A simulation study for improving the warehousing strategy at Pentair X-Flow

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Improving the warehousing strategy at Pentair X-Flow

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Management summary

In its main warehouse, Pentair X-Flow does not have enough space to store and handle products effectively. As a result, the in- and outbound decks are often congested and products have to be placed in the aisles. Additionally, Pentair X-Flow rents external warehouses to store inventory. To improve the way of working in the main warehouse and to save costs, this research will answer the following research question: "How can the current warehouse system at Pentair X-flow be improved by changing the warehouse organization?".

To find the answer to this question, the current situation was observed by collecting data on the different product flows, conducting a literature review and conducting a simulation study. Different solution options were developed, namely changing the layout of the warehouse to a horizontal layout, a fishbone layout and introducing a new warehouse close to the main warehouse. The different layouts are shown in figure I below. In this research, we developed simulation models of the current situation and the different solution options. These simulation models were constructed to compare the different solution options with each other based on the KPIs. The KPIs measure the improved processes in the inbound, outbound, recorded the placement of products in the aisles and measured the total costs.

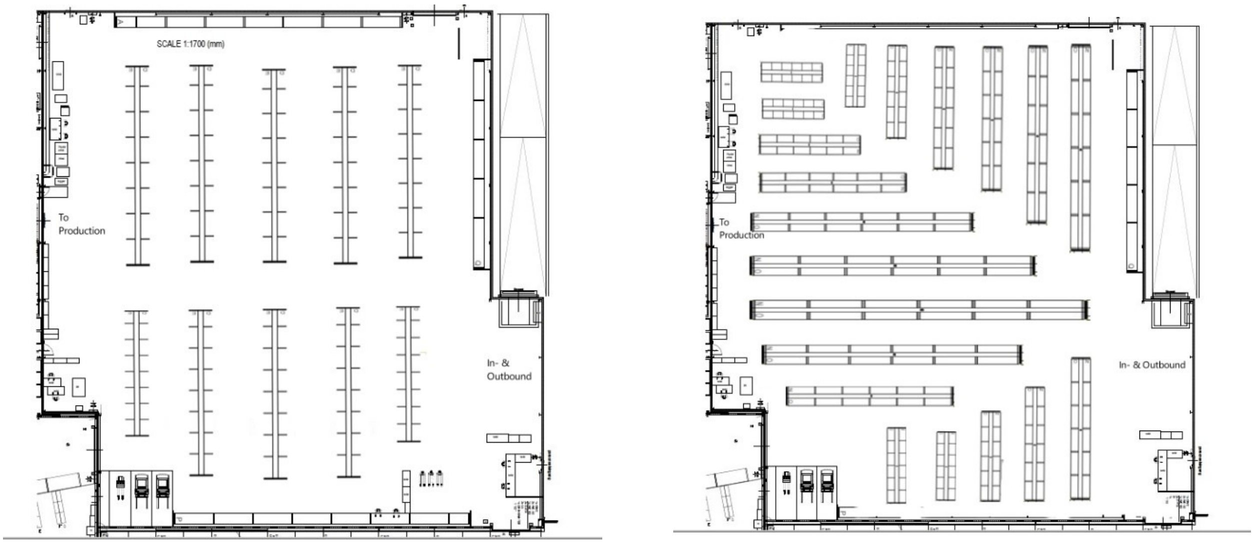

Figure i The proposed horizontal and fishbone layouts

The simulation models were executed for a duration of three months in simulated time, each with one hundred observations. From these experiments, the profitability of the three solution options was calculated. The results of the experiments are reported in table i below:

Table i The results of the simulation experiments of the solution options.

Solution option	Advantages	Disadvantages
Horizontal layout	- Considerable decrease in the average outbound occupation due to a larger order shelf.	- Increase frequency of aisle placement of 47%, increasing total costs by 68%. - Longer average carrying times, with more variation in the durations
Fishbone layout	- Decrease of 21% in the average carrying times.	- Increase of 87% in the occupancy of the outbound deck. - An increase of 2% in the total costs.
Extra warehouse	- No products in the aisles. - Decrease of 18% in average inbound occupation. - Decrease of 73% in the average outbound occupation due to the storage in the extra warehouse. - Shorter inbound time in the new warehouse. - Centralized inventory - No external warehousing costs.	- Investment costs of the new warehouse - Longer carrying times, especially to the new warehouse - More warehouse employees needed

As table I would suggest, the introduction of a new warehouse is the best solution to improve the current problems of Pentair X-flow. The different layouts did not decrease the current problems Pentair faces to a sufficient degree. The fishbone layout did decrease the carrying time considerably, but products were still placed in the aisles and the outbound occupancy increased. However, the introduction of the new warehouse decreases both the occupations of the in- and outbound deck and it removed the necessity to place products in the aisles, resulting in a safer work environment. Furthermore, the external warehouses are not needed anymore and these costs can be saved. This would amount to an average sum of €22.344,29 that can be saved monthly, according to the simulation model. This does not include a potential increase in earnings due to the increase in capacity. Consequently, the introduction of the new warehouse would be a profitable decision in the long run.

Preface

Dear reader,

Before you lies the bachelor thesis "Improving the warehouse organization of Pentair X-Flow". This thesis is written to finalize the bachelor of Industrial Engineering and Management at the University of Twente and is a result of my research at Pentair X-Flow from February until July 2023.

First of all, I would like to thank Martijn Thush for always reserving time for me and giving feedback. I would also like to thank my colleagues at Pentair X-Flow for their help and the welcoming atmosphere they created at the office.

Furthermore, I would like to give a special thanks to Stephan Meisel and Breno Alves Beirigo for their great help and feedback. This thesis was certainly challenging at times and without their help it would not be the way it is now.

Bart Vermeulen,

July 2023

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List of abbreviations

BPMN	Business Process Model and Notation
KPI	Key Performance Indicator
PWPT	Pentair Water Process Technology
SAP	Systems, Applications and Products in Data Processing
SKU	Stock Keeping Unit
SME	Subject Matter Expert

1. Introduction

1.1 Company background and context

In 1984 X-Flow was founded as a spin-off company at the University of Twente. Here a method was developed to produce hollow-fiber membranes. The company continued growing when Leushuis Projects & Engineering, which specialized in liquid flow process systems, acquired X-flow shares and the two companies continued cooperating.
In 1997, Norit purchased Leushuis. Norit was a company specialised in the activated carbon business. As this also plays a significant role in the water, food & beverage industries, Norit and X-flow were a perfect match. X-flow became then part of the Clean Process Technologies division of Norit. They continued working when in 2011, Pentair Inc. acquired X-flow. Pentair is a company from Minneapolis, founded in 1966 (Pentair, 2023).

Together with X-flow, Pentair is a world leading ultrafiltration membrane manufacturer. Ultrafiltration membrane technology is applied in water treatment to filter out unwanted particles. The membranes are used for water treatment in the mining, municipal, oil and gas, pharma, agriculture, food and beverage, power, industrial, health care and commercial markets. Pentair X-flow produces and sells fifteen different membrane filtration modules that can be used for different treatment cases.

Figure 1 Filtration installation consisting of membrane filtration modules

Because of the different and large products, the inventory of Pentair X-flow is large. The products also have long lead times. To store all the inventory Pentair X-flow uses external warehouses. In their internal warehouse, they experience a lack of space. Because products move frequently to and from production, an extra external warehouse is not a valid solution.

1.2 Problem context

At the location in Enschede, there are two branches of Pentair: X-flow and PWPT (Pentair Water Process Technology). These two branches of Pentair both use the same warehouse space. X-flow uses most of the warehouse while PWPT uses one row near their production room. The production halls of both branches are attached to the warehouse. X- flow produces the membranes and modules, PWPT produces the installations in which the modules will be placed. The actual placing of the modules is done at the customers' locations. In the warehouse, there are several kinds of SKUs (Stock Keeping Units). From chemicals and filtration modules to bolts. Some products take in a lot of space, the filtration modules can be as long as four meters.

1.2.1 Problem Identification

The problem that Pentair X-flow faces is that the warehouses are organized ineffectively. In the main warehouse, there is a lack of space. Due to this, time is lost in the inbound, outbound, quality control and products are sitting in and around the aisles. The products in the aisles form a safety issue for the employees. When an employee comes with a fork truck and needs to get a product on the shelves where a product is lying, unsafe situations can occur. It is also harder to drive through the warehouse when products are blocking the path, costing time for Pentair. As safety is particularly important for Pentair, they want no products lying around in the aisles. There are also some products stored outside in the open air. When it rains these products can get wet, which results in the situation that they cannot be put in the warehouse when needed. To achieve more storage space, Pentair also uses several external warehouses, four in total. These extra spaces are in Enschede, Almelo and Rijssen. These warehouses mostly store finished products, but also regular stock and non-valuables. The warehouse of Vivochem stores the chemicals needed to produce the membranes for example. The chemicals need specific conditions to be stored, as some of these are dangerous compounds. Using an external warehouse incurs four types of costs. Firstly they demand storage costs. These are incurred monthly depending on the space that is used. Secondly, there are the handling costs. Here a distinction is made between the handling in and the handling out costs. Thirdly the transportation costs are incurred. The transportation is outsourced, Pentair does not route the vehicles themselves. Moreover, these operations cost time and result in a decentralized inventory, which makes the storage and movement of the inventory more complex.

In this research, I will explore how the issues concerning the warehouse organization can be solved. Two options are separated in this research to solve this problem. One option is introducing a new self-owned warehouse close to the internal warehouses and letting go of the external and the second option is keeping the current organization and only changing the current way of working in the internal warehouse by changing the layout. In the first option, the new warehouse is built next to the main warehouse, so no large-scale transportation is needed. These options will be modelled in a simulation and compared on different indicators. From the simulation we will calculate the optimal layout and we will calculate whether the addition of the extra warehouse will be profitable in the terms of indicators and costs. The indicators are discussed below.

1.2.2 Problem cluster

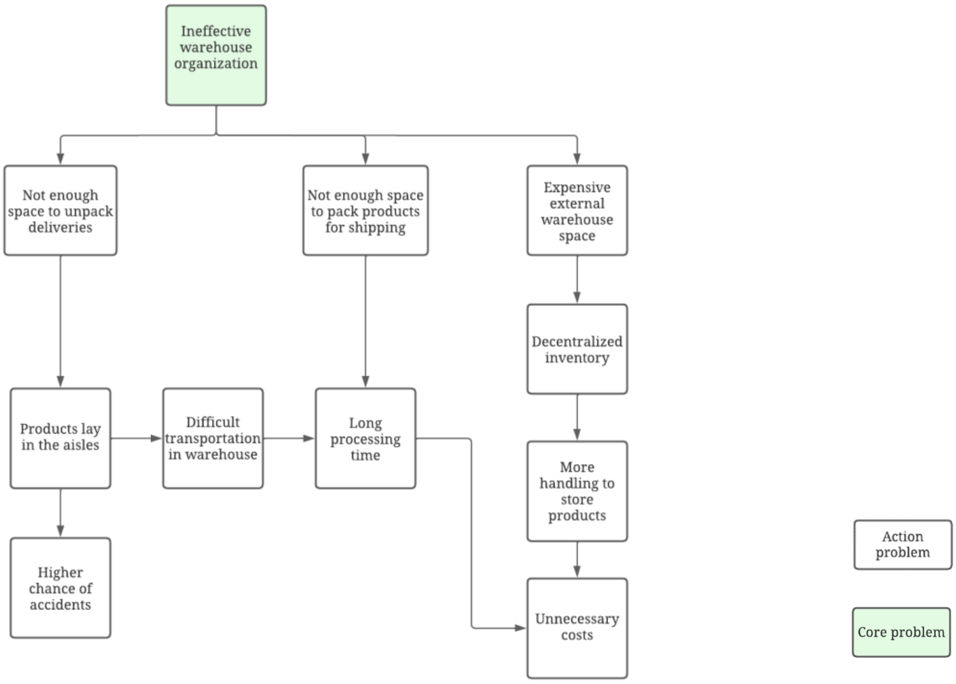

Figure 2: The problem cluster

As figure 2 shows, the core problem is that the warehouse is organized ineffectively. This results in various other problems, which have been discussed already. The core problem has no cause in itself and is therefore the core problem, as defined by Heerkens and van Winden (2017). The problems that are a result of the core problem have their own indicators that provide the level of the problem. With these indicators, the severity of the core problem is described. These indicators will also be used in the simulation to compare the different solutions. Firstly, for the operations in the internal warehouse we use the following indicators:

t_i: the duration of the process of handling the inbound products.
t_o: the duration of the process of preparing the outbound products.
t_t: the duration of the process of transporting the products to their designated spot.
o_i: occupation of the inbound area in percentages
o_o: occupation of the outbound area in percentages
c: the costs of the operations in the warehouse, related to the time and the number of employees.
s: the number of products in the aisles. This is an indicator for the safety in the warehouse.

By the operations of the warehouse we mean the unpacking of the deliveries, preparing the products for shipment and the transportation of these products within the warehouse. So for the problems concerning the in- and outbound space we use the indicators: process duration and deck occupation. For the safety we use the indicator of the number of products in the aisles and for the problem of transportation we use the indicator of time. Under the costs of the warehouse we take the costs of the use of the external warehouses. Every time when a product cannot be stored and there are already products in the aisles, the handling and transportation costs are triggered. Moreover, a penalty concerning the unsafe conditions caused by the products in the aisles is incurred when a worker stores a product in the aisles.

The indicators concerning the use of the external warehouses are:

h_i: the rent costs of external warehouse i
k: the costs related to the use of the external location: transport and the handling in and out.

These costs are known and will be added to the solution option that uses external space. In the solution with the new self-owned warehouse, the costs will not be present. These savings and the savings of the expected improved warehouse operations will be stacked up against the investment costs of the new warehouse.

1.3 Measurement of norm and reality

The reality of the problem is that the current organisation of the warehouses is ineffective. It produces problems ranging from capacity issues to safety issues. The decks of the in- and outbound and quality control are too small. When a large order comes in, products accumulate around these spaces which clog up the storage space of the warehouse. The occupation of the in- and outbound dock are often at their maximum, so that delays will appear and that products end up in the aisles. To compensate for the capacity of the internal warehouse, external warehouses are used. Behind the warehouse there is space that is currently unused. This space of 3000m^2 could be used to place the new warehouse. The current situation is further discussed in section 3.

The norm is having enough space where incoming and outgoing orders can be handled more efficiently and where these products can be placed in a designated space so they do not end up in the aisles. We strive for an occupation of the in- and outbound zones of around 50%. In this situation a full truckload can be placed, while the employees are still working on an earlier delivery. In this way, there will be fewer delays and there will be enough space to work. Pentair wants zero products in the aisles. The outbound area should be on a separate deck, so there is a clear distinction between the in- and outbound. To achieve this Pentair is open for a different layout, but is also interested in having a newly built warehouse which could also replace the external warehouses with their costs. In the simulation we will test the profitability by comparing the saved time, costs and safety with the investment costs of the first option and for the other option we will experiment if considerable improvements can be achieved by changing the layout of the main warehouse. Based on the indicators these options are compared. In the first option we will test the profitability of a new warehouse and in the second option we will reconstruct the layout for the optimal use of space. In this norm the product flow is smooth and the employees have a safer workspace with an overview of which products are where.

1.4 Problem solving approach

To guide solving the problem at hand the methodology of producing a simulation study will be followed. The steps to be taken in a simulation study according to Law (2015) are described in Appendix B. Firstly the problem and the plan of the study must be formulated in detail. We should discuss the objectives of the study, the specific questions to be answered by the study, the performance measures and the scope of the model. This is all specified in the following sections. To achieve this we will hold meetings with both supervisors and SMEs (subject-matter experts). Secondly the data needs to be gathered. The type of data that had to be gathered for the research is described in section 4. The current situation will be studied to specify the model parameters and the level of detail of the model is decided. Thirdly the assumptions of the model are constructed and checked for validity. Then it is time to model the actual simulation and test this system for validity and reliability by pilot runs. If the simulation is valid, the experimentation can start. With these experiments we will describe the costs of the current situation and compare it with the possible solutions that will be constructed. From these solutions the best one will be analysed and we conclude on how much space is needed extra.

1.5 Deliverables

The deliverables of this research will be a simulation study with experiments accompanied by recommendations. The main warehouse will be modelled in this simulation with the product flow in it. With the product flow we mean the movements the products make over time in the warehouse. These flows consist of the inbound of the products, moving the products into the shelves, moving them to and from production and collecting them for the orders. The indicators described earlier will be the KPIs (Key Performance Indicators). The model from the current situation will be compared with models where the situation is changed into one of the two options. In one experiment a warehouse will be added with a fixed layout next to the own internal warehouse. This warehouse will replace the external warehouses. There is a space of 3000m^2 available close to the warehouse. Because this is more space than the external warehouses and it is a lot closer, the situation in the main warehouse will change. The costs and indicators associated with the external warehouses will not be in this option.
In the other experiment the focus is improving the situation by diving deeper in the main warehouse. The external warehouses are kept, but we will look into changing the layout and redistributing space this way. This will not need a huge investment like a new building. The warehouse currently has the traditional warehouse layout without a cross aisle. The layouts we will test are a horizontal warehouse layout and a fishbone layout. Examples of these layouts are in Appendix A. These two experiments will be compared with each other and the current situation, based on the indicators. In both experiments the investment costs will be added to the cost KPI.
The simulation will be an estimation of the processes in the warehouse. In section 4.3.3 the limitations of the simulation study are discussed.

1.6 Research objective

The research objective is to provide solutions for the core problem. The objective is:
- An effective warehouse organization
- No products in the aisles
- Insight into the benefits of an extra warehouse based on the indicators
- Overview of costs associated with the different solutions

The goal of the research is to organize the warehousing strategy more effectively. With effective we mean operating the warehouse where the in- and outbound decks are not congested, extra warehousing costs are minimized and where products can move smoothly through the warehouse. With the use of simulation, multiple solutions to achieve this will be compared. As is known, Pentair is interested in the introduction of an extra warehouse, the simulation will determine whether this investment is worth it based on the saved time, costs and safety or whether other changes are better to introduce. This will give us the insight in the profitability of the extra warehouse based on the improved way of working it will provide and the costs that must be made.

1.6.1 Research design

In order to solve the core problem the following main research question is formulated:

How can the current warehousing strategy at Pentair X-flow be improved by changing the warehousing strategy?

The improvements we strive for in the warehouse have been described in the norm of section 1.3. To gather the information needed to solve the main research question and to structure the research, sub- research questions are formulated:

1. How is the current situation at Pentair X-Flow?

The aim of this research question is to know and understand the current situation at Pentair. A comprehensive overview is needed before improvements can be proposed. To do so, the question is divided in three questions:

   a. How is the warehouse space sorted?
   b. What are the products to simulate and how can they be categorised?
   c. How do the products flow through the warehouse?

These questions are descriptive and were approached by observing the warehouse, having meetings with the employees and managers and by gathering the data in the SAP (Systems, Applications and Products in Data Processing) inventory system.

2. How can the flow of the warehouse be simulated?

After the situation is discussed, we discuss how this is translated into the simulation. A literature study is done on the topic of simulation studies and the conceptual model is made. The steps taken and the assumptions of the model are discussed.

3. How expensive is the current flow in the warehouses?

Based on the experiments of the simulation, the costs of the current way of working in the warehouse are described, that are determined from the KPIs. Included are the costs from the use of external warehouses and the penalty costs of placing products in the aisles. Also the other indicators concerning the way of working are discussed.

4. What are possible solutions to improve the current warehouse situation?

In this question the multiple different solutions are explored in the form of experiments. The different options are set out with their KPI values. These are compared to the current situation and with each other. The solutions are created by changing parameters in the simulation study. We discuss the solution option with the different layouts and the solution option with the new warehouse.

5. What is the optimal solution to the current ineffective warehouse organization?

With the current situation and possible solutions modelled, we set out the best option to combat the current problems in the warehouse. This also then holds for the inbound area in the warehouse. Based on the KPIs and the costs, the optimal solution is selected. This will be an explanatory research.

6. How to secure a successful implementation?

Based on the best solution, we include recommendations on the implementation of this solution. The actual implementation is not part of this research, but to make the research more practical some recommendations are in place. In this question the conditions will be discussed to secure a successful implementation.

   a. How long will it take for Pentair to return on the investment?

As the solution could involve a large investment, it is worthwhile to discuss the degree of this investment. If the investment is large but it will ensure many benefits for Pentair, the return on investment could bring order to the discussion.

1.6.2 Limitations and scope of research design

One limitation of the research pertains to the examination of only three solution options. These options include different layouts such as the horizontal and fishbone layouts, along with the addition of an extra warehouse. While there exist various other layout types, time constraints prohibit their comprehensive investigation. The chosen layouts are frequently discussed in the literature, with the horizontal layout representing a more conventional option that can be adopted with relative ease. In contrast, the fishbone layout requires more substantial modifications but holds promise for yielding interesting outcomes. For future research, the simulation model can be adapted to accommodate alternative layouts.

Furthermore, the other solution option involves the utilization of the new warehouse that closely resembles the main warehouse. This decision is driven by the limitations imposed by time constraints and the suitability of the available space to accommodate a warehouse of comparable dimensions.

Another limitation pertains to the scope of the research concerning inventory management. Exploring the possibility of creating additional space by reducing inventory size falls outside the scope of this study. Pentair X-flow considers it necessary to maintain the current inventory levels due to the extended lead time associated with certain products. Moreover, the company's reliance on several external warehouses and their acknowledgement of the importance of exploring additional space further emphasizes the need for extra storage capacity.

1.7 Assessment of validity and reliability of measurement

Both reliability and validity are important measures for every research. Reliability is concerned with the consistency of the measurements (Knapp & Mueller, 2010). Regarding the reliability of the simulation model, the simulation should produce about the same values for the KPIs with different random seeds. In the case of this research, we should also expect that the KPIs in the different models of the different solution options should not differ too much. During the modelling phase of this research, the reliability was ensured by testing the model at ascending runtimes. Following Gokhale (2005), failures in reliability were observed using the Component-level Stochastic failure process. The values of every process in the models were observed for failures at different runtimes. When we observed a failure, this failure was removed in every model. After executing this process multiple times, the reliability is improved and assessed as sufficient. Regarding the reliability of the research in general, when the research is done again at a later time, it should yield the same results given that the warehouse management is not changed. This research is based on the product flow in the warehouse of Pentair X- flow specifically. If Pentair X-flow changes its strategy or when the processes change because of other factors, the research will yield different results. If Pentair decides to order more deliveries, changes the production schedule or if the demand increases and Pentair sends out more orders, the research will yield different results.

Because the processes are triggered often in the runtime, the processes and KPIs will converge to average values. In simulation studies, the validity of the model is of high importance. According to Cooper and Schindler (2014) there are two categories of validity: internal and external validity. External validity means the research's ability to be generalized across settings, persons and times. As this research concerns the specific situation of Pentair X-flow, this research cannot be generalized for other purposes. Internal validity is concerned with the relevance of an instrument for addressing a study's purpose. If the instrument measures what it is designed to measure (Knapp & Mueller, 2010). Internal validity is divided into content validity, criterion-related validity and construct validity (Cooper & Schindler, 2014). The content validity of a measuring instrument is the extent to which it provides good coverage of the questions guiding the study. To evaluate this, we must first determine what elements constitute adequate coverage. This includes judgement. In this research, we decided that the instrument provides adequate coverage when the SMEs judge it as so. In this approach, we follow the approach of Law (2015). As Figure 13 in the appendix B shows, the validity of the model is tested in step six of the simulation plan by Law (2015). In this step, the model is compared to the existing system and the model is reviewed by analysts and SMEs. During the modelling, it is important to debug at intervals to secure the validity. The validity also needs to be checked. This can be done by running the simulation and comparing it with real life values (Smith, 2019). During the research, the simulation model is shown and explained at different points in time to ensure the validity of the simulation at every process. Also, the simulation uses data of the actual movements of the warehouse of earlier months to uphold the validity of the input values of the models. After running the experiments, certain KPIs of high importance were once more checked with the validity. Especially the transport and handling costs of the external locations were checked. The average value of this KPI in the current situation is compared with how often products were transported externally. This value proved to be in accordance with the validity.

Criterion-related validity relates to the efficacy of measurement instruments employed for prediction or estimation purposes. In the context of this study, this concerns the simulation models utilized to evaluate the potential solutions. To validate these, discussions were held with the Supply Chain manager and the chosen decisions were examined. Conversely, construct validity concerns whether the concepts used are properly operationalized, ensuring that the research has little ambiguity and is substantiated by existing literature. On the topics and the approach of this research, much literature has been written that is used to operationalize the concepts. The processes in the warehouse are explained and the chosen layouts are argued.

Furthermore, this research adheres to the plan of approach formulated by Law (2015), a widely employed methodology in simulation-based studies.

2. Theoretical framework

A theoretical framework is a logically developed and connected set of concepts and premises that is used to structure a study (Varpio et al., 2020). In this theoretical framework we describe the theoretical backgrounds that are relevant to this research. Consisting of simulation theory with definitions and warehouse management theory. The additional descriptions of the simulation study like the conceptual model are set out in section four.

2.1 Simulation model theory

Simulation is defined as: “Experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better understanding and/ or improving that system.” (Robinson, 2014, p5). In the scope of this study, the simulation acts as an imitation of the warehouse system at Pentair X-flow. There are four simulation methods: Discrete-event, Monte-Carlo, System dynamics and agent-based simulation. Discrete-event simulation is used for queuing systems and it concerns the modelling of a system as it evolves over time by which the variables change at separate, countable points in time (Law, 2015). In this study, a discrete-event simulation is used. Monte Carlo models are used to model risks in environments where the outcome is subject to chance. System dynamics is a simulation that uses a continuous approach to represent the world as a set of stocks and flows. Stocks are collections of items that then flows through a population. Finally, agent-based simulation studies complex behavioural systems. It is mainly used in the fields of biological, physical and social systems. Because in this study a discrete-event simulation is used, we describe this method in more detail.

A discrete-event simulation models the operation of a system as a discrete sequence of events in time (Sharma,2015). Events occur at a particular time and mark a change in the state of the system. Between these events, we assume there is no change so the simulation can jump from one event to the next. Examples of these events could be a product arriving, a product being carried to production and a product returning from production. These events occur at an instant of time and these times are recorded (Robinson, 2014). Discrete-event simulations make use of the Three-Phase Simulation Approach. In this approach, events are classified into two types: bound and conditional events. Bound events are state changes that are scheduled to occur. In the simulation of this study, examples of bound events are products being made ready for the orders and products arriving at and returning to production. These events are triggered by generators that become active during intervals. Conditional events on the other hand are state changes that are dependent on the conditions in the model. An example of this type of event is the placement of products in the aisles when the product cannot be stored in its shelf space. Because of the three-phase simulation approach and the approach to time, discrete-event simulation can be used to model a wide range of operations.

There are several reasons for employing a simulation model in this study. In this approach, we opted for simulation because it makes experimentation possible without affecting the operations in the real warehouse. Because we aim to find the optimal organization of the warehouse, a simulation is easier, less expensive and more time-efficient than physically changing the organization of the warehouse. Furthermore, it is hard to predict how the changes will impact the warehouse. As there is much variability in the warehouse, in the manner of what products are coming in and where they must be stored, a simulation is preferred over other modelling approaches. Moreover, a simulation offers more transparency than other modelling approaches. Complex mathematical calculations that substantiate the superiority of a particular solution may pose challenges for the Pentair's comprehension. In contrast, simulation provides a visually animated representation of the system, enabling managers to develop a more comprehensive understanding of the model and engendering confidence in its outcomes (Robinson, 2014).

