt 2	Combined allocation policy	6	Lorry flow 2	53:22	53:09	53:36	30	100	4111.875075
17	CPU layout alt 2	Combined allocation policy	7	Lorry flow 2	53:26	52:44	54:08	32	100	4111.875075
18	CPU layout alt 2	Combined allocation policy	8	Lorry flow 2	53:26	52:26	54:25	34	100	4111.875075

Table 28: Experiment results with lorry flow (2b)

H.3. Resulting Heatmaps Layouts

This section contains all the heat maps of the layouts and allocation policy combinations based on the simulation model. By dividing the warehouse up into zones and counting the number of deliveries to each zone, this indicates the amount of traffic at each zone. Zones with high traffic are indicated in red, whereas zones with low traffic are indicated in green.

Conventional layout C1 with random allocation:

Inbound

128	157	206	207	339	331	456	500	529	452	289	235	230	171	156	98
175	152	245	294	274	361	401	637	608	455	415	318	314	196	208	158
141	211	252	263	343	449	501	617	578	556	425	321	257	218	169	138
166	224	307	306	382	494	683	754	803	589	493	347	321	271	215	150
223	307	309	303	487	539	923	991	1020	811	515	468	325	253	199	237
198	310	395	340	546	679	1012	1286	1345	1055	689	535	386	344	246	256
236	301	309	491	626	784	1221	1434	1357	1241	984	515	449	386	259	257
253	261	340	514	702	1268	1377	1666	1521	1337	1023	703	490	305	315	281
277	350	450	614	931	1335	1651	1565	1608	1358	1122	919	555	411	381	368
360	383	518	763	1068	1342	1692	1937	1883	1681	1417	1114	641	524	414	316
358	427	658	945	1379	1728	1732	2011	1850	1765	1666	1444	1048	602	416	318
406	513	817	1155	1384	1727	1873	2089	2038	1956	1751	1687	1243	758	477	447
460	546	866	1430	1478	1982	2080	1974	2018	2095	1851	1638	1373	983	567	496
503	763	1244	1580	1774	1785	2113	2155	2133	2151	2237	1721	1490	1205	758	512
537	987	1366	1724	1787	2070	2245	2151	2258	2274	2232	1790	1567	1455	1115	689
938	1270	1558	1821	2068	2323	2214	2430	2300	2096	2194	2123	1800	1474	1355	731

Outbound

Figure 36: Heatmap of conventional layout C1 with random allocation

Conventional layout C1 with class-based allocation:

Inbound

153	152	201	252	257	357	468	426	457	393	315	226	208	154	132	150
120	177	185	241	314	361	460	508	533	406	334	328	268	189	177	182
128	229	250	275	406	377	470	551	590	503	390	254	234	250	212	213
131	184	251	312	373	498	505	662	607	545	487	379	295	232	219	162
228	253	268	367	393	460	625	687	730	647	528	414	294	296	204	218
263	248	292	363	490	562	697	859	824	684	613	506	371	293	306	220
274	197	402	376	562	636	871	1158	1085	830	626	503	449	316	194	231
242	378	370	519	563	744	1127	1432	1354	1074	715	573	480	389	322	264
319	343	428	573	697	897	1398	1796	1615	1375	924	637	528	410	398	301
309	381	439	606	789	1179	1443	2060	2121	1498	1265	827	553	508	396	375
366	415	518	682	911	1301	1975	2413	2429	1994	1432	830	667	534	475	297
404	461	587	819	1368	1665	2293	2713	2584	2221	1583	1281	752	579	484	422
437	543	708	1069	1414	2167	2631	2847	2958	2503	2175	1438	1004	626	560	424
490	622	824	1199	1690	2315	2898	3058	3172	2677	2350	1793	1262	728	560	448
602	678	1111	1471	2177	2741	3110	3335	3240	3084	2812	2275	1454	1083	683	527
644	875	1344	1739	2396	2993	3263	3296	3303	3267	2945	2578	1944	1354	808	629

Outbound

Figure 37: Heatmap of conventional layout C1 with class-based allocation

Conventional layout C2 with random allocation:

Inbound

Euro locations									Half euro locations					
13	21	20	71	139	259	320	318	226	99	69	63	39	26	
20	20	37	115	183	313	373	371	271	166	102	77	42	35	10
20	22	60	152	239	425	526	503	327	172	139	87	72	50	19
17	46	116	229	330	550	626	574	432	234	166	108	82	58	25
26	85	154	247	408	571	701	635	591	224	208	148	92	72	48
39	105	211	344	565	714	765	819	654	279	263	193	151	114	64
69	157	264	464	687	723	926	721	691	329	241	220	181	148	67
126	186	337	580	737	829	969	885	793	351	307	278	203	169	94
174	294	439	709	773	992	1352	1320	879	363	353	246	224	174	153
241	365	584	714	823	1172	1949	1577	1097	427	374	313	286	225	160
296	473	679	784	1052	1699	2483	2287	1578	465	394	326	298	217	209
369	571	738	888	1424	2431	3197	2616	1841	449	422	359	285	302	237
506	720	846	1185	1996	2988	4064	3754	2736	464	436	383	347	322	281
631	690	950	1594	2745	4076	4705	4429	3336	464	463	415	427	355	303
681	868	1184	1926	3270	4376	5339	5391	4643	475	437	427	416	376	286
706	903	1552	2862	4243	5327	5776	5966	5233	538	453	427	460	389	387
788	1218	2152	3548	5076	5753	6216	6149	5725	557	504	495	413	389	410

Outbound

Figure 38: Heatmap of conventional layout C2 with random allocation

Conventional layout C2 with class-based allocation:

Inbound

Euro locations									Half euro locations					
14	22	23	57	117	240	346	322	176	143	44	24	30	17	
21	19	30	113	176	343	435	364	236	144	55	39	25	21	11
19	17	55	152	264	431	500	500	324	164	126	41	30	27	29
19	33	102	182	337	460	582	545	422	221	163	138	41	13	22
31	82	138	260	463	582	657	594	463	220	185	162	59	37	25
36	114	208	335	446	598	581	598	585	253	209	155	138	41	26
83	135	290	463	607	597	653	622	599	359	203	195	167	147	53
110	211	366	486	652	665	872	840	581	346	340	233	184	168	129
159	261	444	600	619	819	1047	1065	796	347	334	246	188	166	139
215	386	573	585	689	1017	1316	1289	932	412	365	337	219	210	166
314	481	583	641	864	1275	1885	1816	1188	486	399	336	290	238	175
395	510	603	764	1088	2022	2117	2067	1599	502	495	384	325	246	212
500	624	636	867	1492	2049	4012	3026	1890	462	464	475	358	317	235
556	590	715	1180	1866	3503	5756	4864	2555	516	504	500	365	358	303
583	615	905	1628	2325	5346	6983	6525	4798	487	500	507	439	364	343
574	802	1186	1948	4325	6718	8183	7882	6197	504	537	514	461	490	359
670	923	1706	2772	6014	8093	8950	8388	7399	542	550	510	485	462	414

Outbound

Figure 39: Heatmap of conventional layout C2 with class-based allocation

Flying-V layout with random allocation:

Inbound

118		149	138	236	215	200	355	119	102	112	122	89		126
179	76	213	225	199	245	194	429	106	109	118	100	106	179	183
188	98	342	415	395	466	435	413	388	437	358	381	346	153	181
171	254	436	498	474	430	466	450	439	478	420	362	358	247	151
159	201	548	456	491	503	516	642	491	528	520	467	133	265	182
188	210	124	544	490	592	643	639	698	532	548	572	216	246	197
262	252	272	522	613	643	809	892	811	747	608	607	268	280	195
216	245	368	217	761	938	956	1153	956	878	751	326	402	233	236
278	360	402	170	974	1171	1227	1352	1101	1176	785	314	446	335	306
235	357	447	481	990	1274	1507	1489	1317	1224	1074	493	378	416	324
268	331	571	473	473	1404	1563	1704	1609	1528	754	541	507	391	276
310	475	531	763	378	1695	1645	1758	1732	1635	687	712	506	480	291
464	501	705	1010	1240	1693	1942	1877	1701	1816	1365	957	618	465	332
437	528	767	1093	1414	802	1860	2087	1776	972	1546	1194	872	521	428
458	714	928	1498	1658	780	1917	2002	1990	1067	1605	1174	1032	647	464
613	866	1229	1569	1758	1910	2049	2002	1929	1715	1879	1371	1152	818	559
661	1024	1297	1499	1775	2041	870	2096	1127	2185	1916	1671	1511	971	737
811	1238	1509	1823	1753	2008	908		1245	2171	1943	1806	1592	1204	895
1141	1545	1943	1909	1936	1985	2124		2136	2129	2077	1844	1803	1345	1026