2.2 Definitions in a simulation study

To give a better understanding of some terms used in this study, some definitions are given below:

System
In general terms, a system is a collection of parts that are organised for some purpose (Robinson,2014). For this research, we study a designed physical system. That is, a physical system as a result of human design.

Model
According to Sharma (2015,p2) a model is defined as: "a representation of a system for the purpose of studying the system." To serve this purpose, the model needs to be made in such a way that valid conclusions can be made from it.

Conceptual model
A conceptual model is an abstraction of the simulation model. Conceptual modelling consist of three sub-activities (Robinson, 2014, p66):

- Developing an understanding of the problem situation
- Determining the modelling objectives
- Designing the conceptual model: inputs, outputs and model content

Stochastic simulation model
A simulation model that uses one or more random variables as input. The random inputs are defined to follow a certain predetermined probability distribution. These random inputs conclude in random output, so the stochastic model approximates the characteristics of the model.

Active and passive entities
Entities are the items of interest in a simulation study. There is a distinction between active and passive entities. Active entities correspond to the active parts of the system, take the warehouse employees for example. Passive entities are resources, queues and other non-active parts of the simulation.

System state
The system state is defined by the collection of state variables that are necessary to describe the system at a particular time (Law, 2015). With the state variables being the key variables to be predicted.

Simulation clock
This variable gives the current value of simulated time.

Random seed
As is often the case in computer programs, Plant Simulation does not use truly random numbers. It uses a pseudo random number generator. The random seed is the number used to initialize the pseudo random number generator. The sequence of the random numbers are completely determined by the value of the random seed. Consequently, if the number generator is initialized by the same random seed, it will produce the same sequence of random numbers. In the case of the simulation, to produce different experiments, the model is ran multiple times with different seed values.

2.3 Warehouse management theory

A warehouse is a facility that is used for the storage and distribution of products. Today, the warehouse is playing a more crucial role than it ever has in the success of businesses (Faber et al., 2013). Warehouses play a critical intermediate role between supply chain members, affecting the supply chain costs and service. The management of a warehouse is the art of operating a warehouse and distribution system efficiently (Ten Hompel & Schmidt, 2008). Customers want their orders today rather than tomorrow, therefore it is important for a company to have an efficient distribution process. Warehouse management includes all planning and control procedures to operate the warehouse. Planning and control concerns all the activities in the warehouse to satisfy customer demand (Slack et al., 2001). The processes in a warehouse generally include receiving, storing, transporting and shipping goods. In the warehouse of Pentair X-flow, the process of transporting products to production and receiving these products again is also part of the warehouse operations.

The core concepts of the effects that the organization's environment has on its performance is uncertainty (Faber et al., 2013). Researchers identify two dimensions of uncertainty: complexity and dynamism. Complexity in warehousing is defined by (Faber et al., 2013):

- The number of different SKUs the warehouse has in storage;
- The number and variety of the processes in the warehouse;
- The number of order lines processed per day by the warehouse.

Following these dimensions, the warehouse of Pentair X-flow falls in the more complex category as it holds many different SKUs, there are more processes than a regular storage-only warehouse and several orders are processed per day. Furthermore, environmental dynamism is related to the rate of change in the market as well as the uncertainty or unpredictability of competitors and customers. With regard to warehouse management, dynamism is conceptualized in the following ways (Faber et al., 2013): the unpredictability of the market demand and the rate of change in the preference of customers. In Pentair's situation, the market can be unpredictable, in the way of changing customer's demand. Because of these reasons, it is of importance that the organization of the warehouses of Pentair X-flow is improved on its effectiveness.

To improve the effectiveness of the warehouse organization in this research, we look into adding an extra warehouse to replace the external warehouse in one solution. In the other potential solutions, we study the consequences of changing the layout. The theoretical foundations of layouts are studied below.

The warehouse of Pentair X- flow is a manual-order-picking warehouse. In combination with the use of forklifts, the processes are carried out manually. In these warehouse systems, manpower plays an essential role in conducting the warehouse key functions. The more labour intensive, the more expensive the operations are (Altarazi & Ammouri, 2017). Consequently, we strive for a layout where duration and labour intensity of processes are minimized. Currently, the warehouse of Pentair has a traditional layout with parallel pallet racks, without a cross-aisle (Appendix A1). This layout is an example of a layout that prioritizes storage area (Dukic & Opetuk, 2012). It uses long storage racks in order to store many SKUs in one aisle. Another traditional layout that proves to be more efficient in a wide range of warehouse processes is the horizontal layout with a cross aisle (Dukic & Opetuk, 2012). For this reason, this layout is implemented as a potential solution. Appendix A3 shows this potential layout.

The other solution option uses a non-traditional layout. This is a fishbone layout and is shown in Appendix A4. The fishbone layout has been customized to fit in the specific dimensions of the warehouse. This non-traditional warehouse focuses on optimizing the inbound- and order-picking area. The order-picking process is the most laborious and the most costly activity in a typical warehouse, contributing to 55% of the total operating costs of a warehouse (Tompkins et al., 1996). Additionally, 50% of the total order-picking time is spent on travelling. For these reasons, the fishbone layout is included in this study. The aisles are easily accessible from the in- and outbound zones. A drawback of this layout however, is that the storage aisles have a smaller length, which is also amplified by the dimensions of the warehouse of Pentair. Consequently, there is less storage space and in the situation of Pentair this could prove difficult with the storage of larger modules. As Table 1 shows below, the traditional layout with a cross-aisle has the smallest average picking travel distance of the different layouts, with the fishbone layout has the second smallest values. This study will prove if this is also the case in the situation of Pentair X-flow.

Table 1 Simulation results of average picking travel distance of different layouts (Dukic & Opetuk, 2014)

S-shape routing policy		Order size		Composite routing policy		Order size	
		10	30			10	30
Warehouse layout	Traditional (basic)	258.7	375.8	Warehouse layout	Traditional (basic)	228.2	363.9
	Traditional (middle cross-aisle)	193.9	329.0		Traditional (middle cross-aisle)	182.8	309
	Fishbone	227.5	351.9		Fishbone	213.1	317.3
	Chevron	268.5	397.2		Chevron	233.2	370.2

3. How is the current situation at Pentair X-Flow?

This chapter provides an overview of the current situation of Pentair. Pentair has their own internal warehouse of 2600m^2 of which 1500m^2 is designated for storage of products, including the aisles and 640m^2 of actual shelf space. Appendix A1 shows the current layout of the warehouse. The in- and outbound section use the same deck and have a total space of around 50m^2. The quality control has a space of 15m^2. In this situation, Pentair experiences a lack of space and consequently external warehouses are also utilized. These are the warehouses Twentrex and Vivochem in Almelo, Binnenhaven in Enschede and Pultrum in Rijssen. Binnenhaven primarily stores the skits of the products and is not used as often. On the other hand, Twentrex, Vivochem and Pultrum are considerably larger. In Twentrex and Pultrum finished modules are stored while Vivochem serves the purpose of housing the chemical compounds that are used for the production of the membranes. The costs of the external warehouse Twentrex are 25.770€ per year for the rent alone. The rent costs of another large warehouse near the location is 128.178€ per year. The costs of the other external warehouses are smaller. In total the rent of all the external locations comes to 216.012€ yearly. The sum of the handling and transport accumulates to 235€ per time it is used.

In the internal warehouse they work according to Kanban. Presently, both the inbound and the outbound operations experience frequent congestion, particularly during busy periods. On an extremely busy day, close to 250 different products are delivered to the warehouse in around fifteen deliveries. Moreover, there is a problem regarding the finished orders. Some customers take long to pick up orders, leading to extended periods of storage on the shelves, sometimes lasting up to two months. Orders are also placed at the end of the lanes. In order to make room in the inbound section, the products are quickly transported elsewhere in the warehouse. If the product cannot be stored in the shelves, they are placed in the aisles. Furthermore, products from production are temporarily stored in the aisles to facilitate packaging into boxes. Because of these two flows, the aisles are congested with products that form safety issues for the employees. There are at times up to five pallets in the aisles, often at the end of the shelves, in the aisles and at quality control.
Subsequent sections delve into the description of the warehouse space, including a discussion on the products, the flow and the resources of the current situation that must be simulated.

3.1 How is the warehouse space sorted?

Appendix A1 shows the layout of the warehouse with the locations of the products. The products are distributed over the lanes of the warehouse. There is a clear distinction between the raw materials and the finished products. The raw materials are in the lanes A up to G, with exception of I. The finished materials are stored in the remaining aisles.

The first two lanes, A and B are used for the raw materials and the finished products of Filtrix. These are other filtration products for commercial use. These products have a different production room and are mostly packaged in small and medium sized boxes. In C and D the raw material of the modules are located. These materials are put in large rectangular crates, which are unpacked in the production room. In E and F the housing of the modules are stored. These are longer products in which the modules are placed. These longer boxes are mostly three meter long, with some two meter boxes. In G and H the finished 3 meter modules and the materials required for the modules are stored. For the storage of these modules, the shelves are modified to store these longer modules. In I the materials for the production of the membranes

are put. In J, K and L the finished products are stored. These products contain the smaller sized modules. These are again stored in the large crates. From these lanes the products are picked. The lanes M and N are also lanes used during the order picking, these contain smaller extra products that are often included in orders, like clamps. The shelves of O contain boxes of projects. These boxes are filled with products that are needed for projects. When a delivery comes in that has the products, these products are moved into these boxes for easy access. PWPT store their products in P. In Q the finished 4 meter modules are stored. These are the largest modules and the shelves have been modified also for these products.
The largest part of the warehouse is in use for X-Flow. PWPT uses the bigger part of P and O. In practice the floor in front of P is also in use by PWPT. Here boxes are filled with products of different projects. At the right side of O picked orders are put that are ready for shipping. In practice, customers are often late with picking up their orders, which results in the practice that these order lay ready in the warehouse for some time, as long as a couple of months.

3.2 Which products to simulate and how can they be categorized?

Based on the available time and to keep the running time manageable, the simulation cannot include all the different products. Approximations and decisions are necessary on which products and the number of products to simulate. To simulate the process in the warehouse, we focus on the products that are delivered to the warehouse and the orders that are sent. Moreover we approximate the raw materials going to production and the finished products returning.

To estimate the space utilization in the warehouse, we categorize the products based on their size. There are five categories, which Table 2 shows:

Type of product	Dimensions (mm)
Small box with parts	1200x800x400
Medium sized box	1200x800x800
3 meter crate	3000x800x600
4 meter crate	4000x800x600
Large rectangular crate	1200x800x1800

Table 2The categories of products and their dimensions

Using these, we categorize the products in the different flows. The choice of the categories are based on the type of packages in the warehouse. The five categories can effectively describe the different products. The orders and deliveries are observed and from these observations distributions of the five categories are simulated which the simulation will then use. The small and medium sized boxes are mostly present in the inbound, while the other diameters are more common out of production and for outbound. The diameters are based on the pallet sizes. This allows for many experiments without the constant delivery of data. Also, this allows for the estimation of space utility. With the dimensions of each category, the simulation can check whether there is room for a product of a certain category. Because the amount of space is the bottleneck of the warehouse, this is an important function of the simulation. In the warehouse, there are certain lanes that only store one categorization of products. In shelf O, the four meter modules are stored and in the lanes G and H the three meter modules are stored for example. This is because these lanes are specially constructed to store these type of products.

3.3 How do the products flow through the warehouse?

In the simulation, the modelling of product flows is of high importance. Therefore, it is crucial to thoroughly examine the various flows within the system. Specifically, there are five product flows in the actual system:

- Inbound flow;
- Outbound flow of orders;
- Flow to production;
- Flow from production to the warehouse and
- The flow to either the new warehouse in the solution option or to the external warehouse in the current situation.

The process of the movements of the products is graphically described in a BPMN (Business Process Model and Notation) model. Figure 3 below shows this process. To describe the processes, we employ the notation of the shelves described in Appendix A1.

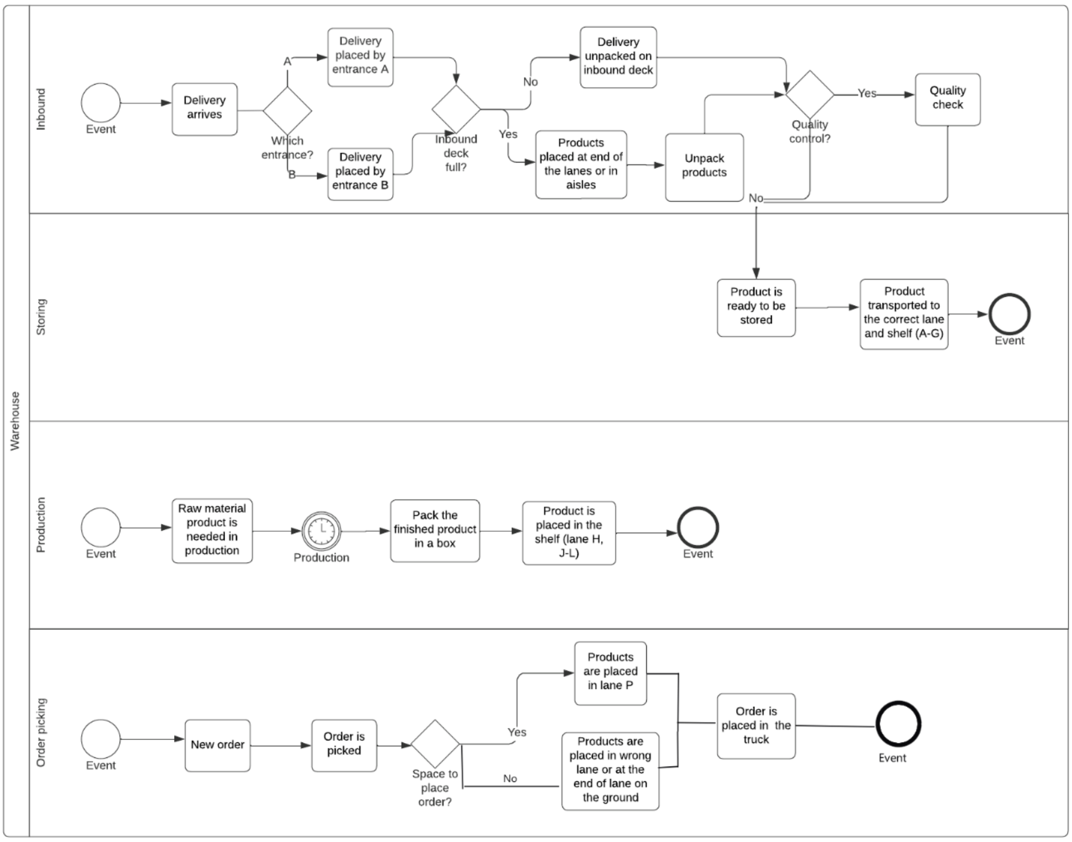

Figure 3 BPMN model of the processes in the warehouse

Regarding the inbound flow, the ideal scenario involves the delivery of goods, followed by unpacking and placement on shelves. Deliveries can enter the warehouse through either entrance A or B. Entrance B, being more spacious, is primarily utilized by larger trucks. However, in reality, the process is often hindered by congestion on the deck, resulting in delayed storage of products. Once the inbound products are unpacked, they are moved to aisles A to G. Smaller products are stored on shelves A to D, which constitute the majority of inbound items. Additionally, there are projects that span multiple days. There are also projects, which are collected over multiple days. This is in general the way of working for PWPT. A project box is filled over several days with the products that are needed for this project. The deliveries for this order come in over multiple days. These project boxes are stored in and in front of storage P.

The flow to and from the production room encompasses the flow of the raw materials being transported to production and returning as finished products. Materials go from lanes A up to G to production and then end up in the lanes H to M and O in the case of the four meter modules. When the products return from the production room, they must be packed in the crates. During this process, the products lay in the aisle between I and J.

Upon receiving an order, employees begin by picking the required products and placing them in the order shelf, which is adjacent to shelf P. The products are retrieved from the shelves holding finished materials. In the simulation, this shelf is labelled as PF. Once the order has been fully assembled, it is prepared for dispatch.

Concerning the flow to the external warehouse, the simulation only represents the preparation of products for shipment to the designated location, without simulating the actual routing. With this flow to the external warehouse, the most important part is to know when this occurs and then to attribute the correct costs to this handling. In reality products are not moved daily to external locations, but rather, on average, once a week. In the actual solution with the addition of the self-owned warehouse, the route from the main to the new warehouse will be modelled. As this is an important characteristic of the solution.

A detailed description of how the flows have been incorporated into the simulation will be provided in the following section.

3.4 Summary

In summary, the warehouse operations encompass five distinct product flows: inbound, outbound, production-related transfers, and transfers to other warehouses. At the moment, the products do not flow effectively, as the inbound deck is often congested and the products that are collected for outbound cannot be placed in their shelf. Consequently, products are placed in the aisles where they contribute to an unsafe working environment in the warehouse. To increase the capacity of storage, Pentair X-flow rents several external warehouses at an annual cost of €216.012.

To facilitate the simulation of product flows, the products have been categorized into five groups based on their volume, enabling estimation of space utilization. This section also provides a description of the warehouse layout and the corresponding product flows.

Pentair X-flow strives to improve their warehouse organization. In order to guide the improvement process, a simulation of the current situation will be compared to potential solutions, offering insights into the feasibility of these proposed improvements. The subsequent section discusses the setup of this simulation.

4. How can the flow of the warehouse be simulated?

As in every simulation study, the reality must be modelled with enough accuracy. For this, the system must be described and a conceptual model has to be made. The system is described in the previous research question. In this research question, we describe how this flow can be translated into a simulation model. For this, a conceptual model, the assumptions and the actual simulation is described. The actual system is simplified for the conceptual model (Robinson, 2014). Marco (2002) breaks down the design criteria to guide the model development: model objective, required data, the entities, locations, resources and the general logic. A logic flow can be used to describe the general logic schematically. All these steps are crucial for a sound simulation. The model objective is the foundation of a simulation study. When the objective of the model is completely clear, we move on to the other tasks. For the required data, we describe what data is used and how this data is collected. In the case of this research, the data of the process is gathered by interviews, observations and from the inventory system. Then the entities, locations and the resources must be described to simulate the process.

4.1 Conceptual model

According to Robinson (2014) a good conceptual model should do the following:

- Produce sufficiently accurate results for the purpose at hand (validity)
- Be believable for the clients (credibility)
- Be feasible to build in the constraints of the available data and time
- Be easy to use, flexible, visual and quick to run (utility)

Based on these requirements the following conceptual model is made.

4.1.1 Model objectives

With the model, Pentair wishes to achieve insight into the profitability of a new self-owned warehouse. This would be a large investment which would also introduce large changes in the way of working. Pentair would like an overview whether these improvements in the way of working in the warehouse weigh up to the investment. With the introduction of the warehouse, the capacity will be vastly improved, external warehouses with their costs and transportation time could be let go and there would be more space to work more safely and efficiently. Pentair would like to see no more products in the aisles and the occupation of the in- and outbound decks should be reduced with 25% to ensure that it will not be clogged up and the employees have space to work. So in the simulation comparisons should be made with the current system and the system with an added self-owned warehouse. Moreover, a situation will be tested where the current situation is changed with a different layout in the main warehouse. In this option a smaller investment is needed and Pentair is curious whether this could alleviate the in- and outbound sections and reduce the number of products in the aisles.

4.1.2 Identifying model outputs

The model outputs are used to see whether the model objectives have been achieved. If they have not been achieved, then the outputs show the reasons why. We have already described the model outputs in the section of 1.2.2. The indicators are the model outputs. These indicators test the effectiveness of the warehouse and will show the possible improvements when the solutions are modelled. The model outputs of the different options will be compared with each other and the conclusions will be based on these.

4.1.3 Identifying model inputs

The model inputs are the means by which it is proposed that the modelling objectives are to be achieved (Robinson, 2014). In our model, we have the qualitative input of changing the model structure by adding a self-owned warehouse close to the main warehouse and removing external warehouses. The size of the self-owned warehouse has a maximum of 3000m^2 and there is a total of four external warehouses that could be removed. The input variables are then the number of warehouses, and in the other option concerning the layout of the warehouse the storage space is the input. The different layouts have different storage capacities, which functions as inputs in the simulation.

4.1.4 Scope and level of detail

We need to specify which aspects of the real- world system actually need to be in the model and what aspects can be ignored (Law, 2015). This is done by specifying what entities, activities, queues and resources should be in the model. The tables in Appendix D show the scope and level of detail of the model. The first table shows the entities, activities, queues and resources that will be included in the model with their justifications. The second table shows the level of detail of the included characteristics.

4.1.5 Locations

In the model, the following locations are of importance in the model:

- Inbound section: The section of the warehouse where the deliveries are coming in. Here they are unpacked and made ready for the warehouse.
- Outbound section: The section of the warehouse where the orders are collected and made ready for shipment.
- Quality control: The section in the warehouse where certain products are checked for quality.
- Storing aisles: The rest of the warehouse space. Here are the products stored in the shelves.

- External and new internal warehouse

As could be seen in the tables, the external warehouses are not modelled with high detail. This is done because much of the activities are outsourced. Modelling the external warehouses would not add more to the objective of the model. The routing and storing is outsourced, so only the costs are relevant and the moment that these costs are incurred when products are transported. The main warehouse is modelled with the level of detail that serves the objective and which is possible in the time provided. The new internal warehouse in one of the solution options will be modelled with more detail than the other external warehouses. This warehouse will have the products flowing through it and being stored. As it is a solution option, it is important to know how the product flow would change in the solution. The new warehouse will have a fixed layout that is similar to the current layout of the main warehouse.

4.1.6 Logic flow diagram

To know how the product flow is in the warehouse and to know what we need to model, a process flow diagram is made. This diagram has already been shown in section 3.3. The simulation follows this logic. The different flows are divided in the four lanes. The processes inbound and order picking are based on the delivery and order data. From this data probability distributions are made that divide these lists in the five product categorizations. The production inter arrival times and durations are based on inventory data of the SAP system. We again made probability distributions of this data that is used in the simulation to make it as accurate as possible. The flow is as expected; from inbound to the lanes A to G for the raw materials. Then to production, and then to the finished materials.

4.1.7 Assumptions

To ensure the feasibility of the simulation within the available timeframe, the following assumptions were made:

1. Exclusion of forklift usage: The assumption was made to exclude the utilization of forklifts in the simulation model for the sake of simplification. Since all the different models under comparison also exclude forklifts, their storing times are inherently shorter and can still be effectively compared. The time required to program the use of forklifts would be better utilized in improving the accuracy of the processes.
2. Evenly spread inter-arrival times: The inter-arrival times of products entering the processes are assumed to be evenly distributed throughout the day. The inter- arrival distributions, derived from SAP data, remain consistent across the entire duration of the simulation, which spans many days. In this longer run time, the number of products that are processed per day will be similar to the reality to a satisfactory degree.
3. Constant processing times: Regarding the processing times at the stations within the different processes, constant values are assumed. These processing times have been estimated based on observations, and due to time constraints, further detailed

observations were not feasible. However, these times can be readily adjusted if necessary.
4. Identical layout and capacity of the new warehouse: It is assumed that the new warehouse shares the same layout and capacity as the current warehouse, primarily due to the limitations of the available timeframe. With a new warehouse space of approximately 3000m^2, duplicating the current warehouse is considered sufficient to illustrate how the flows will be altered in the main warehouse by introducing additional storage capacity. Determining the optimal layout for the new warehouse falls beyond the scope of this thesis.
5. Capacity of the inbound zone: It is assumed that ten products can be temporarily stored in the inbound zone. This has been calculated by dividing the dimensions of the deck and dividing this by the dimensions of a pallet. This assumption is needed to evaluate the operations in the warehouse.
6. Worker's knowledge of storage location: It is assumed that workers possess knowledge of the designated storage locations for products. This assumption is justified by considering an experienced warehouse employee, and programming the decision-making process of employees is not within the scope of this study.
7. Constant batch size: The batch size for arrivals at the processes is assumed to remain constant. Since Plant Simulation does not permit the use of distributions for batch sizes, the average batch size of the process is employed in the simulation. The actual batch sizes have been observed from the SAP data and the average value is calculated.
8. Storage of products externally when six products are in the aisle: Whenever a worker encounters an empty shelf, the product is transported to the aisle. To simulate the decision-making process for storing products externally, it is assumed that this occurs when the sixth product enters the aisle.
9. 10% of deliveries stored in the new warehouse: Additionally, in the proposed solution involving the new warehouse, it is assumed that 10% of incoming deliveries will not be immediately required for production and will instead be stored in the new warehouse. Because there are several products that are sent with the orders as they come and due to the congestion of the inbound zone, it makes sense to store these immediately in the extra warehouse.
10. The random selection of finished products for outbound shipments from the warehouse: In the simulated scenario where orders are selected and placed on designated order shelves, the finished products are assumed to leave the warehouse in a random order. The simulation algorithm retrieves a batch of products from the order shelf and removes them from the warehouse. This assumption is introduced to simplify the model within the constraints of the available timeframe.

4.2 Probability distributions of the processes

To simulate the arrival of products close to the reality in the simulation, we have analysed the inventory data of Pentair. The inventory system that is used is SAP. In the different processes, the bookings from one location to another location are collected over a longer period of time. This data was then summarised and made accessible in Excel. These tables were then put into Wolfram Mathematica to determine the best fitting probability distributions with their parameters. The graphs of the probability distributions and their parameters of the four different processes are shown in the Appendix E. Every process has a different distribution with different parameters. These probability distributions are used in the simulation model to model the arrival patterns. The data that is taken from the inventory data was the number of unique orders or deliveries per day. As appendix E shows, the deliveries and bookings to production follow a normal distribution, the bookings back from production follow a binomial distribution and the orders follow a gamma distribution. Because the simulation works with interarrival times, we transformed the data of number of products per day to the interarrival times between the bookings. In this, we assume that the bookings are distributed evenly over the day. The distributions of the inter-arrival times can also be found in Appendix E.

4.3 The simulation

In the simulation study, we strive to model the reality and the possible changes as accurately as possible. The simulation is made in Plant Simulation. Plant Simulation is a simulation software developed by Siemens Digital Industries and is used in the industry to model, simulate, visualize and analyse systems and processes to optimize material flow and resource utilization. To guide the process, we have determined the characteristics that need to be modelled.

4.3.1 The processes

As is known, the simulation of the main warehouse involves five distinct processes, which have been analysed and shown in a BPMN. Each process will be discussed independently to analyse their specific characteristics in the simulation.

In the inbound process, products enter the warehouse following an interarrival time distribution. The product type is determined based on the distribution outlined in the "ProductDist" table file. Upon arrival, the product is unpacked in the inbound zone and then transported to the appropriate storage lane. The "ExitStrategy" method is utilized to ensure the product is directed to the correct lane. If quality inspection is required, the product undergoes the necessary checks before being taken to its designated storage location. When storage space is limited, products are placed in the aisles, resulting in penalties. The simulation calculates the occupation of the inbound zone and the average time products spend there. Additionally, the average carrying time of all operations performed by workers is recorded.

During the flow of products to production, batches of products are called and transferred to the production area at the predetermined intervals. The "ToProd" generator prompts workers to retrieve parts from storage and transport them to the production hall. The selection of products to be transported to production follows the distribution that closely resembles the real-world scenarios. A worker carries the parts to the production facility's entrance. It is important to note that the simulation does not incorporate production services, as the focus lies solely on the warehouse operations.

After production, the products re-enter the warehouse at calculated intervals and in predetermined batches. The majority of products leaving production belong to the large category, representing finished modules. An available worker retrieves these products and transports them to their assigned storage location. If the designated location is full, the products are placed in the aisles.

In the outbound process, workers initially pick products for each order and store them on the order shelf. The selection of products for picking is determined by probabilities generated through the "GenOrderpicking2" method. Workers execute this operation when prompted by the "OP" generator, following real-world frequencies. To facilitate the movement of products out of the warehouse, the "GenOrderAway" method is triggered by a generator of the same name. This operation involves workers transporting a batch of products out of the warehouse. When the order shelf reaches maximum capacity, any excess products are stored in the aisles.

If four or more products accumulate in the aisles, they are moved externally, resulting in additional costs in the simulation. It should be emphasized that the routing aspect is not within the scope of this thesis. The products ultimately leave the warehouse when they are transferred externally. In the case of the solution involving an extra warehouse, the products are redirected to the new warehouse instead of the external warehouse.

Moving the focus to the real system, the problems arise in the handling of deliveries and orders. The first solution option models a modified process in the main warehouse, where 10% of inbound deliveries are allocated to the newly constructed warehouse. Furthermore, the product transportation between these warehouses is introduced. The inbound products destined for the new warehouse represent items that do not require further processing in production. These products are shipped to the customer for the installation of the modules, for example the clamps. The product flows that also will be transported to the new warehouse are orders and finished products that cannot be stored in the shelves. By adopting this approach, the aim is to prevent these products from occupying the aisles. Products leave the new warehouse when the orders are sent away or when products need to go to production. With this warehouse, a lot of capacity will be added close to the main warehouse. This means that there will be more space available for storage. These new processes are the main focus of this option.

In the other solution option, the focus is again on the process of the handling of deliveries and orders, in another layout. Different layouts will be tested to select the optimal layout to improve the handling of the process while minimizing the problems. These layouts have been discussed in the earlier section.

On the other hand, the second option prioritizes the handling of deliveries and orders within a different layout. Various layouts have been explored and tested to identify improvements in process efficiency while minimizing issues. These layout alternatives were previously discussed in section 1.5.

4.3.2 The objects

The most important objects to be modelled are the products. These entities move through the warehouse during the various processes. We categorize these products in five categories based on their volumes. As the products cannot move on their own, the employees of the warehouse are closely related to the products.

4.3.3 The level of detail implemented

The simulation of the main warehouse involves modelling the product flows in high detail, albeit with a limited selection of products. Due to the complexity of simulating all the different products, a decision is made regarding which products to include in the simulation. The focus is primarily on the in- and outbound processes, as these are the areas where issues arise. Additionally, the flow of products to and from production is modelled to complete the cycle.

Incoming deliveries are categorized into the five volume categories described in the previous section. This categorization enables the simulation to determine suitable storage locations for deliveries and identify situations where placement is not feasible. Pentair receives multiple deliveries per day, each containing several parts. The distribution of product categories is studied and implemented in the simulation for each process. For instance, the majority of inbound products have smaller volumes, whereas products leaving production are predominantly larger in size. This approach allows the simulation to estimate space utilization within the available timeframe. By focusing on specific product categories, the simulation avoids the time-consuming process of observing numerous individual products and ensures an adequate number of movements to test various solutions.

The inter-arrival times for the processes in the simulation are derived from probability distributions reflecting the frequency of operations. Consequently, these inter-arrival times are evenly distributed throughout the day, without differentiating between morning and afternoon periods. This simplification is employed for the sake of streamlining the analysis in the timeframe we are working with. However, since the simulation is executed over an extended duration, the overall frequency of processes per day aligns closely with real-world conditions. Hence, the simulation's validity is maintained for longer run times.

The main warehouse is a crucial component in both experiments and the current situation model, necessitating its reliability. In the current situation, external warehouses are only simulated to account for additional costs, as the routing and storage are outsourced. The focus is primarily directed towards the docks involved in the in- and outbound processes, where most handling occurs and problems arise. In experiment one, the extra warehouse is modelled similarly to the main warehouse, adopting the same layout and space but excluding processes irrelevant to the new warehouse. These are the processes sending the products externally and placing the products in the order shelf. If products must be transported for an order, they are taken out of the regular shelves. As the products will be shipped to the main warehouse, the new warehouse is represented as an additional facility with a specific capacity. In experiment two, the main warehouse is the primary focus, but with a layout modification. The level of detail in this experiment aligns with that of the current situation.

4.3.4 Data Aggregation

To prepare the data for use in the simulation model, the entries in the SAP system were aggregated. Data aggregation is the process where data is gathered and expressed in a summary form, often in the form of statistics (Mullins, 2020). Every change in the inventory system is recorded in the SAP system with the product's code, location and time. Together with the addition of the product volume, the data was aggregated to make the product distributions, the number of unique bookings per day, the batch sizes and the times between the bookings. Consequently, a higher level of abstraction of the data was achieved that is used in the simulation model. Instead of modelling every single event, the simulation uses distributions to model the real life system accurately.

4.3.5 KPIs

In order to keep track of the indicators that were described in section 1.2.2, the simulation keeps track of the KPIs. The KPIs are programmed in the methods TrackProducts and EnterArrival..

In the model of the main warehouse, the KPI of the external rent and transport and handling costs are described. When the aisle is emptied out and the products are shipped to the external locations, the costs are incurred.

4.4 Summary

In summary, the objective of the model is to give insight into the profitability of a new self-owned warehouse. This would be a large investment which would also introduce large changes in the way of working. Moreover, to give more dimension to the recommendations, other solution options are modelled to show the best approach. The model that is used for this purpose in this research is thoroughly described in this section. The conceptual model is described with all its components. Furthermore, the model and its uses are described. The processes in the simulation are modelled close to reality and the data used is based on inventory data of SAP. The data is analysed in such a way to provide distributions of the inter-arrival times of the processes. In order to simulate the warehouse system as accurately as possible in the timeframe, the assumptions are given. Some of these assumptions are a result of the given timeframe, for example the assumption of the fixed batch sizes and the constant processing times. The assumptions regarding the moments when products are moved externally are choices that have been determined discussed with SMEs. These assumptions can be changed for future research.

Moreover, the KPIs on which the results are judged are set out. In the following sections, we dive into the values of these KPIs of the current situation.

5 How expensive is the current flow in the warehouses?

During the processes of the simulation, the model calculates the values of the indicators. In the model frame of the simulation, these KPIs can be seen and as the simulation runs, they collect the data and calculate the corresponding values. These values are calculated in the method TrackProducts. The KPIs indicate the effectiveness of the warehouse organization.

Apart from the costs, the simulation also captures other indicators that reflect operational efficiency. The KPIs, their respective function and values within the simulation of the current situation are presented below. The KPIs are also used in the other models of the potential solutions, enabling comparative analysis of the different situations.

5.1 Experimental setup

To obtain the values, the model undergoes multiple observations. To calculate the values, the model is ran one hundred times and the confidence interval is set to 95%. The runtime duration of the model spans three months. So the values of the KPIs are averages of many observations. It is important to note that each observation utilizes distinct random seeds, ensuring variability across iterations. The goal of these values is not to simulate the current situation of the warehouse with maximum accuracy. These values are a result of a simulation model that is made with an accuracy that was reachable in the timeframe. However, the base values like the number of deliveries per day are in line with reality and are considered credible by the SMEs. The strength of the values lies in the comparison that is made possible with the other potential solutions. In order to take account for the start-up period, the model is initialised with a given number of products in the shelves. Appendix F shows the boxplots of the values of the indicators.

5.2 The indicators

nProducts
The variable "nProducts" functions as a simulation counter, incrementing each time a product enters the warehouse. While this variable is not directly indicative of the warehouse's effectiveness, it plays a crucial role in calculating other KPIs that evaluate averages.

nCarry
This indicator is again a counter that is used to calculate the average carrying time. When a worker starts carrying a product, this counter is incremented by one. This counter is used for the calculation of the average carry time.

AvgInboundTime
The KPI "AvgInboundTime" quantifies the average duration that a product remains in the inbound zone. This duration is recorded from the moment a product enters the inbound deck until it is stored. The corresponding average value is continuously updated based on these recorded durations. In the current situation, this value is :

Table 3 The average inbound time of the current situation

Experiment	root.AvgInboundTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	1:26:57.5001	8:15.1530	1:05:56.4363	1:45:16.2599	1:25:19.2286	1:28:35.7715

After three months of simulation, the average time a product spends in the inbound zone is one hour and twenty six minutes. The maximum and minimum times do not deviate too much as the boxplot shows graphically in Appendix F

AvgOutboundTime
Conversely, "AvgOutboundTime" represents the average time a product spends in the outbound shelf. It measures the duration from when a product is placed in the shelf for ordered items until it is retrieved from the warehouse. The average value is updated accordingly. Current situation values are as follows:

Table 4 Average outbound time of the current situation

Experiment	root.AvgOutboundTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	7:00:34:01.9805	16:03:42.6062	5:16:31:10.0180	8:14:17:33.8672	6:21:22:46.1140	7:03:45:17.8471

The time a product spends in the outbound zone varies considerably. The average time a product waits for dispatch is seven days. As is the case in the real situation, a product often has to wait before the customer can pick it up.

AvgCarryingTime
The KPI "AvgCarryingTime" reflects the average time required for each carrying operation, encompassing movements from the inbound area to storage, storage to production, and the other processes in the warehouse. The duration is recorded each time a product is carried and subsequently placed in a different location. This indicator is especially crucial for testing the different layouts. The value of the current warehouse is:

Table 5 Average time of carrying operations in the current situation

Experiment	root.AvgCarryingTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	10.3147	0.2158	9.9478	11.2073	10.2719	10.3576

This indicator shows a precise average value with little deviation. This is due to the fact that the carrying operations have pre-determined destinations. The time of a carry operation is not long, because the simulation does not model the use of forklifts. This is also the case in the other models, therefore the different models can still be compared.

OccupationInbound
The "OccupationInbound" KPI indicates the occupation of the inbound area as a percentage. It assumes a predefined capacity of the inbound zone, accommodating ten pallets of products. Calculation involves dividing the actual number of products present in the inbound zone by the designated capacity. This value is updated in real-time, therefore it is used to calculate the next indicator, "AvgOccupationInbound".

AvgOccupationInbound
To facilitate comparative analysis between different situations, the "AvgOccupationInbound" indicator calculates the average occupation of the inbound zone. While the real-time occupation value reflects the ongoing occupation, the average indicator is periodically updated using these real-time values. The current value for this situation is as follows:

Table 6 The average occupation of the inbound deck

Experiment	root.AvgOccupationInbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.448628942608011	0.0169088604717803	0.402851435493521	0.489514424529727	0.445273095495318	0.451984789720705

The occupation of the inbound deck is around 45% on average. This is close to the actual situation in the warehouse.

OccupationOutbound
Similar to the "OccupationInbound" KPI, "OccupationOutbound" signifies the occupation of the outbound area as a percentage. The capacity of the outbound zone corresponds to the shelf space dedicated to storing collected orders. When the shelf reaches its full capacity, products are subsequently transferred to the aisles. This value is updated in real-time, therefore it is used to calculate the average value.

AvgOccupationOutbound
This indicator calculates the average occupation of the shelf area destined for the outbound orders. It calculates the average in the same way as the other value, when the real time value of the occupation is calculated, the average is updated with this value.

Table 7 Average occupation of the outbound zone

Experiment	root.AvgOccupationOutbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.339213436254999	0.0460531943816224	0.17125917498879	0.431557055598901	0.330073406999106	0.348353465510891

The occupation of the outbound shelf contributes to around 34%, however the deviation is considerable. Appendix F shows the boxplot of the average occupation. In figure 37 the deviation is more observable.

NProductsAisles
This real time value holds the number of products that are in the aisles. When this value exceeds six, the products are transported and costs are incurred. This is a crucial indicator of the simulation, as we strive to minimize this value. In the solution option with the extra warehouse, the products are moved to the other warehouse.

AislePenalty
Every time a product is placed in the aisles, a penalty of €100 is incurred. This value holds the total amount of penalty that has been given during the runtime of the simulation. Consequently,

the total amount of products that are placed in the shelves can also be deduced from this KPI. Because products are also placed in the aisle when a product cannot be stored in the shelf, it shows when parts of the warehouse become full. The value of this KPI is:

Table 8 The Aisle Penalties of the current situation

Experiment	root.AislePenalty	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	33432	3880.77051601609	25400	41600	32661.7959668581	34202.2040331419

In the simulation duration, around 334 products have been placed in the aisles. This amounts to about four products per day. This penalty is also included in the total costs indicator.

NDeliveriesDay
The "NDeliveriesDay" indicator serves as a counter, primarily utilized to regulate simulation operations. However, it holds limited significance when evaluating different warehouse solutions.

TotalCosts
The "TotalCosts" variable represents the cumulative costs associated with warehouse operations. It encompasses external rent costs, transport and handling expenses, as well as aisle penalties. This KPI provides a comparative metric for assessing different warehouse approaches. The current value for the situation is as follows:

Table 9 Total costs of the current situation

Experiment	root.TotalCosts	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	100323.1768	5385.04032689522	89199.13	111660.87	99254.4251793388	101391.928420661

ExternalRentCosts
To keep track of the rent costs, this indicator is used. Every month, the rent costs of all the external locations are added to this variable. These costs are constant and will be the same for the situations where the external warehouses are used. Because the runtime is whole number of months, the rent costs are added monthly. During the runtime of the experiments, the rent costs accumulate to €54.003.

ExternalTransportHandlingCosts
The "ExternalTransportHandlingCosts" variable captures the costs associated with transportation and handling when products are dispatched to external locations. These costs are incurred based on real values. The current value of this indicator in the model is:

Table 10 Transport and handling costs of the external locations

Experiment	root.ExternalTransportHandlingCosts	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	13029.786	1516.85934970911	9896.04	16257.78	12728.7398072315	13330.8321927685

5.3 Summary

In this section we have calculated the KPIs for the current situation. These are calculated by letting the simulation run for a runtime of 3 months. This is done for a total of 100 observations, to ensure that the values converge to values within 95% confidence interval. he identified KPIs deemed crucial for evaluation are presented in tabular format, and graphical representations in the form of box plots are provided in Appendix F. The KPI values obtained possess credibility and can be effectively employed for evaluation purposes based on comparing them to their values in reality. Subsequently, the following section will outline potential solutions that will be compared against the existing system.

6 What are possible solutions to improve the current warehouse situation?

In this section, we provide a more detailed analysis of the potential solutions under consideration. As previously mentioned, the potential solutions being examined in this research are the implementation of a horizontal layout, a fishbone layout, and the introduction of a new warehouse. The simulation model of the current warehouse organization is adapted to model the potential solutions accordingly. Other than the necessary changes of the system, no other changes have been made regarding the product flow, the KPIs and the measuring of these KPIs. For every solution option, we discuss the changes made, the expected results based on literature and we discuss the actual results from the simulation. We run the models for the same runtime and for the same number of observations.

6.1 The horizontal layout

The horizontal layout with a cross aisle incorporated in the warehouse of Pentair is graphically described in Figure 11, appendix A3. Notably, three additional storage shelves have been introduced to accommodate products, albeit with reduced length of the shelves. The smaller storage areas are incorporated in the capacity of the shelves in the simulation. Certain storage areas use both sides of the shelf due to their proven activity, including the spaces B, D, L and J. The storage areas are divided over the space similarly to the current layout, as this minimizes the travelling time. Furthermore, the orders that are ready for dispatch have their own shelf and the storage space that was used for the orders in the current warehouse serves now as extra storage space. When products cannot be stored in their destined shelf, the simulation assesses whether it can be stored in the 'extra' storage area. If not, it is relocated to the aisles. Next to these changes, the footpaths of the workers are also changed in the simulation. Importantly, no other changes have been made to the code or the product flow, ensuring that the situations can be effectively compared.

6.1.1 Expectations of the horizontal layout

An important change in the horizontal layout is the introduction of a cross-aisle. Based on earlier studies in the literature (Altarazi, 2017), this should enable the workers to reach their destination quicker. For all the five product flows, we expect the handling to be done quicker, because the cross aisle is located close to the inbound, outbound and the production. The travel distance is often considered as the primary objective in warehouse design and optimisation (Koster et al., 2007). Short travel distances translate to a shorter inbound process and flexible order picking. Figure 4 below shows the percentage of an order picking's time that is used for travelling.

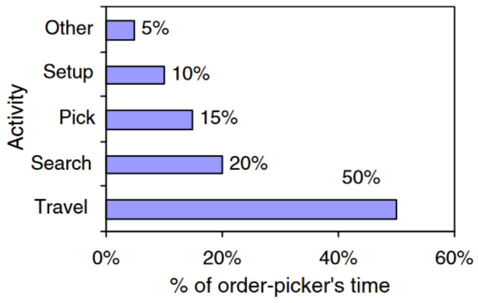

Figure 4 Distribution of an order picker's time (Tompkins et al., 2003)

Regarding the storage space, we expect some drawbacks. The shelves C up to H are considerably smaller in size, which could result in more products in the aisles, even though there is an extra shelf space.

6.1.2 Results of the horizontal layout

Appendix G shows the results of the horizontal layout, with the values of the KPIs in the tables and in box plots. Firstly, the average carrying time is not entirely as expected (Table 17). The minimum value of the carrying time is two seconds smaller and a considerable amount of averages are lower than the average carrying time of the current layout, however there is a larger variation with the maximum recorded carrying time. The maximum is 44 seconds. But looking at the box plots, this is an outlier. The interquartile range of the box plot is between 10.9 and 14.42 seconds. The current layout proves to be more consistent with interquartile range being on ten seconds.

A positive result for the horizontal layout is the average occupation of the outbound shelf, which shows a fraction of the occupation of the current layout in Table 22. This is due to the fact that the outbound shelf is changed to another shelf. The average occupation of the inbound is the same as the current layout.

However, a negative consequence of the horizontal layout is that more products are stored in the aisles. This results to an increase of 68% in the total costs, as Figure 5 shows. As expected, Pentair needs the storage capacity in its warehouse to store its products effectively. In the horizontal layout, products are placed in the aisles on average 47% more than in the current layout. Even with the extra shelf space, we can conclude that the capacity the horizontal layout provides is not enough for Pentair.

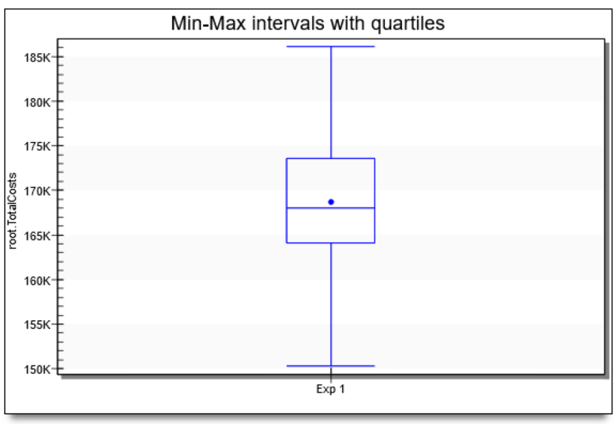

Figure 5 Total costs of the horizontal layout

6.2 The fishbone layout

In Appendix A4, Figure 12 illustrates the fishbone layout employed in the Pentair's non-rectangular warehouse. Due to the unique shape of the warehouse, modifications were made to accommodate the fishbone layout within its dimensions. Similar to the horizontal layout, specific storage shelves were shortened, and the pathways for the workers were altered. Moreover, the fishbone layout encompasses a greater number of shelves compared to the current arrangement, resulting in additional storage shelves located in the top left section of the warehouse to prevent the need for aisle placement. Notably, certain storage spaces utilize multiple shelves, such as C, D, E, F, O, and P. Furthermore, the shelf designated for finished orders has been relocated to a larger shelf space. In conjunction with these alterations, the horizontal storage shelves of A and P have been relocated to vertical storage shelves.

6.2.1 Expectations of the fishbone layout

The fishbone layout is a non-traditional layout that was designed to decrease the traveling distance in a warehouse. According to Gue and Meller (2009), the fishbone layout could offer 20% reduction in the expected travel distance. This is made possible due to the diagonal main aisles that make the distance between the pickup and deposit point (P/D Point) and the item to be picked smaller. The savings that can be achieved by implementing a fishbone layout depend on certain factors. In the research of Cardona et al. (2012) these factors are described: the effects depend on the storage policies, the number of P/D points and the slope of the dimensional aisle. Only in a system which uses different storage policies in a manual order picking system, could the fishbone system prove detrimental (Cardona et al. 2012). In a system with one storage policy, they found that the fishbone layout could decrease the travel distance by 18%.

Regarding the storage space, we expect less disadvantage than the horizontal layout. Especially the shelves that store the large crates, have more shelf space than in the horizontal layout.

6.2.2 Results of the fishbone layout

The results of the fishbone layout can be found in Appendix H. Following the expectations, the average carrying time is decreased by a substantial amount. The average carrying time is 8.16 seconds as Table 31 in appendix H shows. This is a decrease of 21% in comparison with the value in the current situation. The maximum recorded average carrying time in the fishbone layout is still smaller than the left interval bound of the carrying time in the current layout. The boxplot of the average carrying time, Figure 6 below, shows that there is no large variance in the values either.

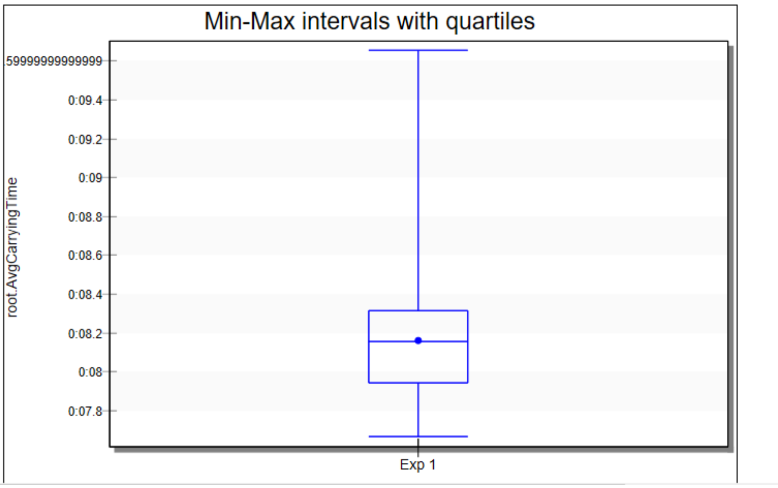

Figure 6 Average carrying time in the fishbone layout

The average durations in the in- and outbound zones are similar to the durations in the current layout. The average occupation of the inbound is also similar. The average occupation of the outbound is considerably higher on the other hand. As Table 36 in appendix H shows, the occupation is almost double of the occupation in the current layout. Moreover, when looking at the boxplot of the real time values, the "OccupationOutbound" is at times at maximum capacity. This proves to be the largest drawback of the fishbone layout.

The total costs of the fishbone layout are a bit higher, but not by a large margin. The average value of the experiments show a 2% increase in the total costs. This is a direct results in the similarly increase in the number of products that are placed in the aisles. However, this is not much when compared to the increase in costs with the horizontal layout.

6.3 The new warehouse

In this particular alternative, the simulation model has undergone additional modifications beyond those implemented in the previous solution options. To accommodate the inclusion of a second warehouse in the model, a new model frame has been incorporated and interconnected with the original frame. This integration facilitates the seamless movement of products between the two warehouses. As mentioned previously, the product flows that move to the new warehouse are 10% of the inbound and the orders and finished products that cannot be stored. This prevents the products from being placed in the aisles. Another important change in this solution is that the external warehouses are not used anymore due to the added capacity of the new warehouse. The new warehouse has the same layout as the current warehouse. Moreover, the new warehouse calculates the same KPIs for the processes occurring in the new warehouse.

6.3.1 Expectations of the introduction of the new warehouse

It is widely recognized that the expenses associated with holding products in rented warehouses surpass those incurred when utilizing owned warehouses. Rented warehouses encompass various costs, including storage fees, handling charges, warehouse maintenance expenditures, and transportation expenses. Additionally, the decentralization of inventory in rented warehouses can result in prolonged order preparation times, leading to increased operational delays (Rastogi et al., 2017).

A study conducted by Huq et al. (2006) reveals that the introduction of an additional warehouse can significantly reduce delivery lead times, thereby elevating the overall service level, without incurring substantial supplementary costs. In the case of Pentair, the elimination of external warehouses implies the elimination of rental, transport, and handling costs. Consequently, these factors no longer pose a concern in the present situation. However, the principal costs in this scenario stem from the investment required for the establishment of the new warehouse, which has been estimated at €3.500.000,- based on the calculation tool provided by BMVV (2023).

Furthermore, we anticipate that the average occupancy of the inbound and outbound zones will decrease, and there will be a complete absence of products within the aisles. However, it is expected that the average carrying time will increase due to the transportation of certain products to the alternate warehouse.

6.3.2 The results of the introduction of the new warehouse

The results of the model with the new warehouse can be found in appendix J. Because both warehouses calculate their own KPIs, some KPIs are discussed for both warehouses. Similar to the expectations, the average occupation of the inbound has decreased. Namely with a decrease of 18%, as Figure 7 below shows.

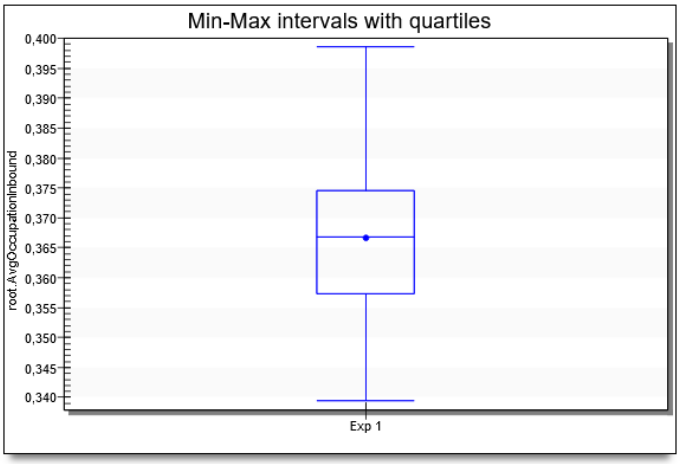

Figure 7 Box plot of the average occupation of the inbound section

The occupation of the inbound deck of the new warehouse is also considerably smaller with an average occupancy of around 15%. Also, the occupation of the outbound is greatly reduced. The average occupancy of the outbound section is 9%, with maximum values reaching 23%, as Figure 8 shows below.

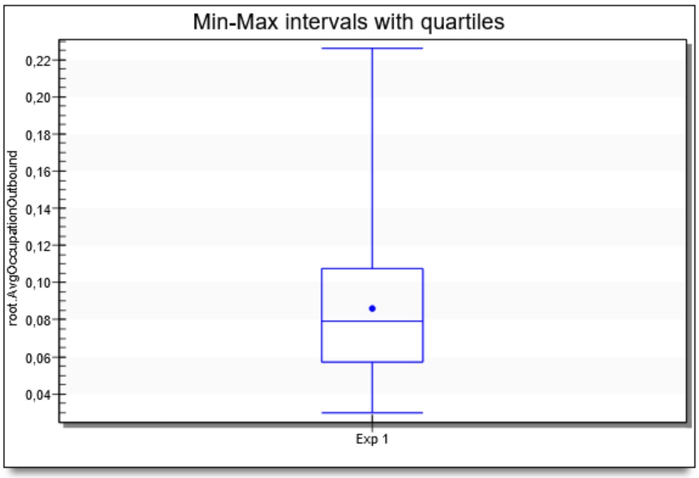

Figure 8 Box plot of the average outbound occupation

Moreover, the objective of having no products in the aisles is achieved. During the runtime, the products could always be stored in the new warehouse and no products were placed in the aisles in both of the warehouses. The time products spend in the inbound section is similar to the current situation in the main warehouse, but in the new warehouse the average time a product spends in the inbound deck is shorter with an average value of 48 minutes (Table 52 in Appendix I). Furthermore, this solution option has no costs concerning the external warehouses.