Outbound

Figure 40: Heatmap of Flying-V layout with random allocation

Flying-V layout with class-based allocation:

Inbound

87		142	151	159	228	179	316	102	81	109	73	81		82
113	77	164	132	125	161	176	362	108	105	106	96	93	140	89
119	67	292	269	303	370	358	398	377	322	251	293	304	158	94
187	194	344	328	335	353	426	431	389	327	323	297	289	208	161
146	221	134	345	332	428	436	508	418	416	403	321	218	175	182
149	198	109	409	391	517	540	552	519	447	442	369	142	189	162
206	211	234	495	498	533	613	706	660	530	485	415	229	190	200
149	200	255	176	555	621	683	793	706	641	505	314	298	244	186
220	264	279	142	728	815	832	911	841	772	685	300	364	260	248
280	288	380	418	825	1024	1146	1060	1017	943	736	412	315	260	217
275	362	366	486	310	1045	1092	1480	1142	1015	413	504	395	308	280
307	368	475	639	334	1459	1665	1999	1617	1390	512	589	416	351	261
362	441	508	639	954	1853	2283	2170	2224	1919	943	689	518	431	318
352	470	645	843	1104	701	2528	2494	2408	1265	1106	822	555	472	363
393	509	745	1010	1421	780	2845	3082	2761	1386	1511	998	649	544	432
524	634	856	1113	2071	2570	3320	3386	3114	2541	2147	1104	896	614	456
507	719	1052	1550	2363	2968	1303	3387	1972	2810	2406	1464	1072	765	522
541	888	1299	2222	2634	3081	1433		1947	3139	2626	2080	1282	914	625
821	1130	1809	2368	3124	3393	3454		3587	3326	2998	2355	1709	1063	764

Outbound

Figure 41: Heatmap of Flying-V layout with class-based allocation

SCANIA

CPU based layout with combined allocation:

Inbound

E-sections (left)

102	91	114	139	149	154
122	119	162	179	267	280
156	176	260	291	353	388
226	250	299	376	413	472
163	196	237	238	290	292
404	474	486	520	606	550
474	579	547	595	647	776

S-section (upper)

212	203	251	239
225	240	271	217
210	285	274	255
264	284	270	291
263	352	293	288
267	343	315	301
282	308	290	350
343	337	347	319
375	354	321	360
352	361	385	320
389	365	364	393

E-sections (right)

175	138	131	119	94	103
295	227	218	147	130	114
341	358	239	204	194	158
447	459	376	320	233	199
274	287	249	257	183	150
567	591	497	456	415	414
728	701	635	532	493	478

P-section (left)

887	901	952	984	908	938
17	16	17	48	43	425
251	930	4002	2574	5187	2586
1014	7812	10395	10237	10497	10642

S-section (lower)

351	416	461	393
393	435	452	390
433	439	399	414
432	409	461	447
442	490	440	472
468	444	470	456
417	453	504	457
497	452	475	452
439	500	537	497
491	474	460	510
566	475	605	555

P-section (right)

735	930	790	747	722	723
1995	972	1509	1519	1435	1420
10469	15851	7749	3247	43	1239
10611	10586	10333	9868	5359	317

Outbound

Figure 42: Heatmap of CPU based layout with the combined allocation policy