On the other hand, there are also KPIs that do not perform better than the current situation. The average carrying time is longer by around 15% in the main warehouse and in the new warehouse the average carrying times are increased by more than six minutes as the tables show below.

Experiment	root.AvgCarryingTime
Exp 1	11.9009

Table 11 Carrying time main warehouse

Experiment	root.Test.AvgCarryingTime
Exp 1	6:32.6924

Table 12 Carrying time in new warehouse

This is due to the carrying that is done between the two warehouses. When a product is in the main warehouse and cannot be stored in the shelves, it will be carried to the new warehouse where it will enter the inbound. Moreover, to operate the new warehouse, more warehouse employees should be hired. The introduction of the new warehouse also results in a longer outbound time for the products. Certain finished products enter the outbound zone of the main warehouse where they then are stored in the new warehouse. This is also partly due to the workings of the simulation, where finished products are earlier picked from the main warehouse. This is a result of assumption 10 in section 4.1.7.

6.4 Summary

In this section, the outcomes of various potential solutions considered in this research are presented. The simulation model was executed over a duration of three simulated months, repeated one hundred times to obtain the results.

The implementation of the horizontal layout did not yield the anticipated reduction in average carrying times. Despite improvements observed in outbound occupation, this layout led to a significant 68% increase in total costs. This cost escalation was attributed to the increased presence of products occupying the aisles.

In contrast, the fishbone layout demonstrated more favourable results. It achieved a noteworthy 21% decrease in average carrying times. However, the implementation of this layout resulted in a considerable increase in outbound occupancy and a marginal 2% rise in total costs.

Furthermore, the introduction of a new warehouse in the model produced beneficial outcomes. For instance, it resulted in an 18% decrease in average occupancy within the inbound zone. Similarly, the average occupation of the outbound zone exhibited a significant decrease, with no products occupying the aisles. The added capacity of the new warehouse proved sufficient. However, this solution entailed 15% longer carrying times in the main warehouse and considerably increased time spent in the outbound zone. Also the new warehouse comes with a large sum of investment costs, while it saves on the costs of the external locations.

Based on these findings, the subsequent section will select the optimal solution among the evaluated alternatives.

7 What is the optimal solution?

This chapter discusses the final trade-offs among the solution options and identifies the optimal solution for addressing the issues faced by Pentair X-Flow. Additionally, the conclusion is formed. The following section outlines the solutions compared to the current model. When KPIs of a proposed solution have similar values to the current situation, these results are taken as neither advantageous or disadvantageous. The results of the solution options are summarized in Table 13 below.

7.1 The optimal solution

Based on the findings from Chapter six, it can be initially concluded that the horizontal layout is not suitable for the warehouse of Pentair X-Flow. The horizontal layout offers insufficient storage capacity and leads to a significant increase in total costs, specifically a 68% increase. Despite this increase, it only reduces occupation in the outbound section and fails to fulfil Pentair's objectives of achieving lower occupancy in the inbound section and keeping the aisles free of products. Additionally, external locations are still required under this solution option.

On the other hand, the fishbone layout provides more favourable outcomes. It results in a 21% decrease in average carrying times. However, the average occupation of the outbound deck experiences an 87% increase, and there is a 2% rise in total costs. In terms of other KPIs, the fishbone layout performs similarly to the current warehouse organization. There are still significant product placements in the aisles, and the average occupation of the inbound section remains high.

Table 13 demonstrates that the introduction of the new warehouse offers the most advantages and aligns with all of Pentair's objectives. It reduces the average occupation of both the inbound and outbound sections, eliminates product placements in the aisles, and decreases inbound duration in the main warehouse. Moreover, the capacity of the additional warehouse proves sufficient, eliminating the need for costs associated with external warehouses. The new warehouse effectively addresses all the identified problems in this study without major trade-offs. The average carrying times are increased, but this could be expected when adding a new warehouse. Consequently, it is selected as the optimal solution. However, the implementation of the new warehouse requires a substantial investment, and the return on this investment is detailed in the following section.

Table 11 The advantages and disadvantages of the different solution options

Solution option	Advantages	Disadvantages
Horizontal layout	- Considerable decrease in the average outbound occupation due to a larger order shelf.	- Increase frequency of aisle placement of 47%, resulting in an increase of total costs of 68% - Longer average carrying times, with more variation in the durations

		- External warehouses still in use.
Fishbone layout	- Decrease of 21% in the average carrying times.	- Increase of 87% in the occupancy of the outbound deck. - An increase of 2% in the total costs. - External warehouses still in use.
Extra warehouse	- No products in the aisles. - Decrease of 18% in average inbound occupation. - Decrease of 73% in the average outbound occupation due to the storage in the extra warehouse. - Shorter inbound time in the new warehouse. - Centralized inventory - No external warehousing costs.	- Investment costs of the new warehouse - Longer carrying times, especially to the new warehouse - More warehouse employees needed

7.2 Conclusion

This research aimed to improve the warehouse organization of Pentair X-flow, with emphasis on the profitability of the addition of a new warehouse. Additionally, different layouts were tested to study whether the warehouse problems could be improved without the investment of a new warehouse. To study these potential solutions, simulation models of the current system, of different layouts and a model including a new warehouse were made. These models were then compared with each other. The main research question in this research was:

How can the current warehouse system at Pentair X-flow be improved by changing the warehouse organization?

In order to answer this question, firstly we needed an overview of the problems in the warehouse, including the relationships between these problems. The current situation was studied to identify these problems. We observed the product flows and interviewed the warehouse employees. Secondly, the findings were related to the literature in the theoretical framework, where we focused on warehouse management theory and on how simulation studies should be performed. Next, we used the literature to build the model of the warehouse system. We gathered the data, found the probability distributions, and built the model by following the steps of Robinson (2014). We made the conceptual model, studied the logic flows and described the workings of the simulation. The validity and reliability of the simulation were secured during the development of the model.

After the model was built and the validity approved, the simulation model of the current situation was executed. The average values of the KPIs were reported. Subsequently, the models of the potential solution were run for the same duration and with the same initial values.

Ultimately, the pros and cons of the different solution options were compared and the main research question could be answered as follows. The warehouse system at the company can best be improved by adding an extra, self-owned warehouse to the warehouse organization. This warehouse can effectively replace the four rented warehouses, saving on the rent, handling and transportation costs. By adding this warehouse close to the main warehouse, the inbound and outbound sections are relieved of congestion. Moreover, products do not have to be placed in the aisles. With this decision, the problems in the current warehouse system are solved. The other solution options that considered changing the layout did not provide the necessary improvements. They could not eliminate the occurrence of product in the aisles and the inbound zone had the same level of occupancy.

The final section outlines a brief implementation of this solution and provides an estimate of the return on investment.

8. How to secure a successful implementation?

In this section, we firstly discuss the time it would take to return on the investment of the construction of the new warehouse, based on the cost values of the simulation. For the construction costs, we hold on to the estimate of €3,5 million (BMVV, 2023). Additionally, we give recommendations on the implementation.

8.1 How long will it take for Pentair to return on the investment?

With the use of the external warehouses, two types of costs are relevant: the constant rent costs and the variable costs, including the transport and handling costs. The latter is contingent on the frequency of product transportation. Based on the simulation model reflecting the current scenario, the estimated transport and handling costs over a three-month period amount to €13.029,79, resulting in an average monthly value of €4.343,26. Additionally, the monthly rent costs for the external warehouses sum up to €18.001,03, leading to a total monthly cost of approximately €22.344,29.

To assess the return on investment, the construction costs are divided by the monthly costs of the external locations, indicating that the investment will be recouped in a span of thirteen years. Nevertheless, it is essential to note that this calculation solely takes into account the cost savings achieved by employing external locations. Notably, there is a potential for accelerated return on investment if Pentair can leverage the additional storage to increase their production capacity. However, this aspect falls beyond the scope of the present research, and a comprehensive analysis of such production capacity improvements would require a separate investigation.

8.2 Recommendations

In this section, we aim to present several recommendations concerning the introduction of the new warehouse. These recommendations serve to make the transition to the improved warehouse organization as smooth as possible.

8.2.1 During construction

Firstly, during the construction of the new warehouse, we recommend to keep the external warehouse locations. Because the added capacity of the new warehouse is not ready, the external locations are still needed for their storage. Moreover, the main warehouse should remain to be accessible for transport, to prevent hindrance in logistics near the warehouse.

8.2.2 Warehouse design and operations

Additionally, ample time should be reserved for considering the optimal layout of the new warehouse. The layout should make smooth product flow from one warehouse to another possible. To decide on this, a clear overview of the operations and the type of inventory to be stored in the new warehouse is needed. We recommend to store those products that stay in the warehouse for longer durations in the new warehouse. For example, finished products that are ready for outbound. Regarding the layout, we recommend a traditional layout that prioritizes capacity, but with a spatial inbound zone to ensure enough space to handle the products efficiently.

8.2.3 Collaboration and Communication

Furthermore, we recommend to uphold effective communication and collaboration between the Pentair's current and newly constructed warehouses. Ensuring a seamless information flow that will enhance the coordination and prevent disruptions in the supply chain. To achieve this, we recommend to train the workforce in effective collaboration between the two warehouses.

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10. Appendices

Appendix A1- Current layout of the warehouse with product locations

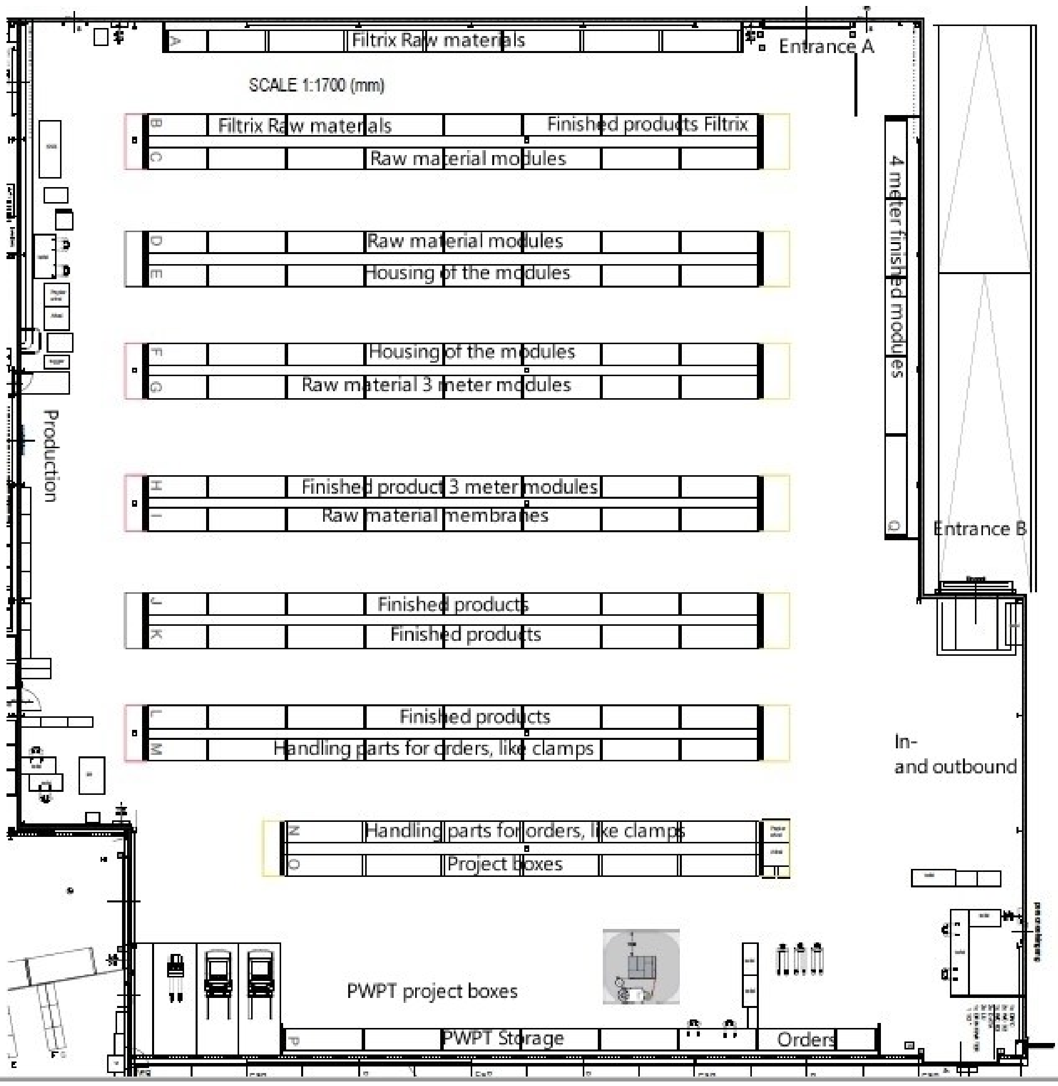

Figure 9 Layout of the warehouse with details

Appendix A2 – Measurements of the warehouse

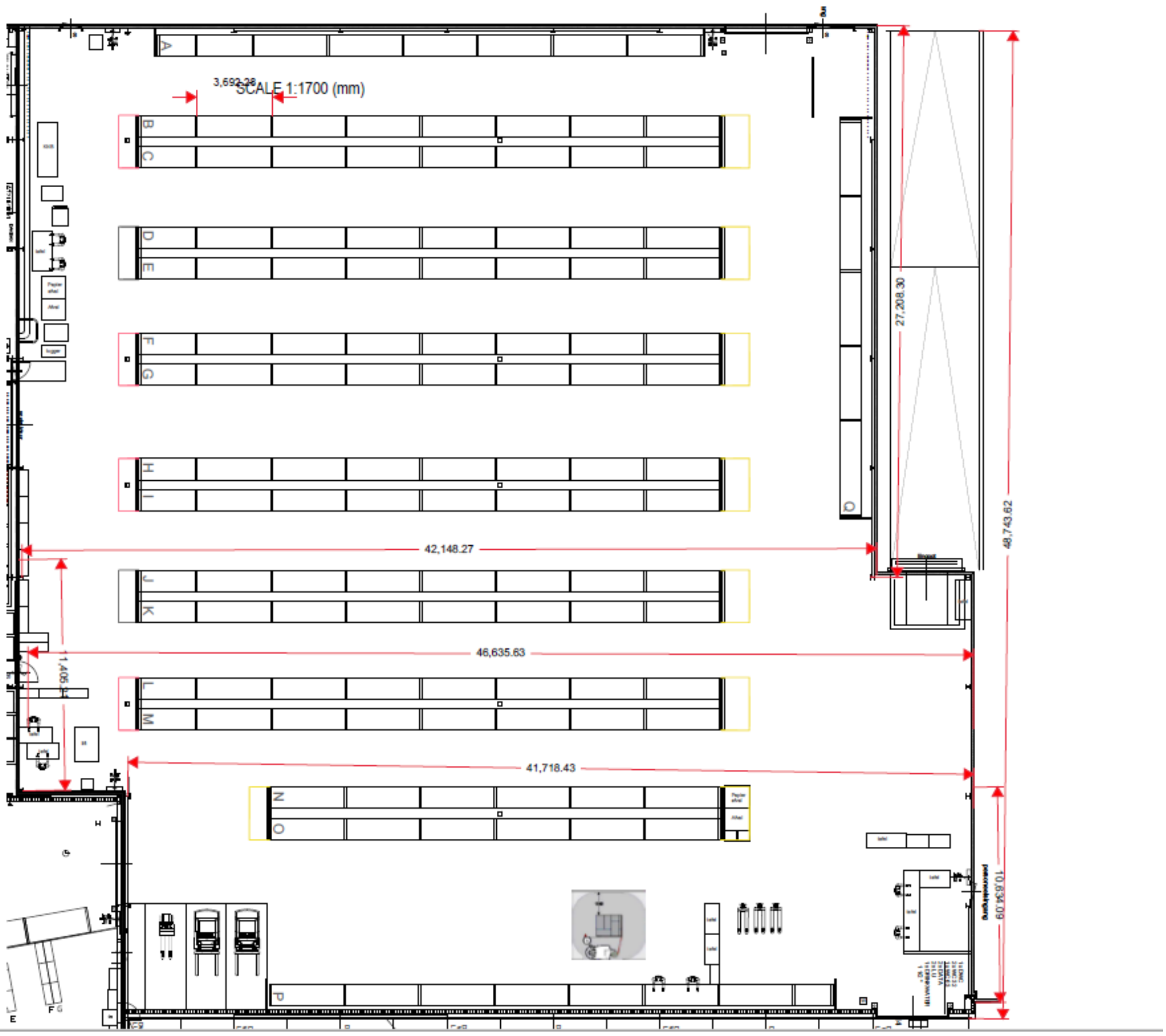

Figure 10 Warehouse with measurements

Appendix A3- Horizonal layout with a cross-aisle

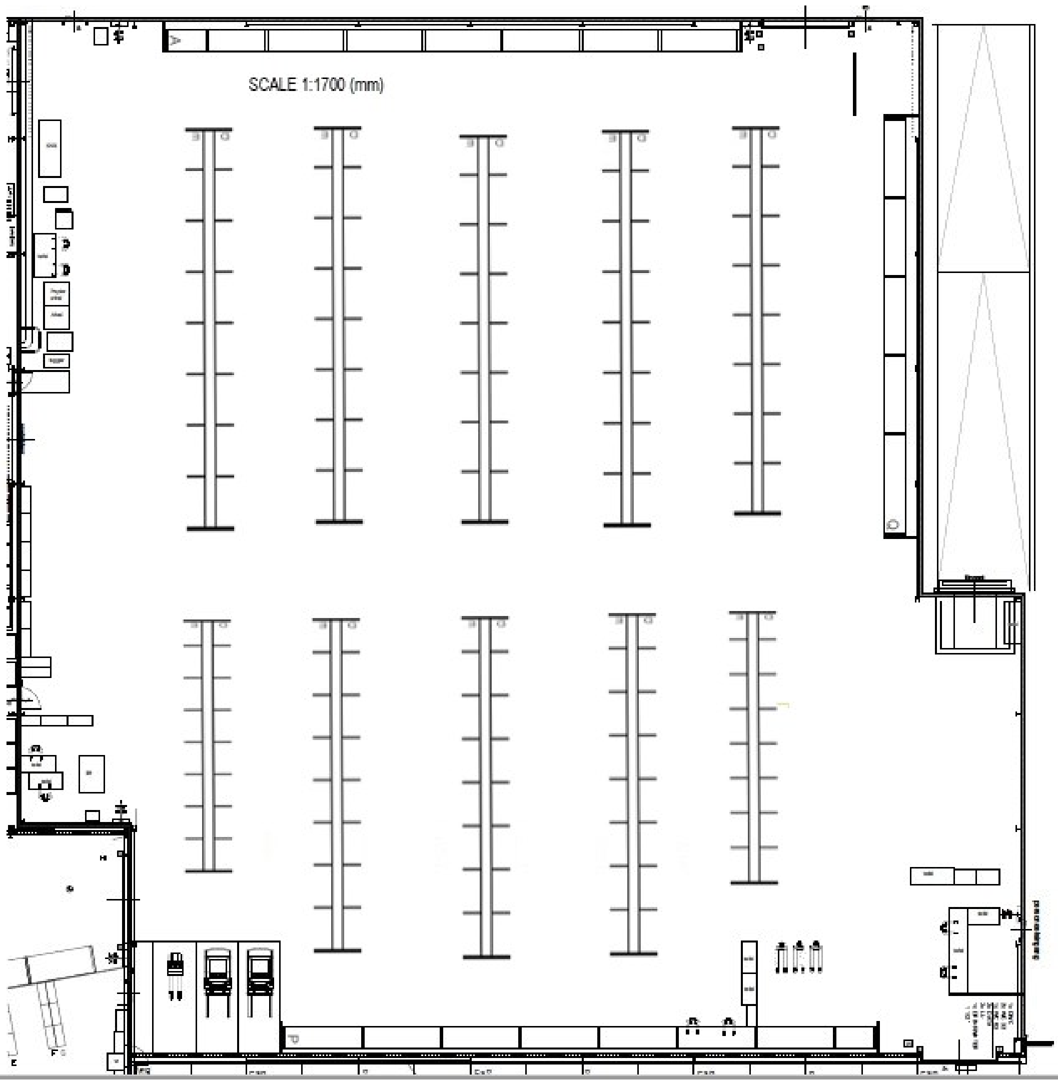

Figure 11 Horizontal layout orientation of the warehouse

Appendix A4- Fishbone layout

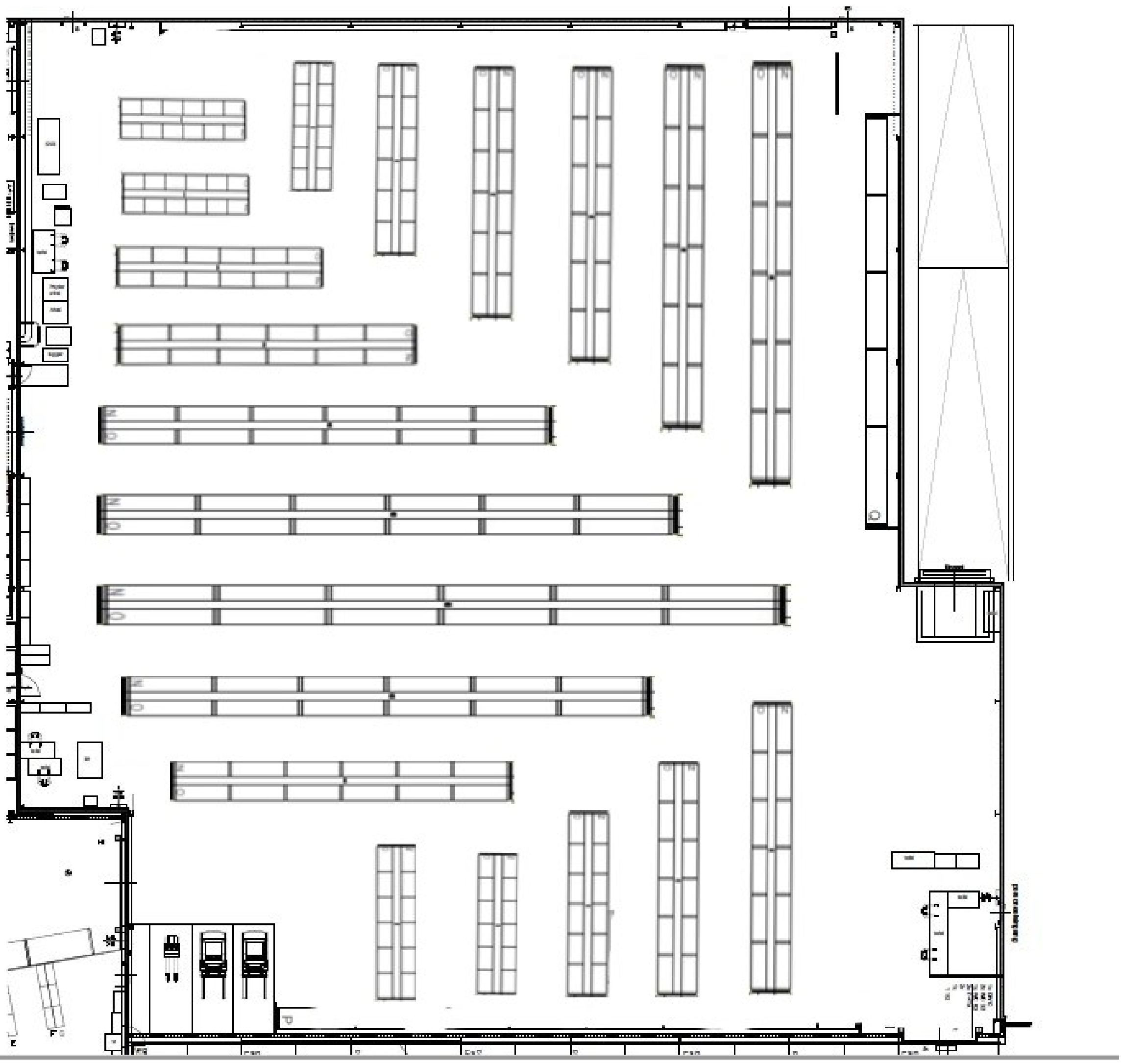

Figure 12 Customized fishbone layout

Appendix B

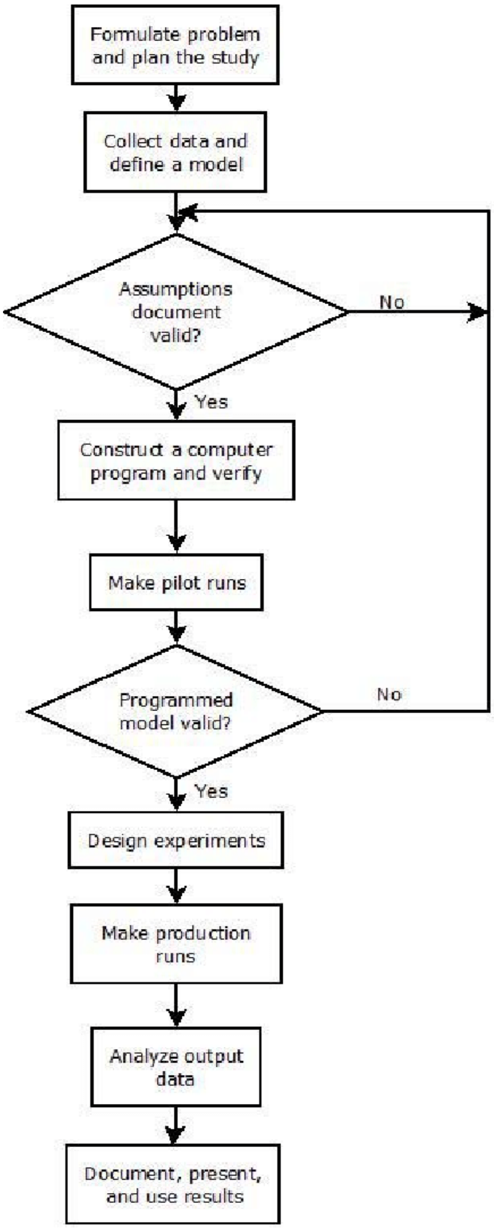

Figure 13 Steps to be taken in a sound simulation study (Law, 2015)

Appendix C1 – Distribution of deliveries

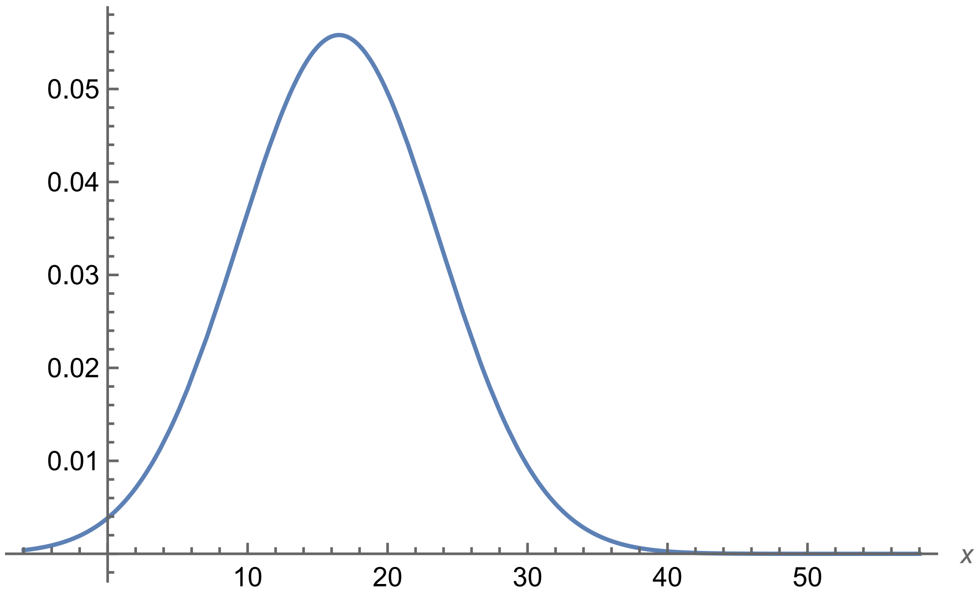

Figure 14 Frequency of number of unique deliveries per day. Normal distribution (16.5324, 7.1489)

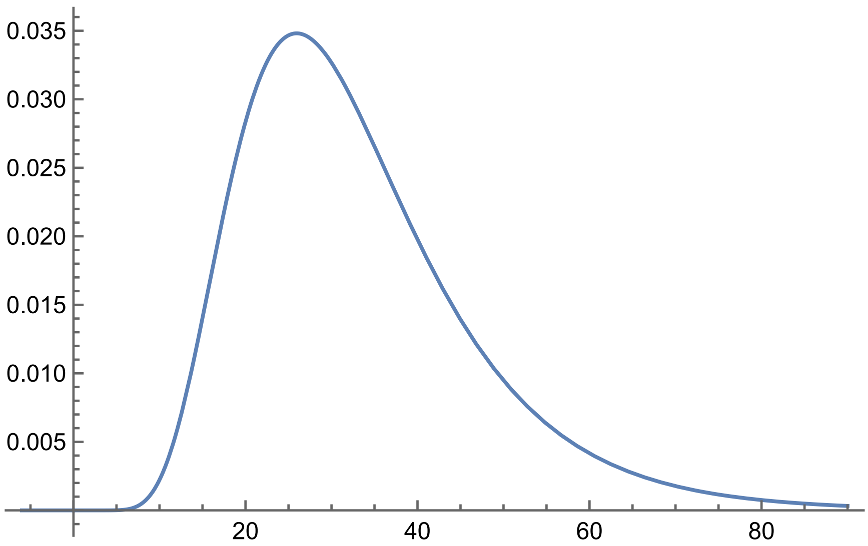

Figure 15 Distribution of the average inter-arrival times per day in minutes. LogNormal distribution (3.421522, 0.4065672809)

Appendix C2 – Distribution of bookings to production

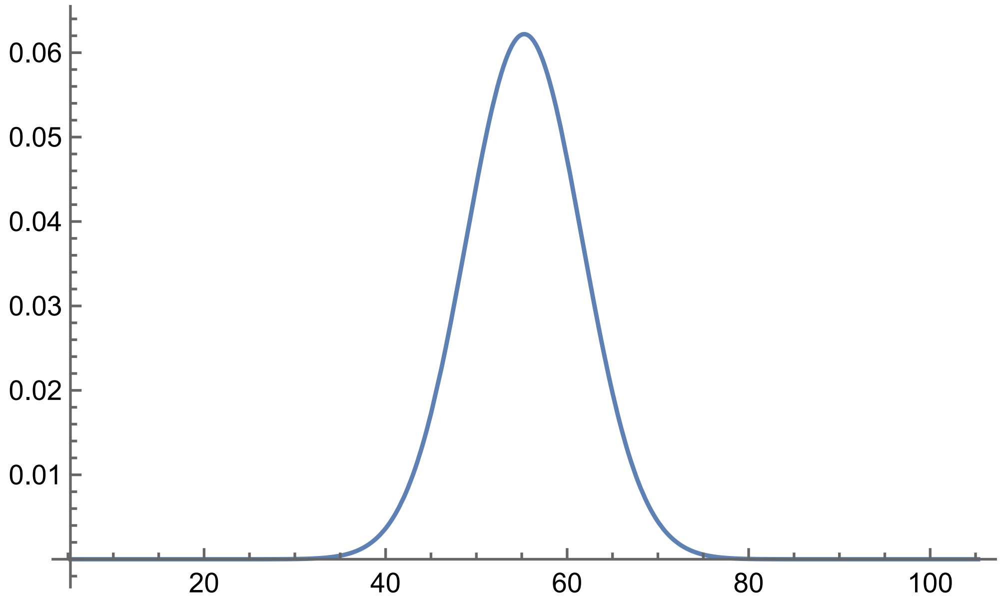

Figure 16 Frequency of number of unique bookings going to production per day. Normal distribution (55.2743, 6.4147)

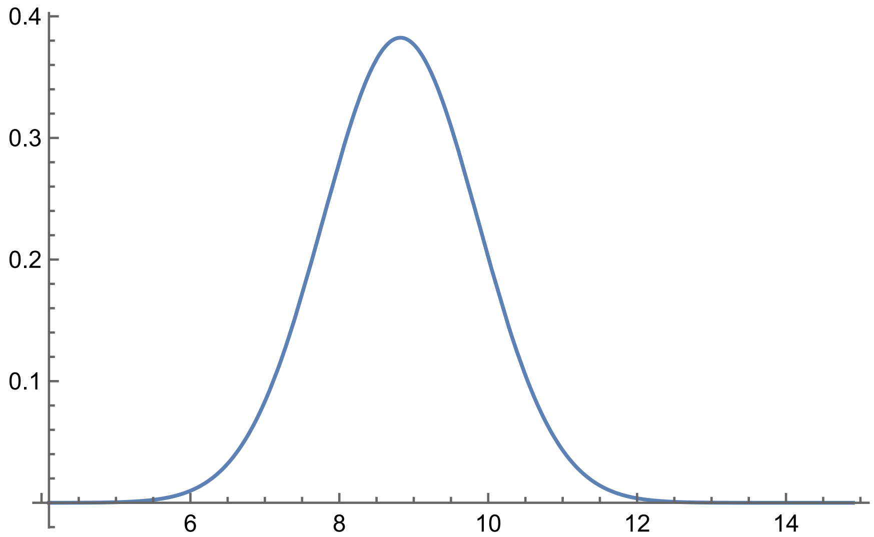

Figure 17 Distribution of average time in minutes between bookings. Normal distribution (8.82172, 1.0432743)

Appendix C3 – Distribution of booking from production to warehouse

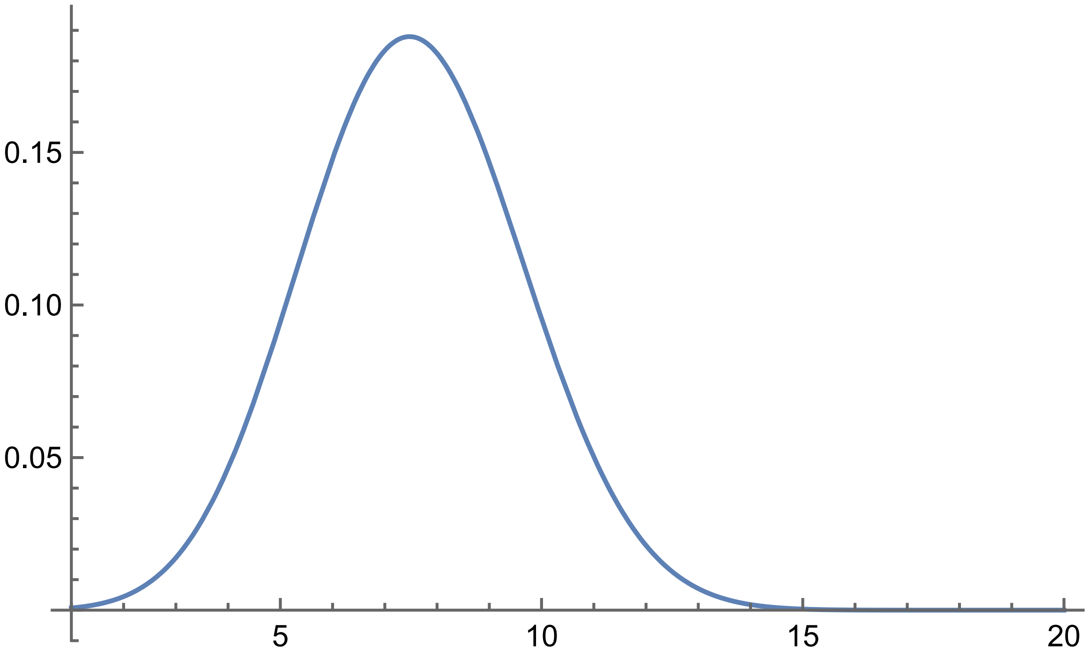

Figure 18 Frequency of unique product orders per day. Binomial distribution (18, 0.419753)

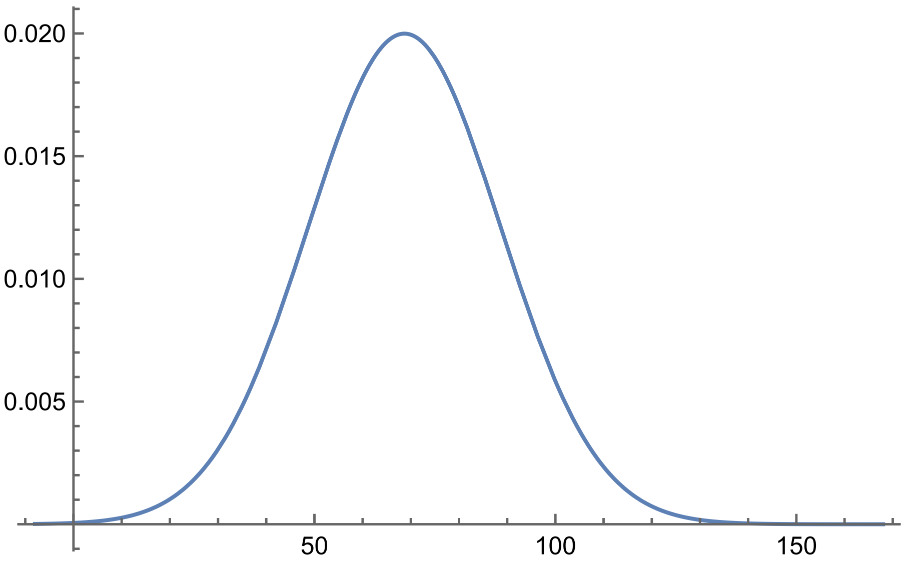

Figure 19 Distribution of the average time in minutes between bookings. Normal distribution (68.67608, 19.95463)

Appendix C4 – Distribution of orders

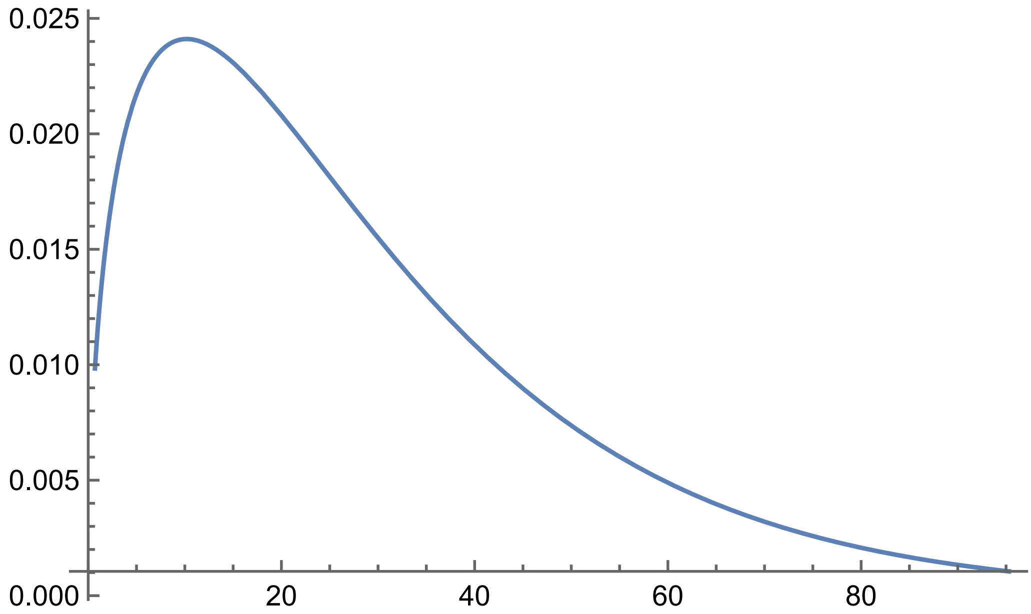

Figure 20 Frequency of unique orders per day. Gamma Distribution[1.5128, 19.8906]

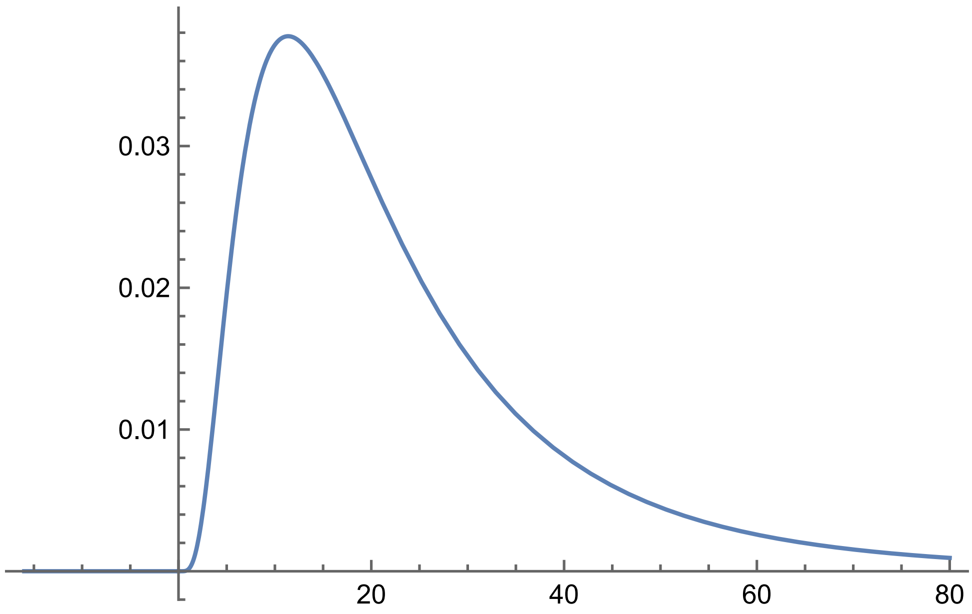

Figure 21 Distribution of inter-order time in minutes. LogNormal distribution (2.94698, 0.717853)

Appendix D – The model's scope and level of detail

Table 14 Model scope

Component	Include/Exclude	Justification
Entities:		
Deliveries	Include	The flow of products entering warehouse
Order	Include	The flow of products leaving warehouse
Production products	Include	Raw materials flowing to production and returning as finished products
Activities:		
Unpacking	Include	Process on inbound deck
Transporting in warehouse	Include	Moving products from one place to another
Unloading	Exclude	Not related to flow in warehouse
Packaging	Exclude	Not related to flow in warehouse.
Order picking	Include	Collecting products for an order
Production	Exclude	Not related to warehouse process
Quality control	Include	Checking inbound goods
Updating/ checking SAP	Exclude	Not related to warehouse process
Vehicle routing between warehouse	Exclude	Is outsourced
Queues:		
Inbound queue	Include	Waiting time for the reception of goods
Outbound queue	Exclude	Simplification: negligible waiting time
Aisle queue	Include	With this we mean the placement of products in the aisles.
Resources:		
Warehouse employees	Include	Regular employee handling the products in the warehouse
Quality control	Include	Warehouse employee that can do quality inspection
External warehouses	Include	External warehouse that store additional products
Extra self-owned warehouse	Include/Exclude	In one option it is added, in the other option it is not

Table 14 Model level of detail

Component	Detail	Include/Exclude	Justification
Entities:			
Deliveries	Quantity: one entity represents one box	Include	Simplification: removes the need to model individual products
	Arrival pattern:	Include	
	Attributes: Size of delivery	Include	
	Distribution of products	Include	
	Location	Include	Place where the product should be stored
	Specific type of product	Exclude	Simplification: there are too many distinct SKUs
	Quality check	Include	Does the product need a quality check
	Entrance	Include	Affects the flow
Order	Quantity: one entity represents one box	Include	Simplification: removes the need to model individual products
	Arrival pattern: Inter arrival time	Include	
	Attributes: Size of delivery	Include	
	Distribution of products	Include	
	Location	Include	Place where the product is stored
	Specific type of product	Exclude	Simplification: there are too many distinct SKUs
	Entrance	Include	Affects the flow
Production products	Arrival pattern	Include	

	Production time	Include	Necessary to predict when product comes back in warehouse
	Production process	Exclude	Not relevant for process in the warehouse
	Location	Include	Location of the product after production
Activities:			
Unpacking	Duration	Include	
	Dividing in multiple products	Exclude	Simplification: the total number of products is immediately on deck
Transporting in warehouse	Forklifts	Include	Necessary to get products on the shelves
	Absenteeism	Exclude	Simplification: could be modelled by changing number of employees
	Incorrect routing	Exclude	Simplification: employees know where to place products
	Full shelves	Include	When shelf is full, product is placed on another spot or on the ground.
Order picking	Collecting products	Include	
	Lacking products	Exclude	Simplification: The ordered products are always available
Quality control	Checking products	Include	The main function of the quality control
	Faulty products	Exclude	Simplification: Not relevant to the process in warehouse
Queues:			
Inbound queue	Quantity: One for each product (box)	Include	
	Capacity: limited	Include	The inbound deck has a limited space
	Queue discipline: First in first out	Include	
	Priority	Exclude	All products have the same importance

Aisle queue	Quantity: One for each product (box)	Include	
	Capacity: limited	Include	The inbound deck has a limited space
	Queue discipline: First in first out	Include	
	Priority	Exclude	All products have the same importance
Resources:			
Warehouse employees	Handling the products	Include	
	Checking processes at tables	Exclude	Employees are only busy with the handling of the products
	Shifts	Include	To a certain degree: all employees have the same normal shift
	Preferences employees	Exclude	Simplification: all employees have the same skill set. No distinction between handling of deliveries or orders.
Quality control	Checking products for their quality	Include	This action has priority
	Handling the products	Include	
External warehouses	Storage process	Exclude	This process is outsourced
	Space	Include	Necessary how many products can be stored
	Transport routing	Exclude	This process is outsourced
	Costs	Include	For comparison of solutions
Extra self-owned warehouse	Storage process	Include	Necessary to model how the products flow from main to new warehouse
	Space	Include	Necessary to know how many products can be stored
	Transport routing	Include	The (small) transportation of products from main to new warehouse

	Inbound	Include	To ease the amount of deliveries at the main warehouse
	Outbound	Exclude	Simplification: outbound will be done at main warehouse
	Costs	Include	For comparison of solutions

Appendix E – The product distributions of the processes

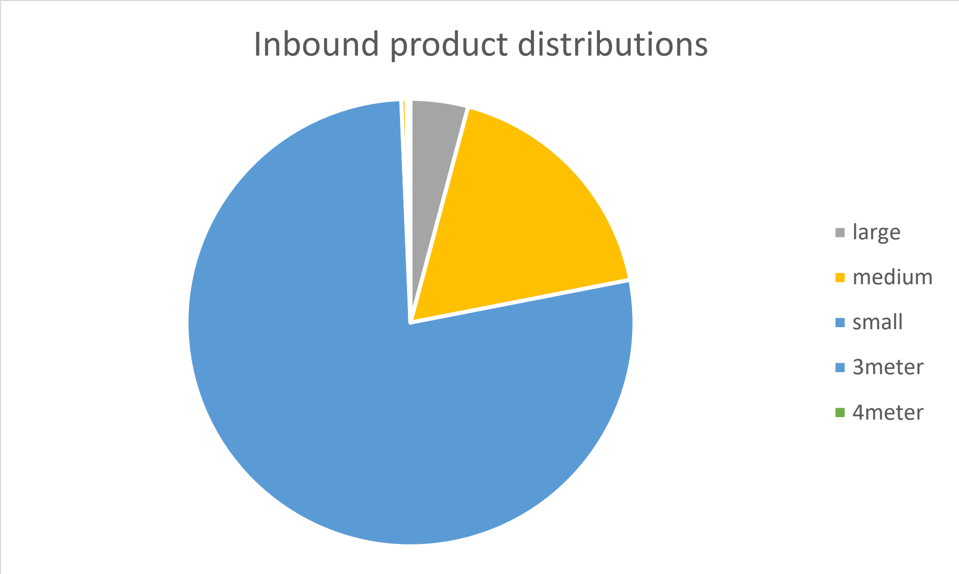

Figure 22 Product distribution of the inbound products

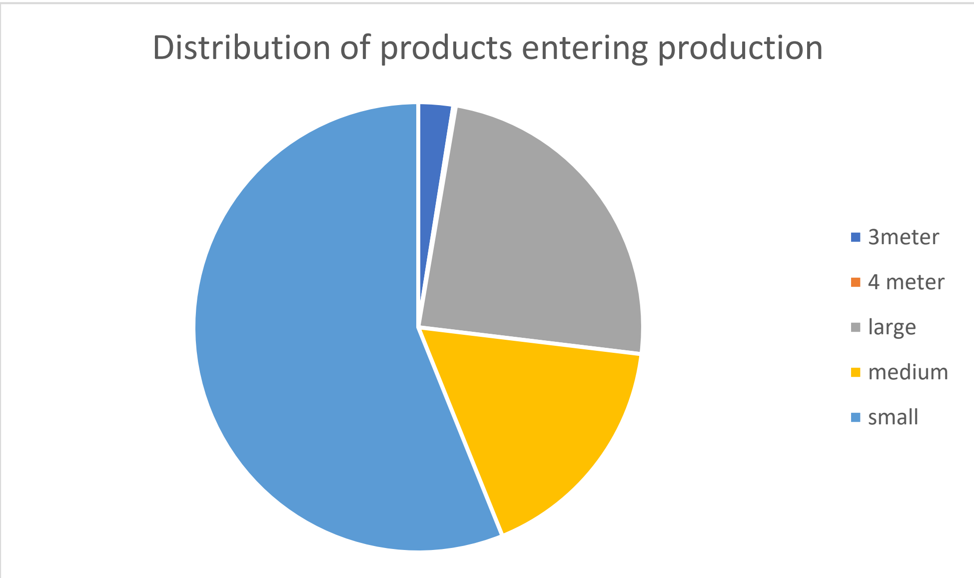

Figure 23 Product distribution of the products entering production

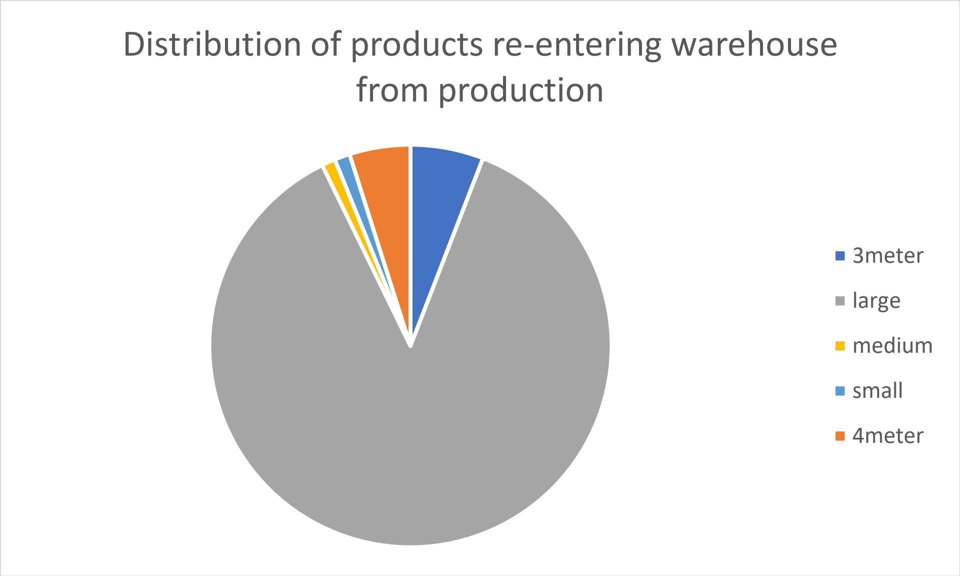

Figure 24 Product distribution of the products coming back from production

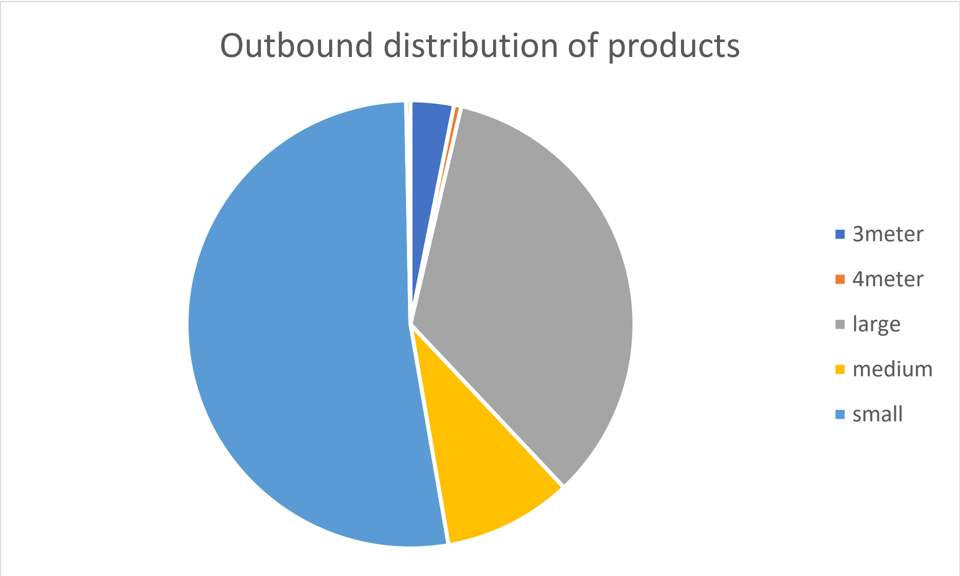

Figure 25 Product distribution of the outbound products

Appendix F- Results of the simulation of the current situation

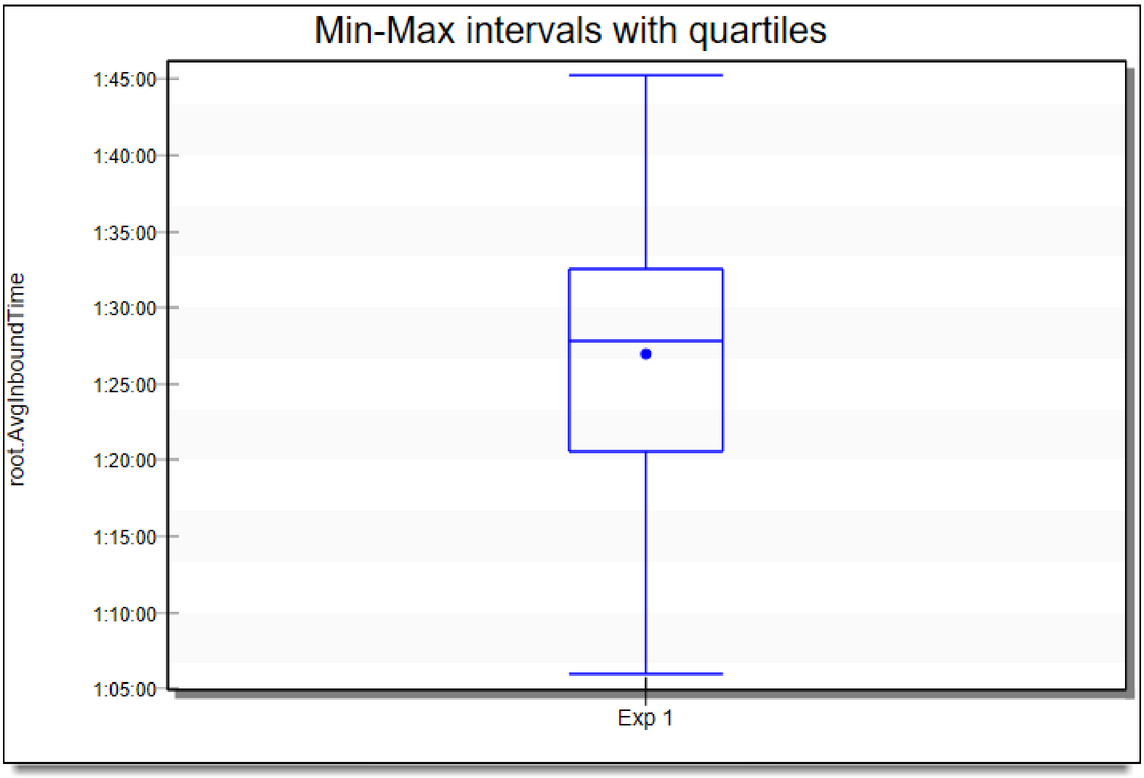

Figure 26 Box plot of the average inbound time

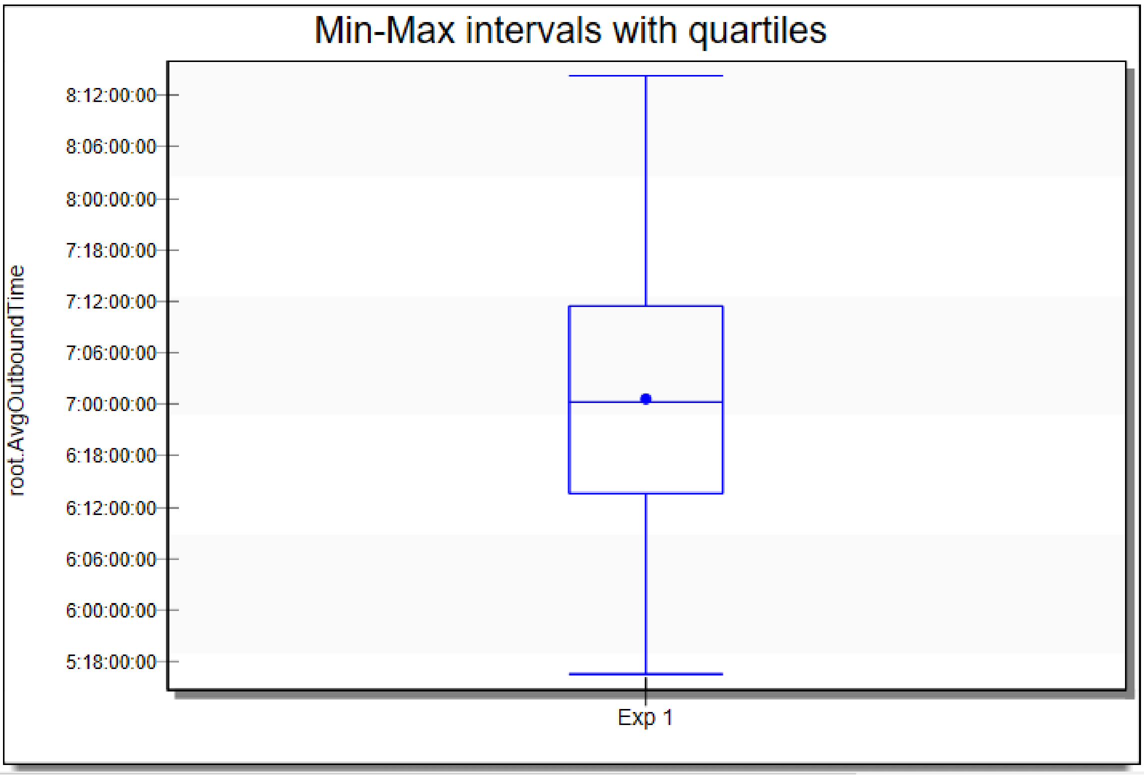

Figure 27 Box plot of the average outbound time

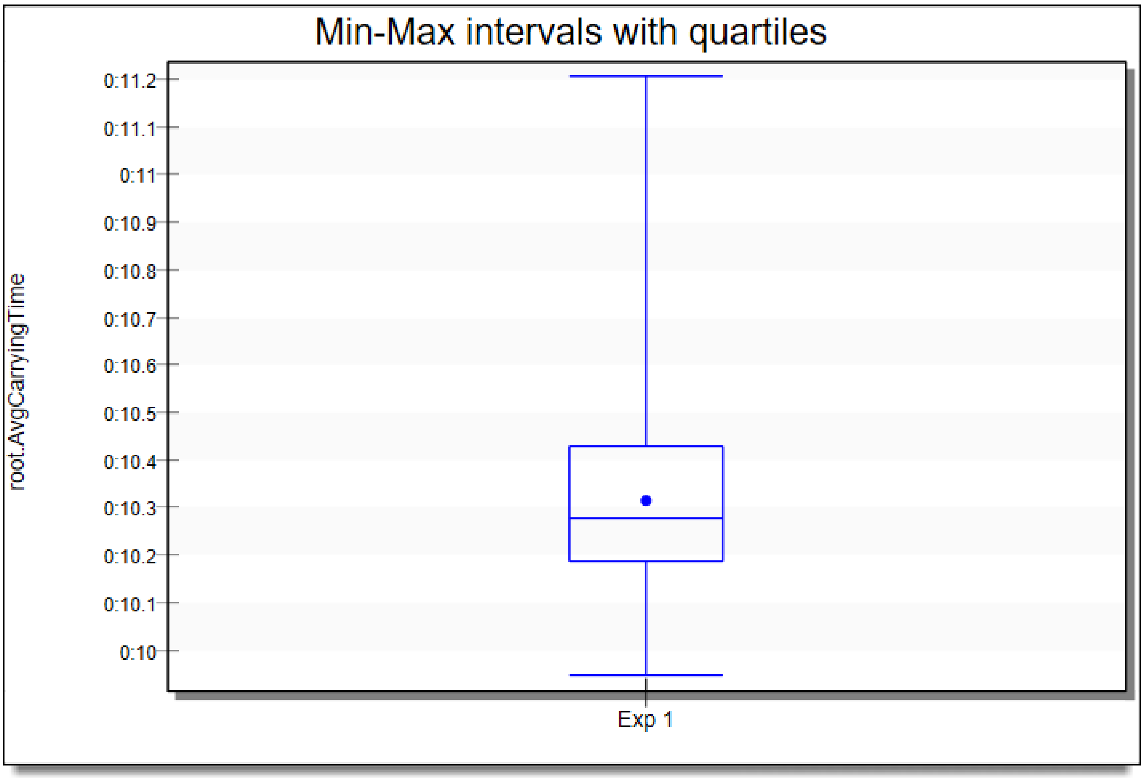

Figure 28 Box plot of the average carrying time

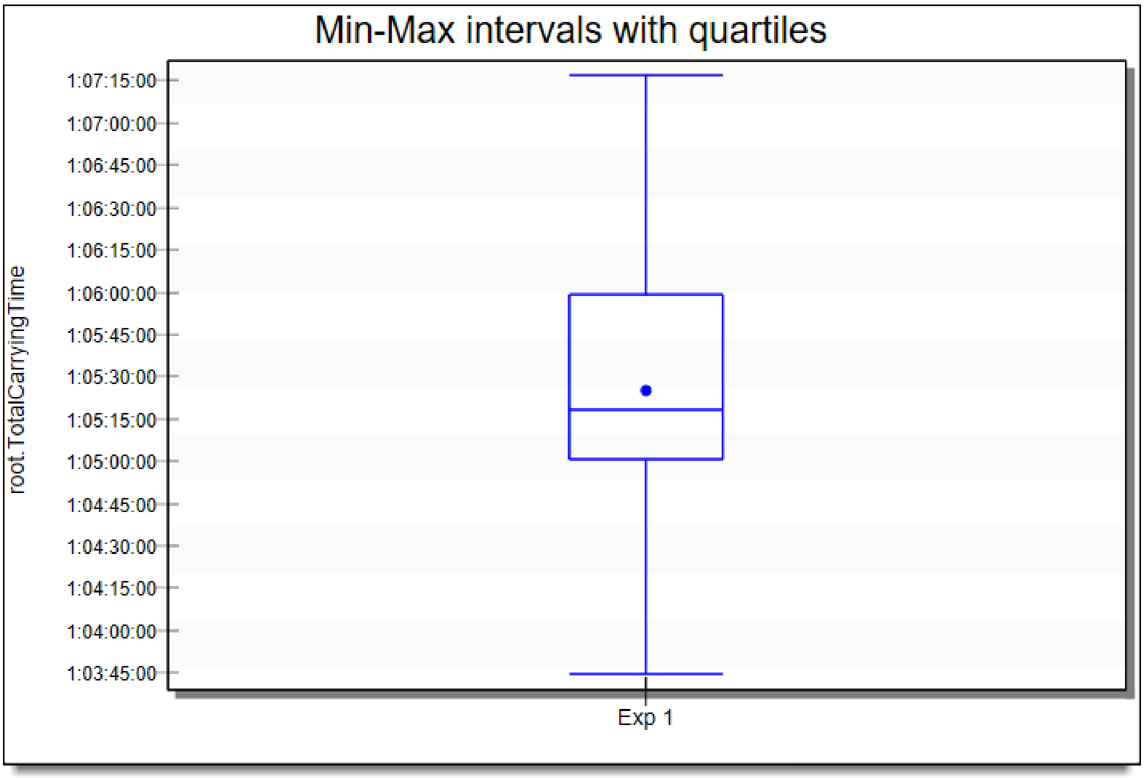

Figure 29 Box plot of the total carrying time

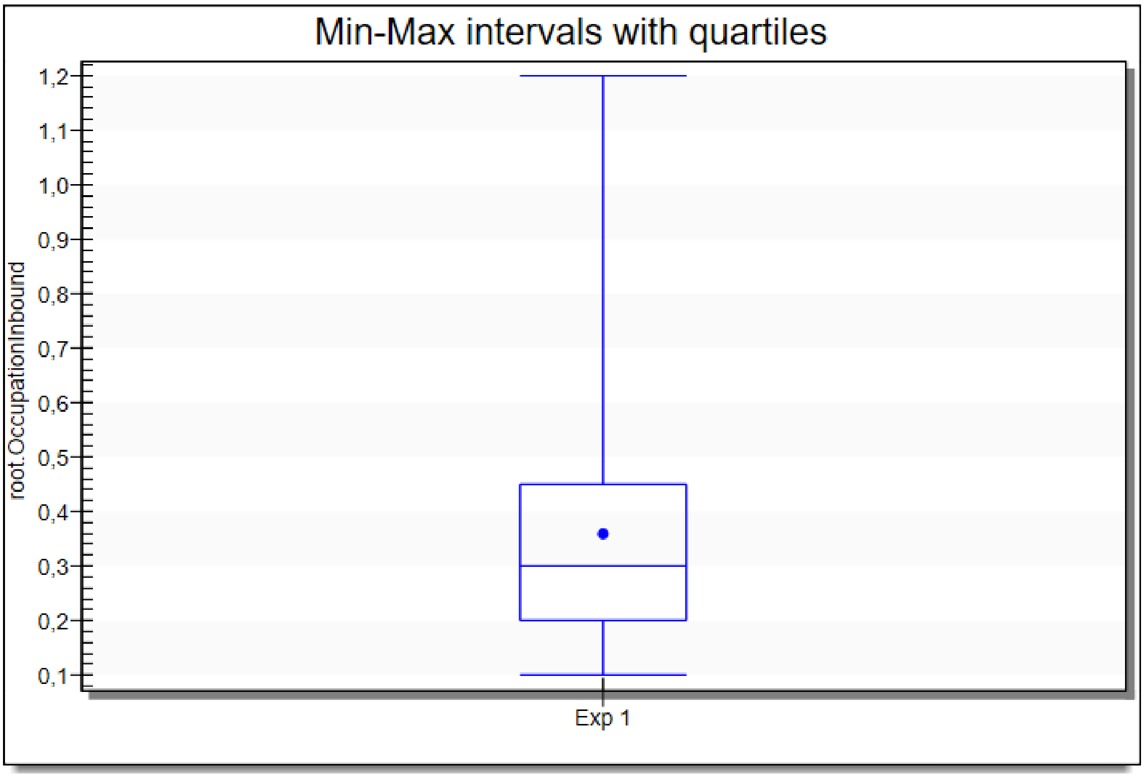

Figure 30 Box plot of the inbound occupation

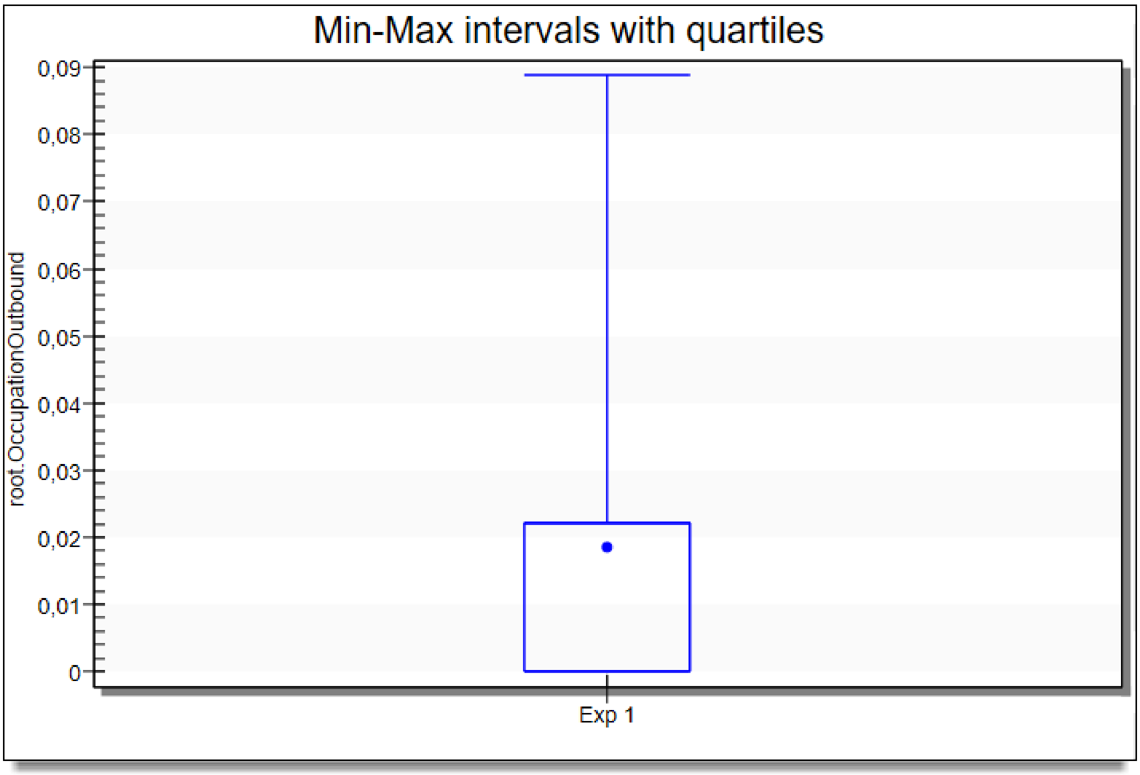

Figure 31 Box plot of the outbound occupation

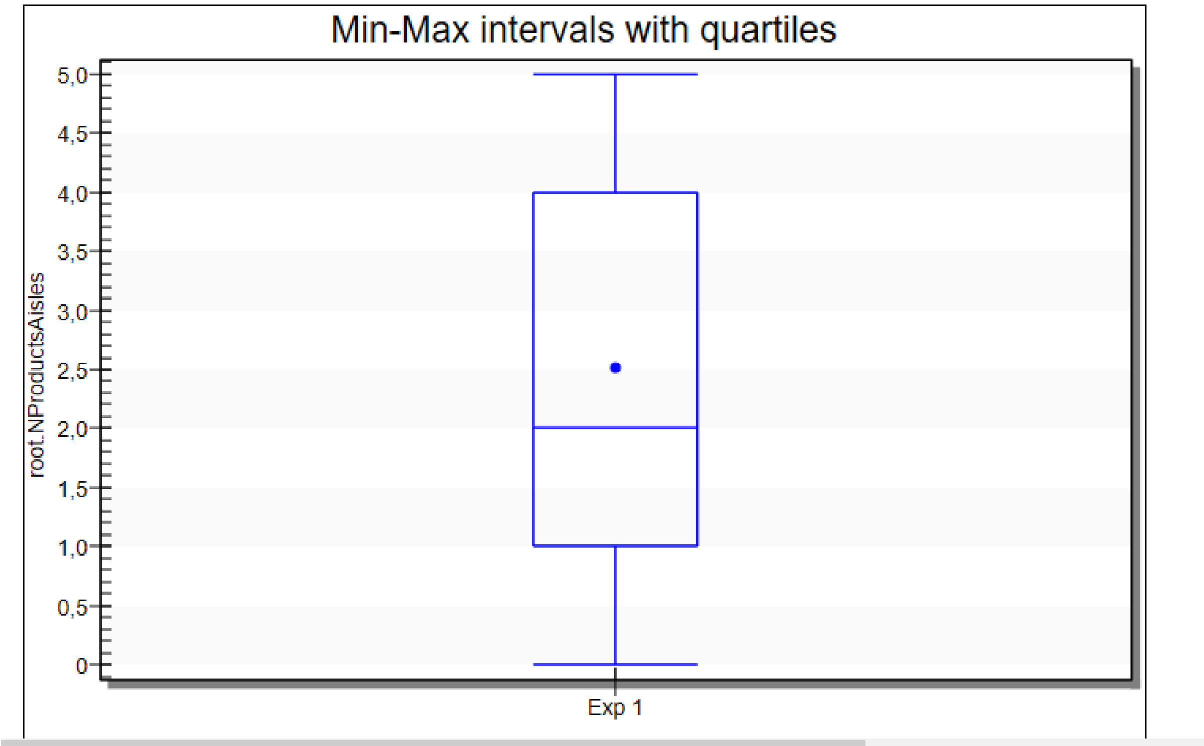

Figure 32 Box plot of the real time value of the number of products in the aisle

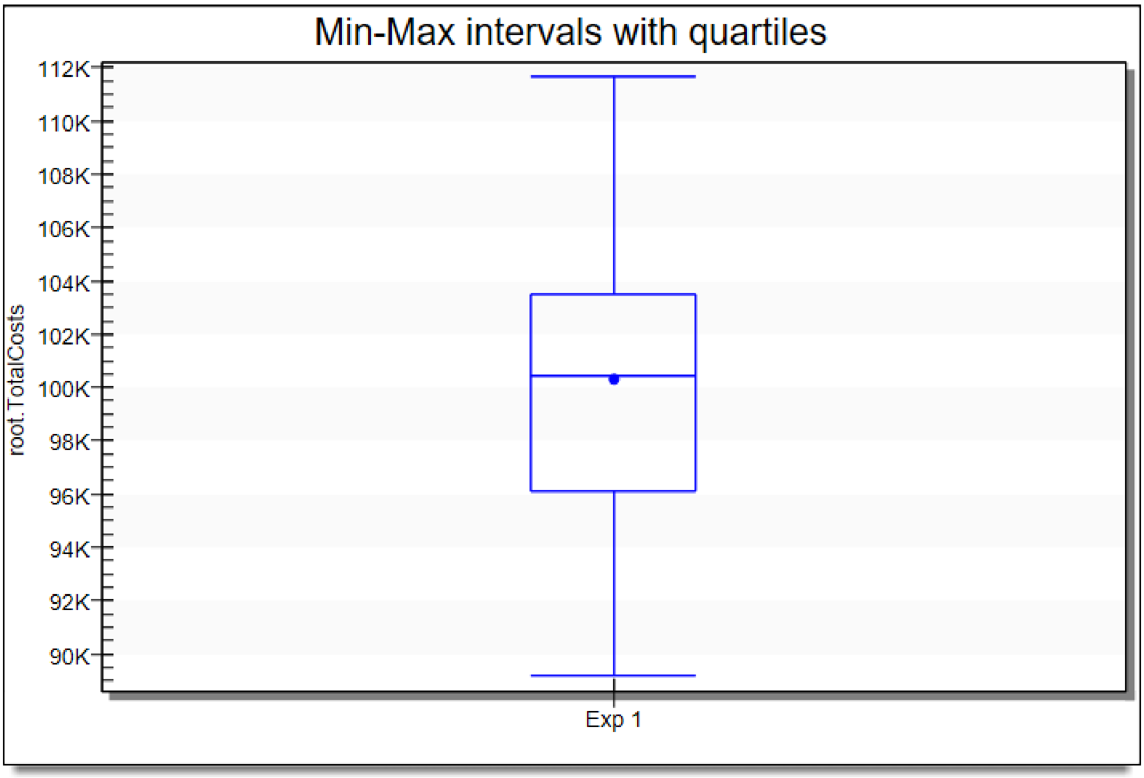

Figure 33 Box plot of the total costs

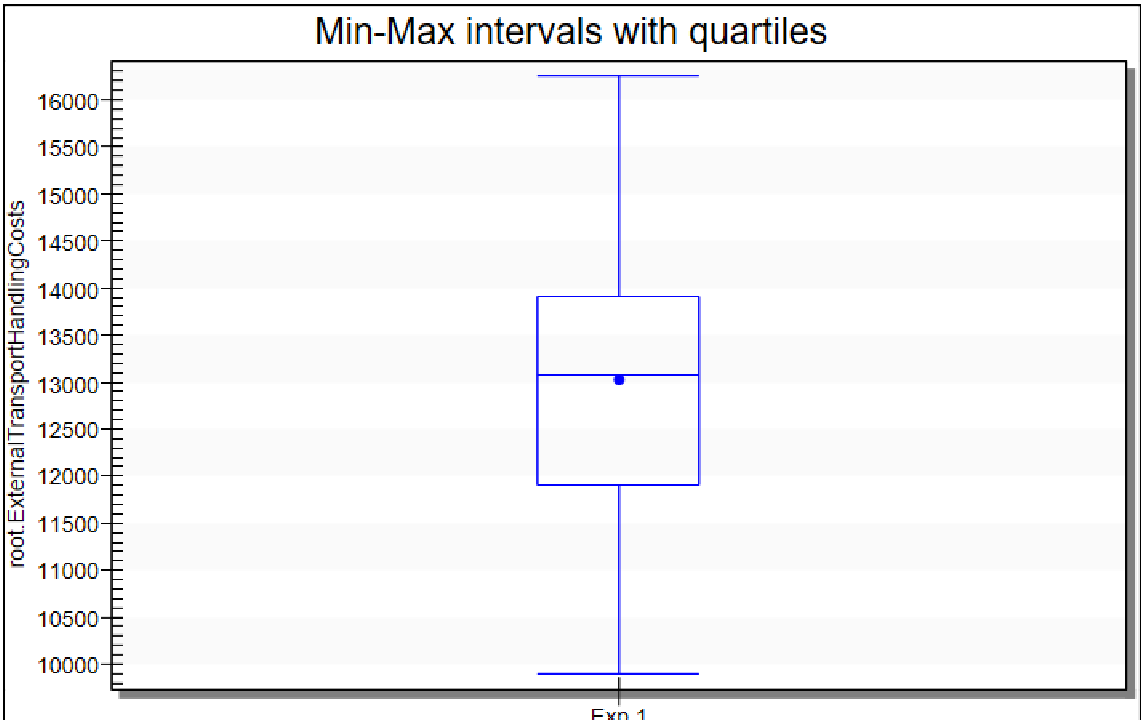

Figure 34 Box plot of the transport and handling costs of the external locations

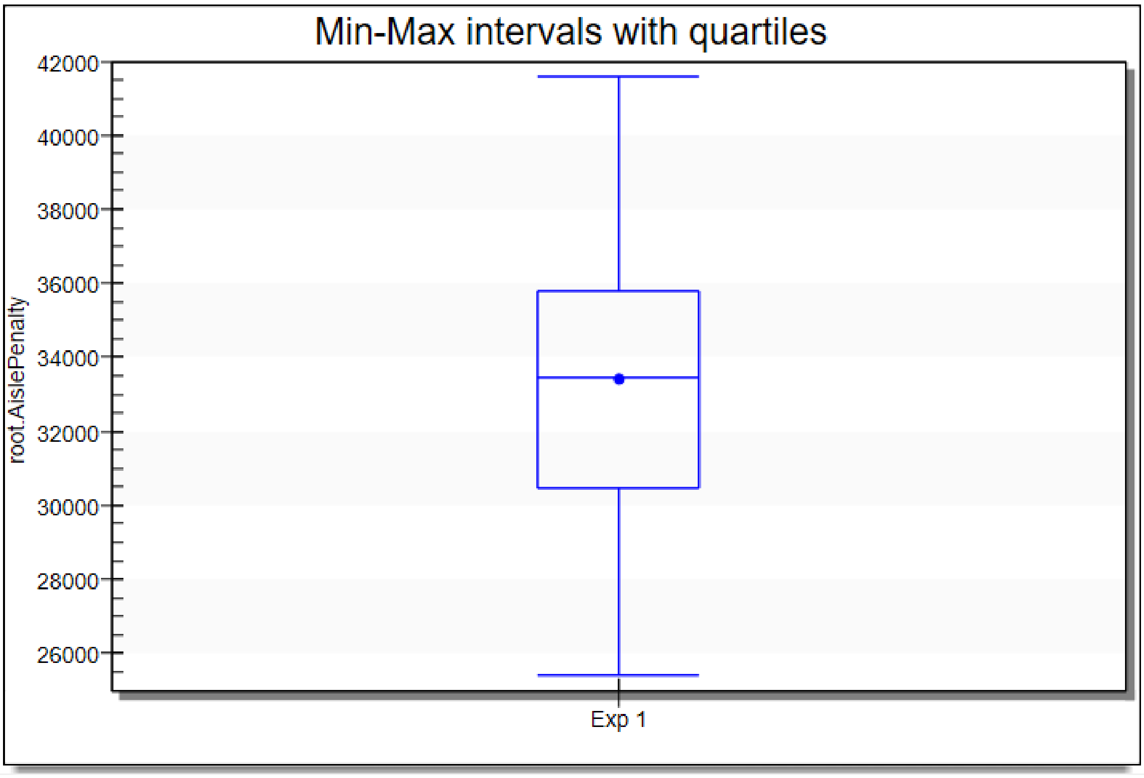

Figure 35 Box plot of the total penalties incurred by aisle placement

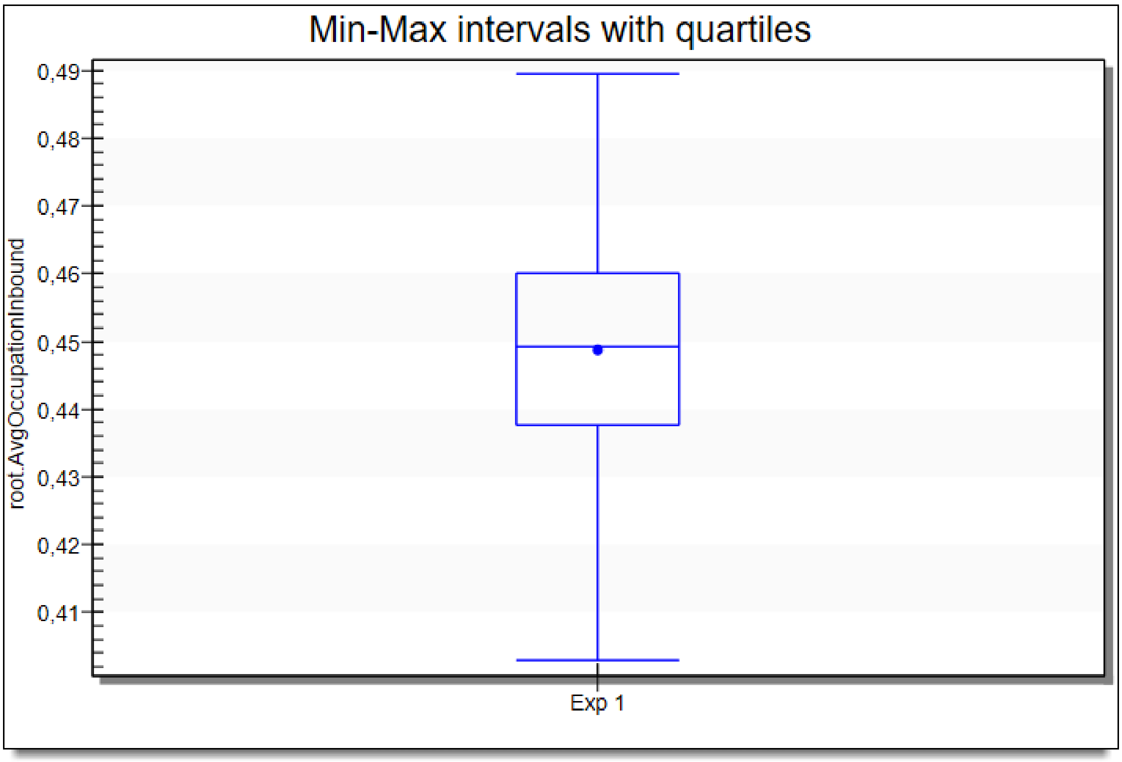

Figure 36 Box plot of the average occupation of the inbound zone

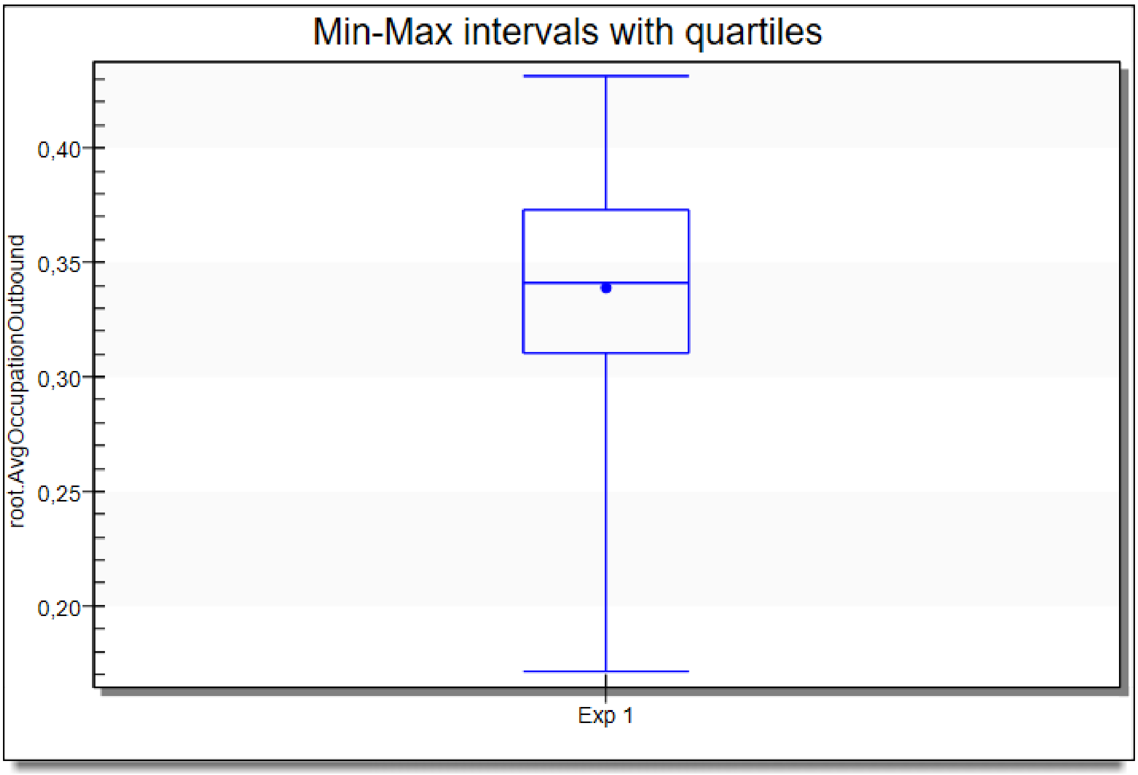

Figure 37 Box plot of the average occupation of the outbound

Appendix G- Results of the horizontal layout

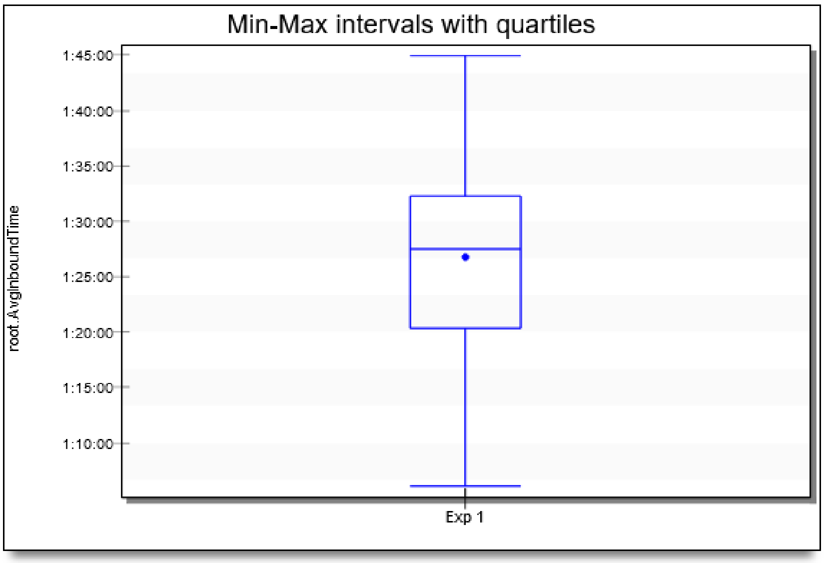

Figure 38 Box plot of average inbound time in horizontal layout

Experiment	root.AvgInboundTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	1:26:44.2908	8:14.7101	1:06:05.5378	1:44:57.3767	1:25:06.1072	1:28:22.4743

Table 12 Average inbound time horizontal layout

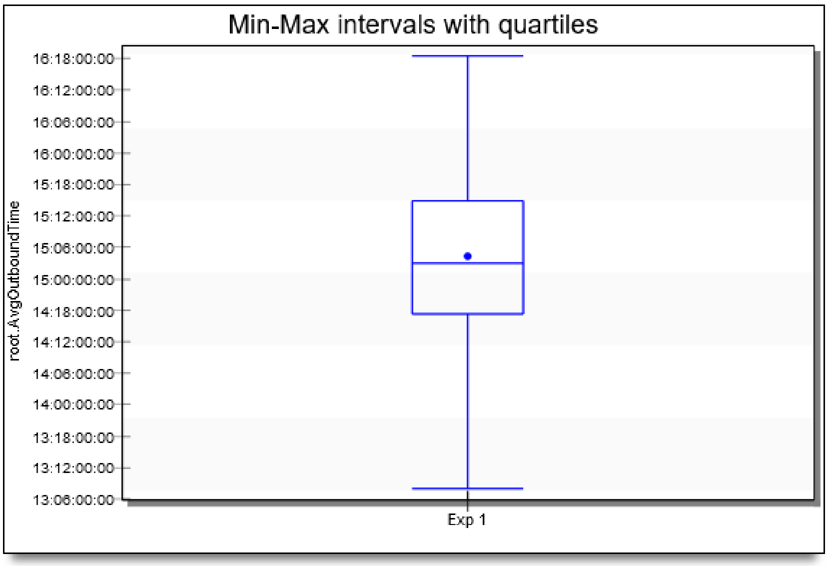

Figure 39 Box plot of average outbound time in horizontal layout

Experiment	root.AvgOutbound Time	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	15:04:23:42.1471	17:30:47.8528	13:07:56:06.6718	16:18:29:45.2460	15:00:55:09.2427	15:07:52:15.0515

Table 13 Average outbound time horizontal layout

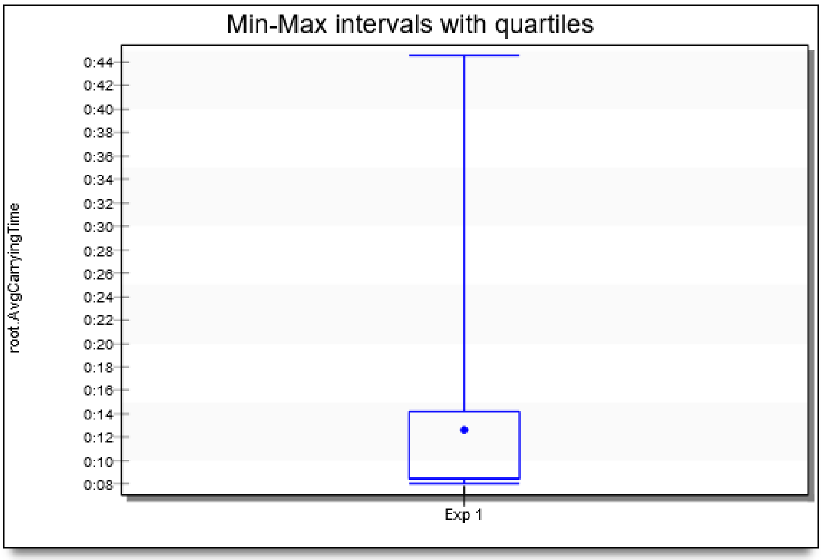

Figure 40 Box plot of average carrying time in horizontal layout

Experiment	root.AvgCarryingTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	12.6703	8.8363	8.0218	44.5914	10.9166	14.4240

Table 14 Average carrying time horizontal layout

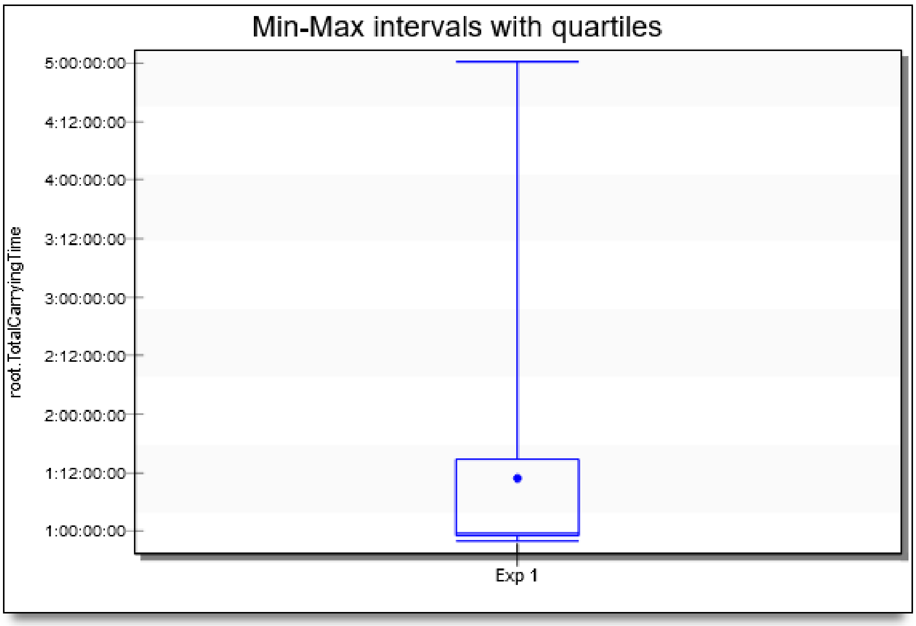

Figure 41 Box plot of the total carrying time in the horizontal layout

Experiment	root.TotalCarryingTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	1:10:46:24.3119	1:00:10:58.2599	21:54:26.5440	5:00:18:16.1690	1:05:58:26.1393	1:15:34:22.4845

Table 15 Total carrying time horizontal layout

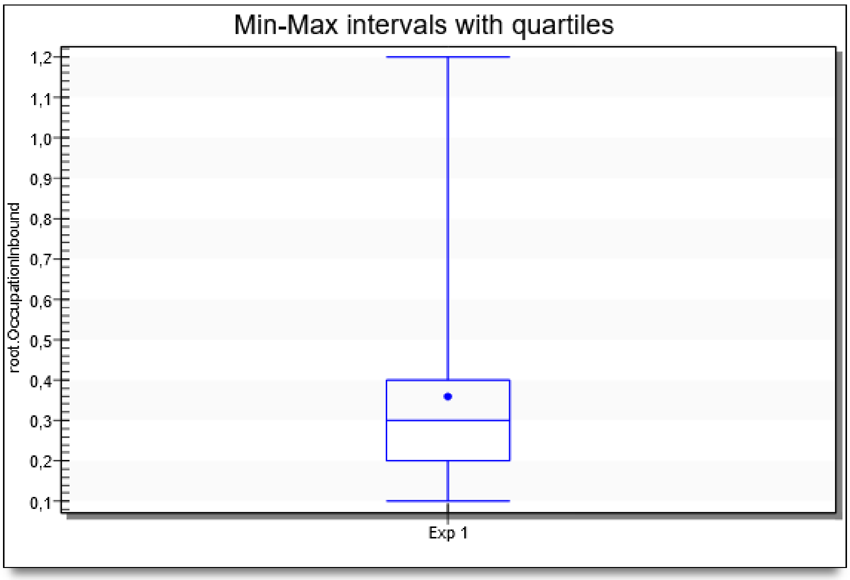

Figure 42 Box plot of the inbound occupation in the horizontal layout

Experiment	root.OccupationInbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.359	0.211819915890071	0.1	1.2	0.316960783085472	0.401039216914529

Table 16 Occupation inbound horizontal layout

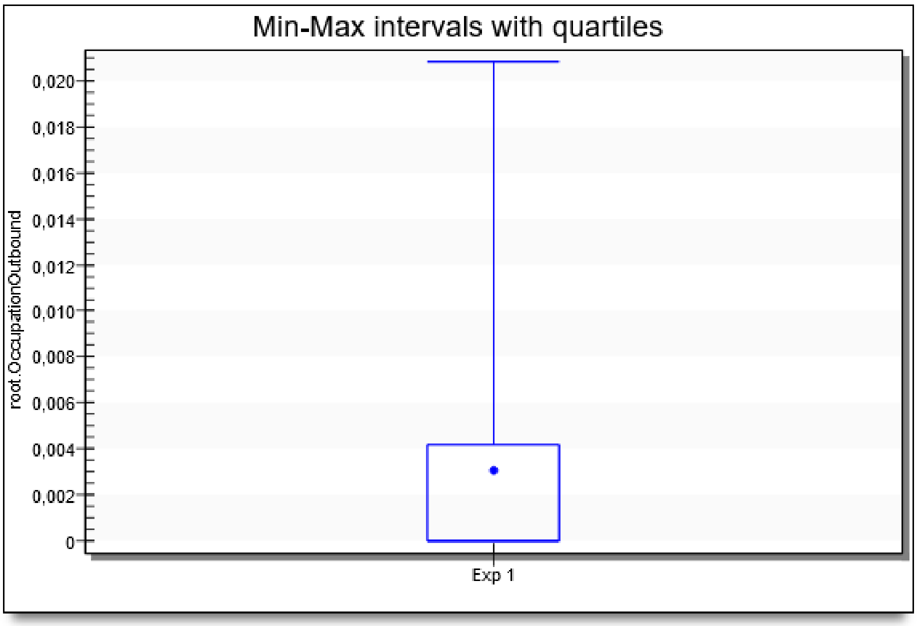

Figure 43 Box plot of the outbound occupation in the horizontal layout

Experiment	root.OccupationOutbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.00308333333333333	0.00445626584428846	0	0.0208333333333333	0.00219891259475618	0.00396775407191049

Table 17 Occupation Outbound horizontal layout

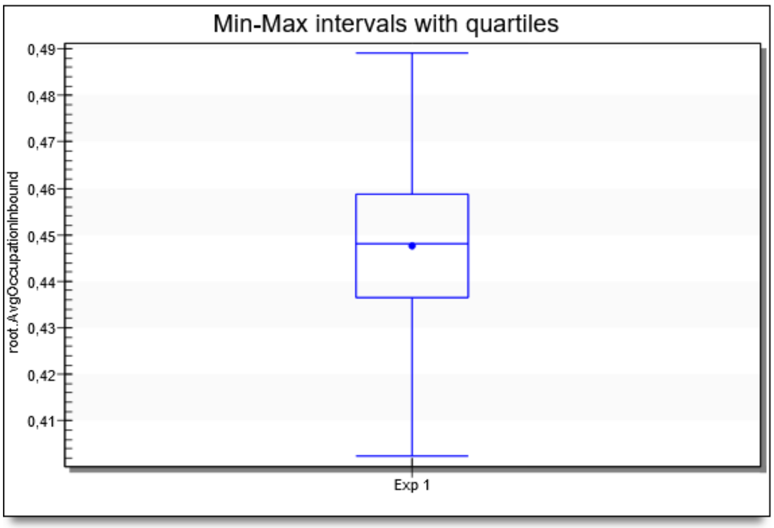

Figure 44 Box plot of the average inbound occupation in the horizontal layout

Experiment	root.AvgOccupationInbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.447670490948783	0.0167578479351918	0.402392864611962	0.489125904299918	0.444344614808157	0.450996367089409

Table 18 Average occupation inbound horizontal layout

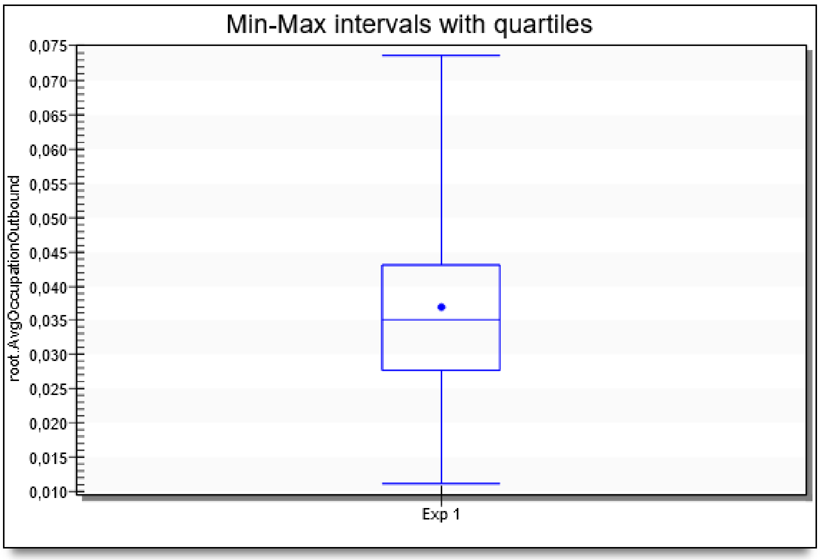

Figure 45 Boxplot of the average outbound occupation in the horizontal layout

Experiment	root.AvgOccupationOutbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.0368764922212371	0.0130050538272809	0.0111610098102991	0.0737015712636338	0.0342954210479584	0.0394575633945158

Table 19 Average occupation outbound horizontal layout

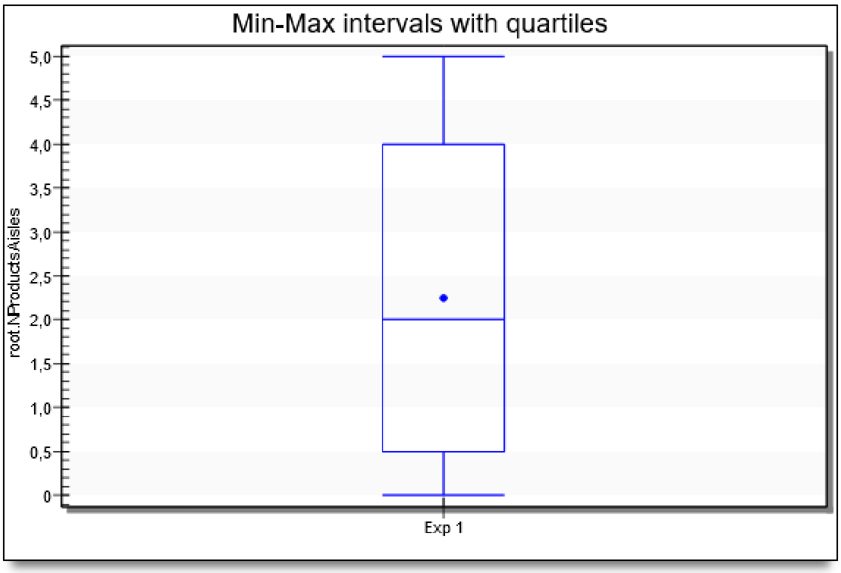

Figure 46 Box plot of the products in the aisles

Experiment	root.NProductsAisles	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	2.24	1.78161202682891	0	5	1.88640919557223	2.59359080442777

Table 20 Number of products in the aisles in horizontal layout

Experiment	root.NDeliveriesDay	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	1074.41	18.9955311065571	1026	1127	1070.64001808286	1078.17998191714

Table 21 Number of total deliveries

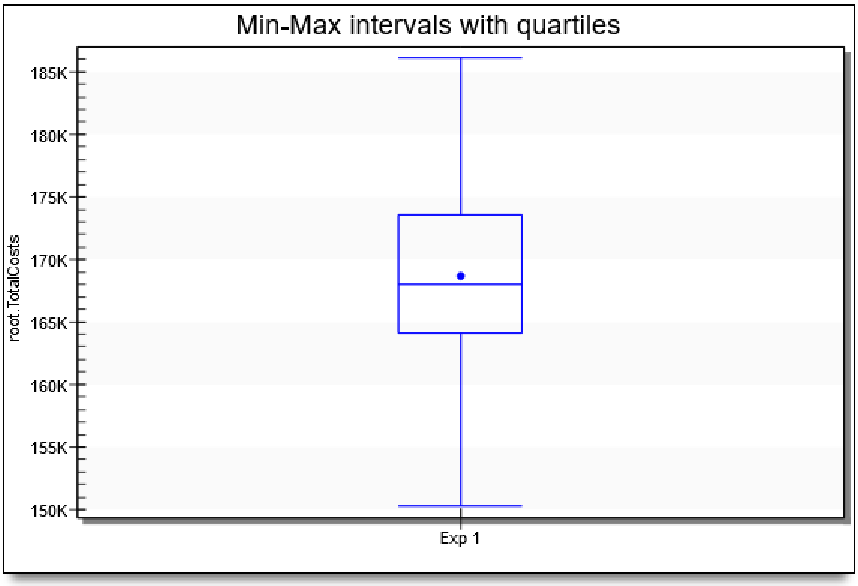

Figure 47 Box plot of the total costs of the horizontal layout

Experiment	root.TotalCosts	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	168727.03	7414.04833589129	150299.39	186131.05	167255.587690632	170198.472309368

Table 22 Total costs in horizontal layout

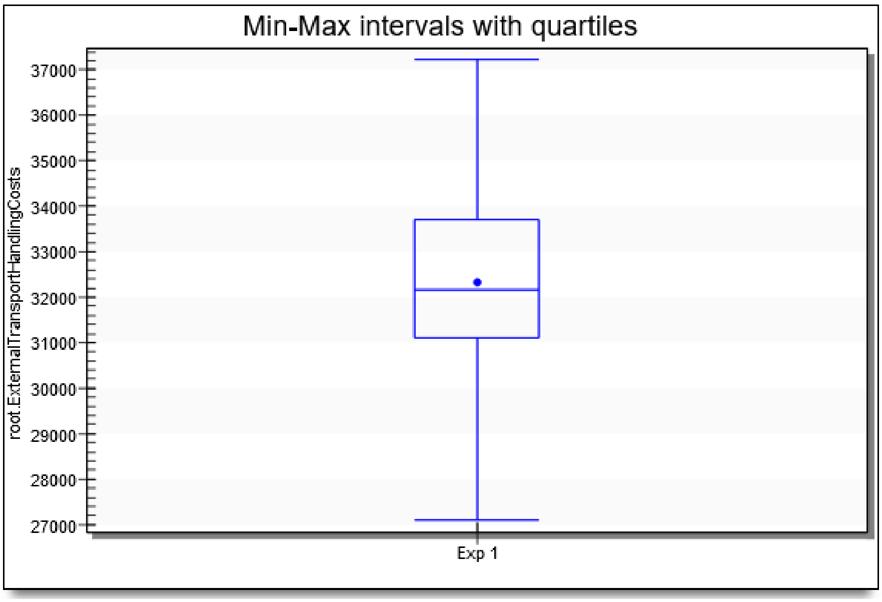

Figure 48 Box plot of the external handling costs of the horizontal layout

Experiment	root.ExternalTransportHandlingCosts	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	32334.1326	2098.07669904508	27096.3	37227.96	31917.7340706934	32750.5311293066

Table 23External transport and handling costs horizontal layout

Experiment	root.AislePenalty	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	82562	5326.298011288	69300	95100	81504.9067776414	83619.0932223586

Table 24 Total aisle penalty horizontal layout

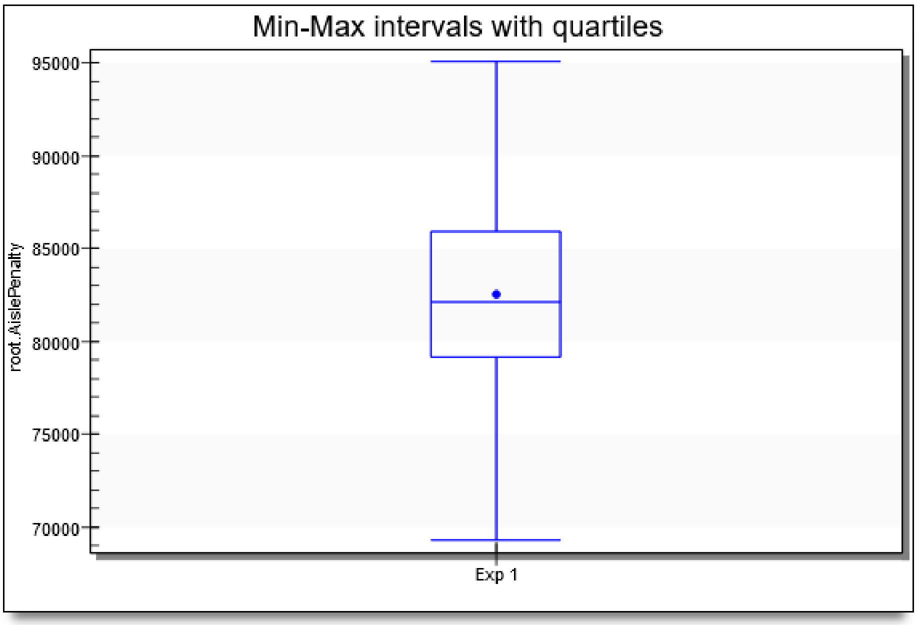

Figure 49 Boxplot of the total aisle penalty in the horizontal layout

Experiment	root.nCarry	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	10654.64	201.966069757627	10152	11151	10614.5564442105	10694.7235557895

Table 25 Total number of carrying operations in horizontal layout

Appendix H – The results of the fishbone layout

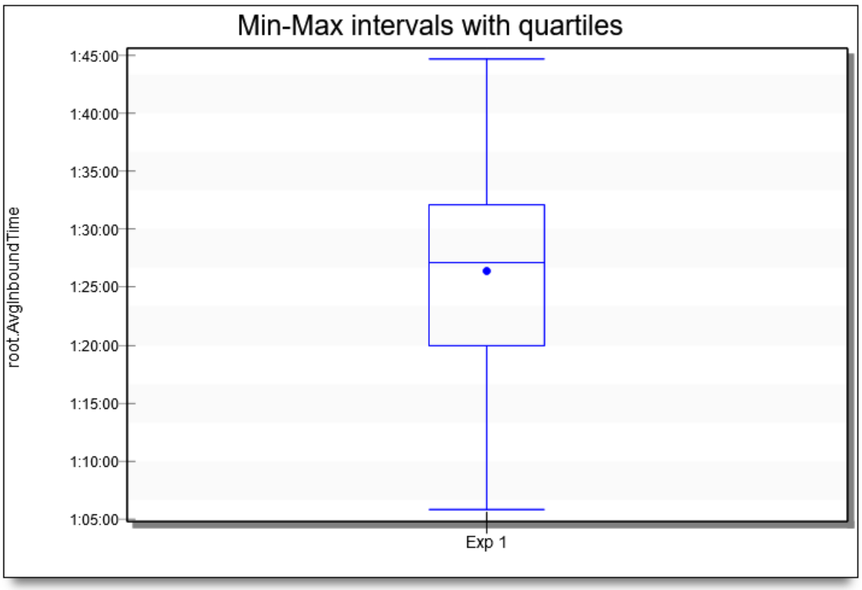

Figure 50 Box plot of the average inbound time in the fishbone layout

Experiment	root.AvgInboundTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	1:26:22.6508	8:07.5896	1:05:49.2111	1:44:40.3762	1:24:45.8805	1:27:59.4212

Table 26 Average inbound time of fishbone layout

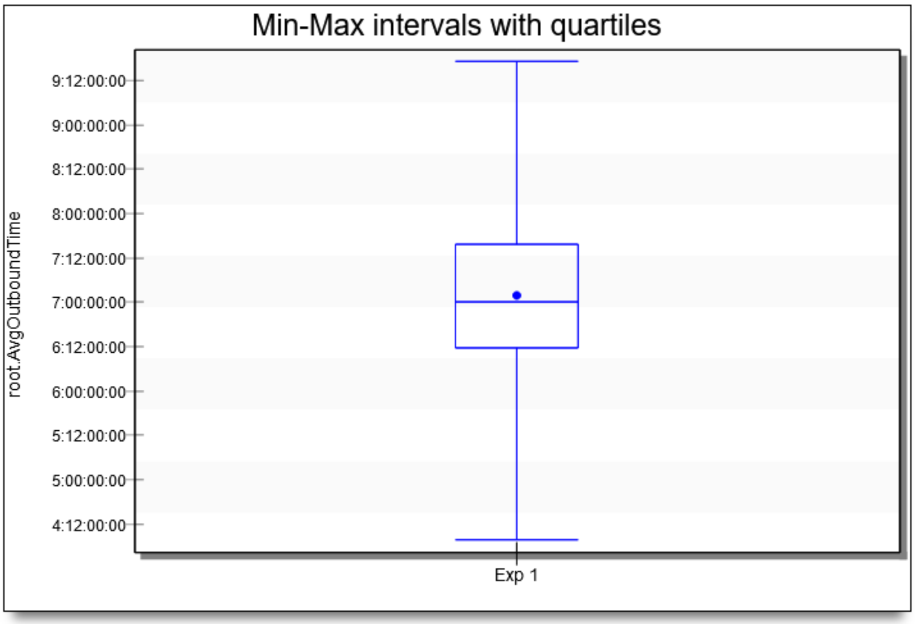

Figure 51 Box plot of the average outbound time in the fishbone layout

Experiment	root.AvgOutboundTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	7:01:43:14.5205	23:11:36.8064	4:07:40:58.6454	9:17:13:21.5378	6:21:07:03.1781	7:06:19:25.8629

Table 27 Average outbound time in the fishbone layout

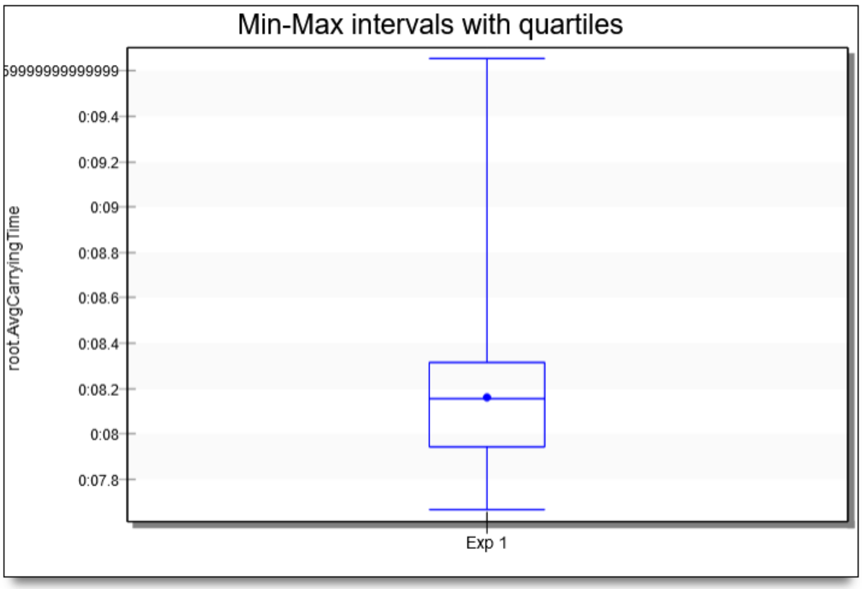

Figure 52 Box plot of the average carrying time in the fishbone layout

Experiment	root.AvgCarryingTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	8.1619	0.2759	7.6658	9.6555	8.1071	8.2167

Table 28 Average carrying time in the fishbone layout

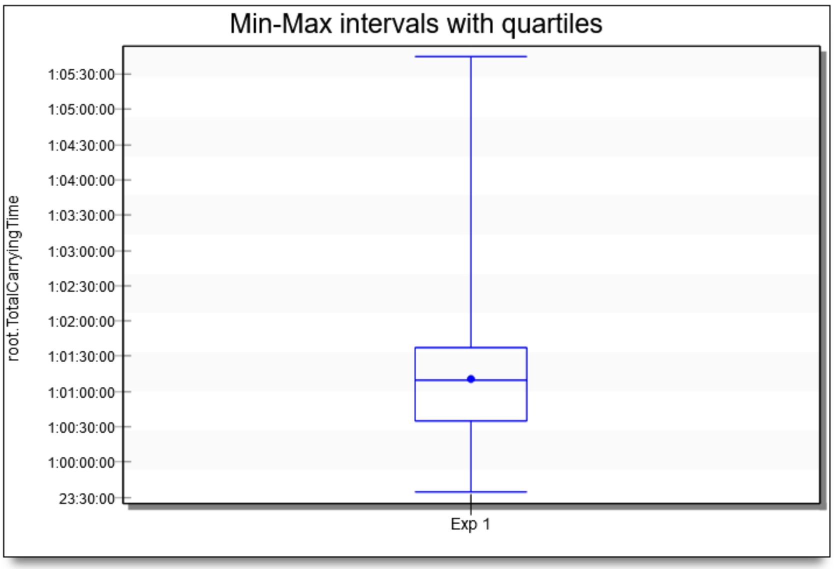

Figure 53 Box plot of the total carrying time in the fishbone layout

Experiment	root.TotalCarryingTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	1:01:10:45.6187	49:18.1596	23:34:20.8638	1:05:45:03.7105	1:01:00:58.5223	1:01:20:32.7152

Table 29 Total carrying time in the fishbone layout

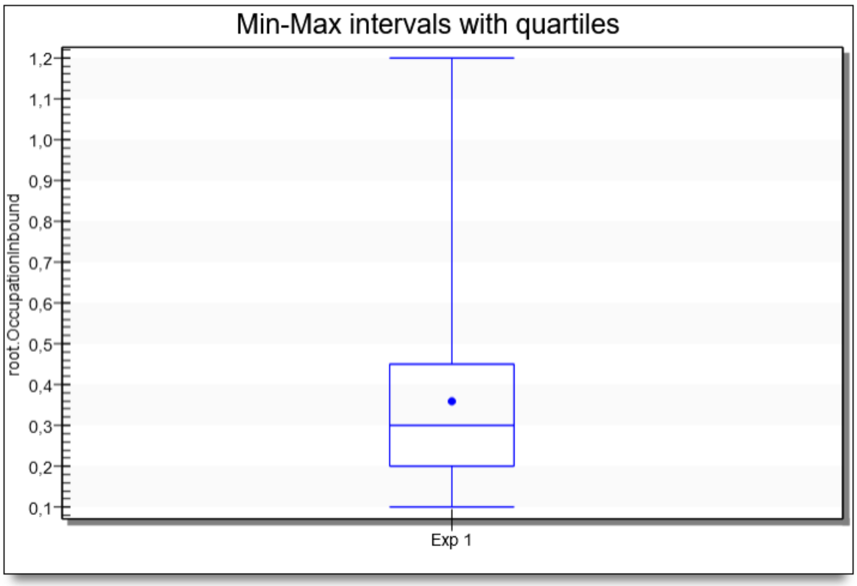

Figure 54 Box plot of the occupation inbound values in the fishbone layout

Experiment	root.OccupationInbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.36	0.208893187146837	0.1	1.2	0.318541641518777	0.401458358481223

Table 30 Inbound occupation in the fishbone layout

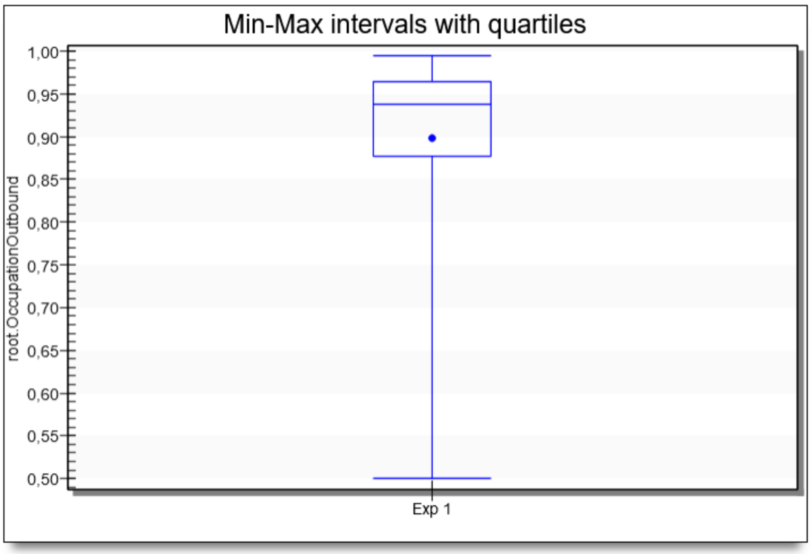

Figure 55 Box plot of the occupation outbound values in the fishbone diagram

Experiment	root.OccupationOutbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.89815	0.0984466604283552	0.5	0.995	0.878611608178494	0.917688391821505

Table 31 Outbound occupation in the fishbone layout

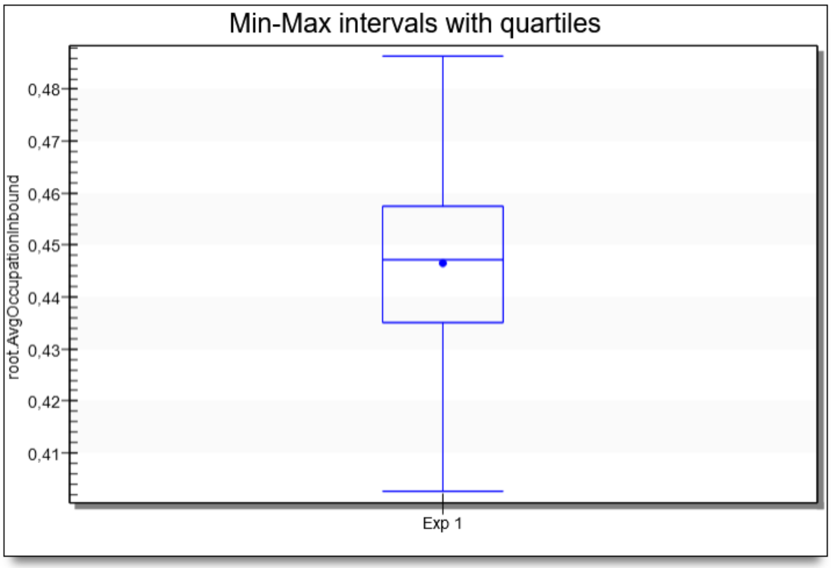

Figure 56 Box plot of the average inbound occupation in the fishbone diagram

Experiment	root.AvgOccupationInbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.446599699128359	0.0166430620660343	0.402584195659487	0.486404764073694	0.443296604169719	0.449902794086998

Table 32 Average inbound occupation in the fishbone layout

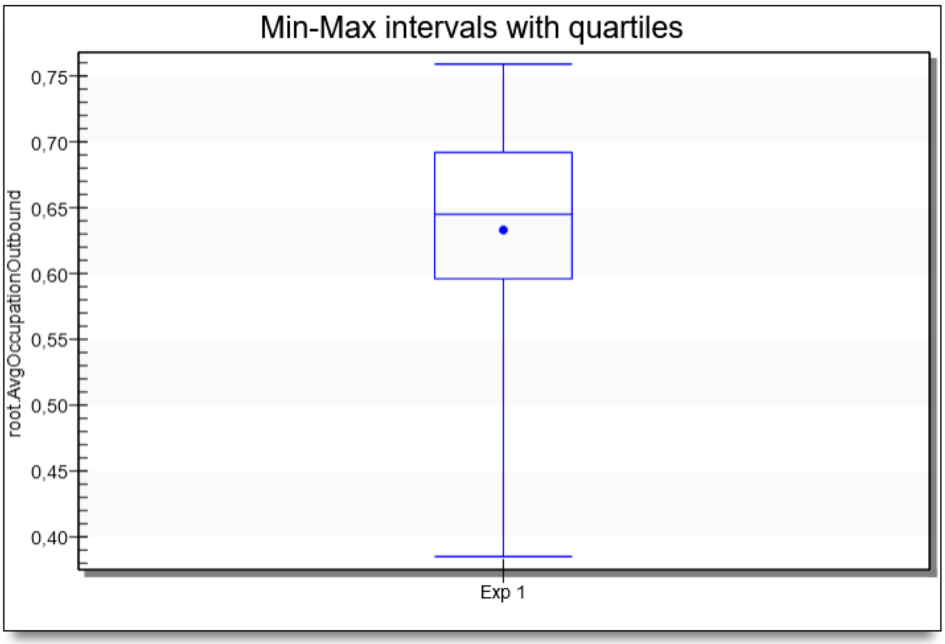

Figure 57 Box plot of the average occupation of the outbound in the fishbone layout

Experiment	root.AvgOccupationOutbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.633231444271051	0.0760950380213157	0.384648152703533	0.759518592923158	0.618129107004721	0.64833378153738

Table 33 Average outbound occupation in the fishbone layout

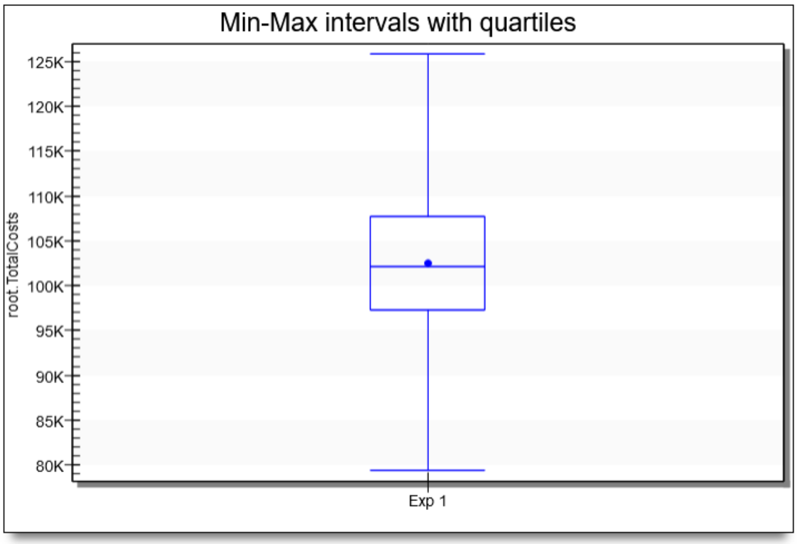

Figure 58 Box plot of the total costs of the fishbone layout

Experiment	root.TotalCosts	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	102522.8574	8571.96096154372	79371.69	125866.41	100821.607898833	104224.106901167

Table 34 Total costs of the fishbone layout

Experiment	root.ExternalRentCosts	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	54003.0899999999	0.00207740634171215	54003.09	54003.09	54003.0895877038	54003.0904122961

Table 35 Rent costs of the external locations in fishbone layout

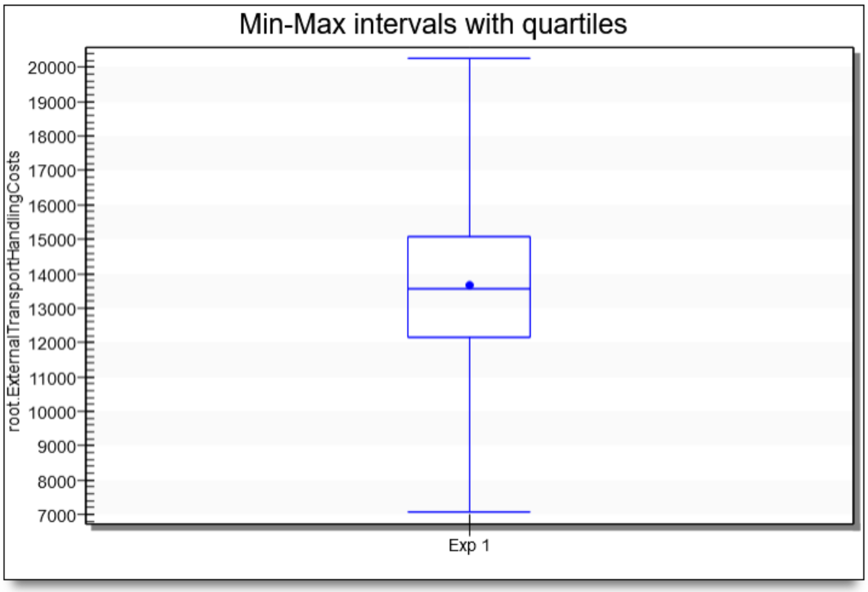

Figure 59 Box plot of the external handling and transport costs in the fishbone layout

Experiment	root.ExternalTransportHandlingCosts	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	13654.179	2418.07092271918	7068.6	20263.32	13174.2722470974	14134.0857529026

Table 36 Transport and handling costs of the external locations in the fishbone layout

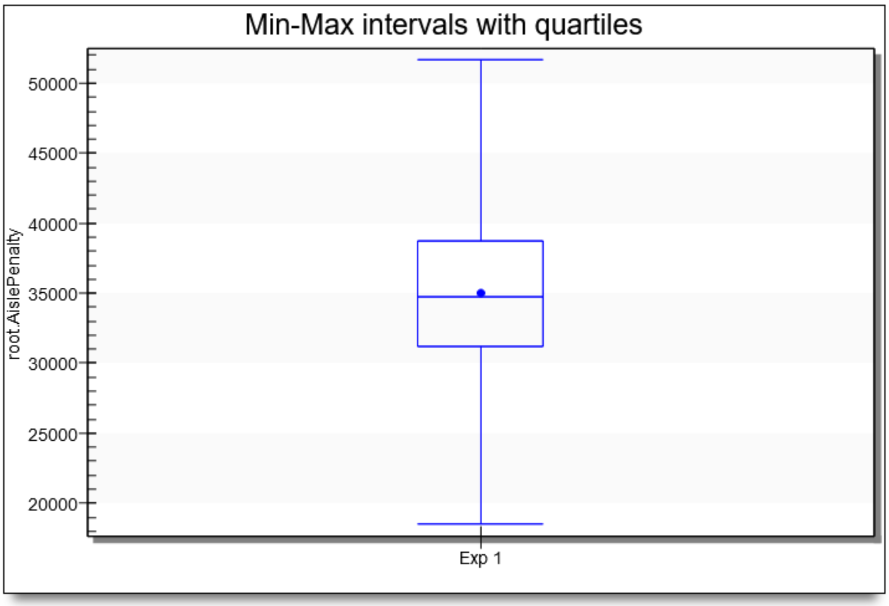

Figure 60 Box plot of the total aisle penalty in the fishbone layout

Experiment	root.AislePenalty	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	35036	6141.27483228495	18500	51700	33817.1609511726	36254.8390488274

Table 37 Total aisle penalties in the fishbone layout

Experiment	root.nCarry	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	11410.9	225.021592678787	10846	12096	11366.2406887859	11455.5593112141

Table 38 Total number of carrying operations in the fishbone layout

Appendix I - The results of the model with the new warehouse

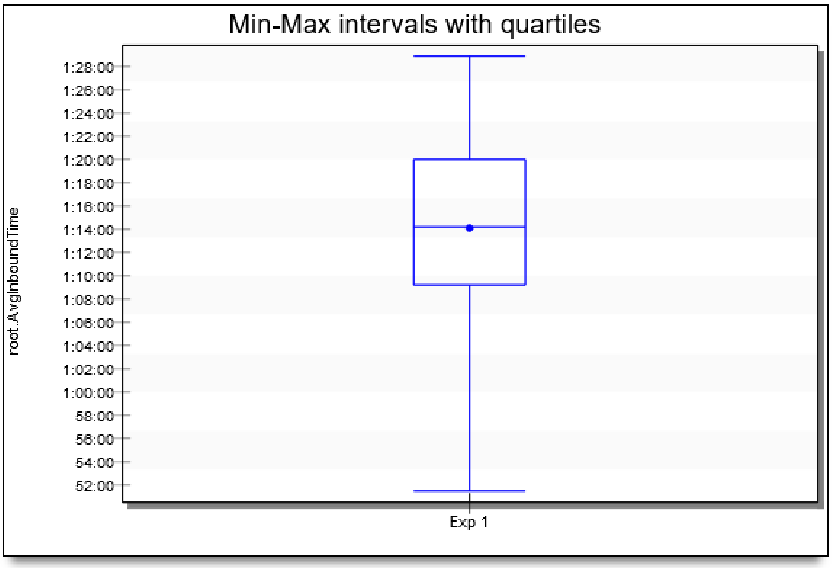

Figure 61 Box plot of the average inbound time of the main warehouse

Experiment	root.AvgInboundTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	1:14:04.7982	7:23.7872	51:29.2468	1:28:53.9606	1:12:36.7212	1:15:32.8752

Table 39 Average inbound time of the main warehouse

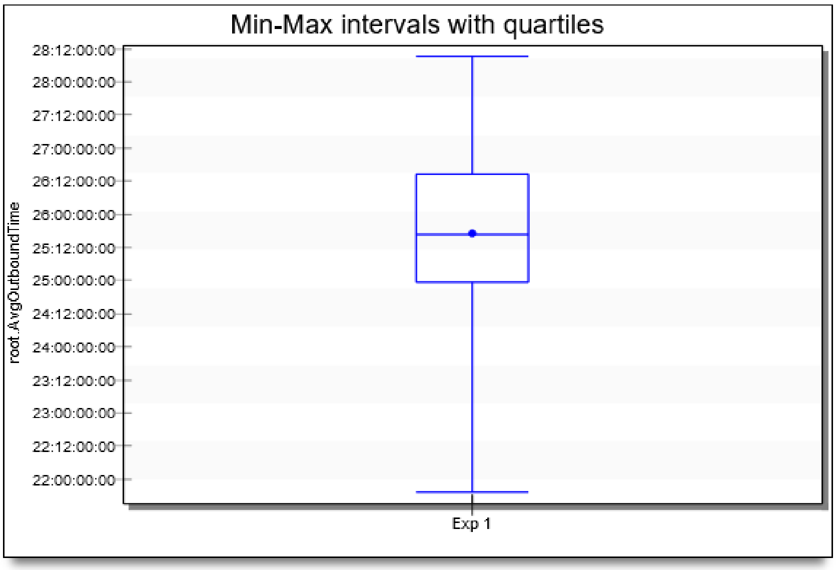

Figure 62 Box plot of the average outbound time in the main warehouse

Experiment	root.AvgOutboundTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	25:17:15:36.3470	1:06:51:09.9540	21:19:12:29.4607	28:09:23:58.8046	25:11:08:12.6507	25:23:23:00.0433

Table 40 Average outbound time of the main warehouse

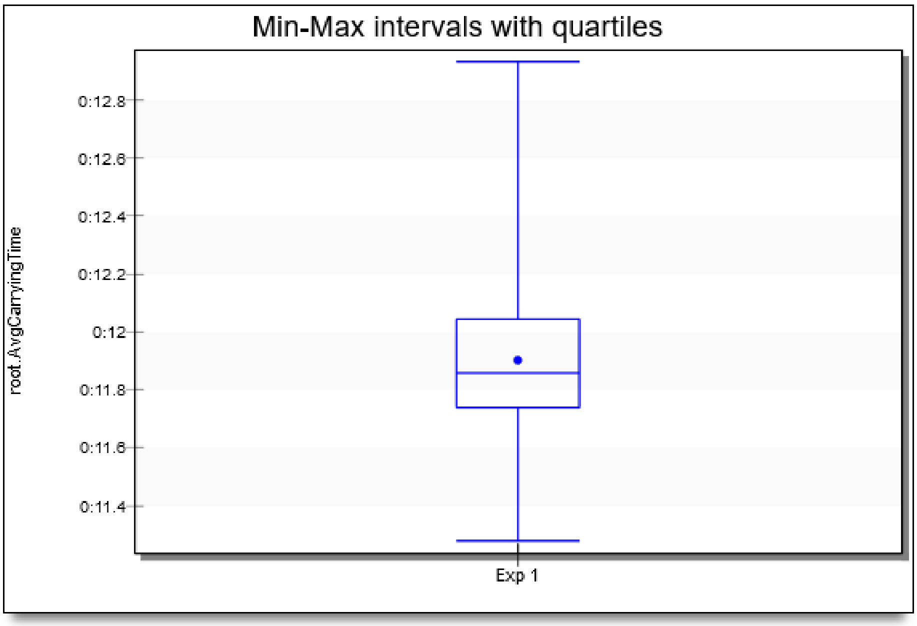

Figure 63 Box plot of the average carrying time in the main warehouse

Experiment	root.AvgCarryingTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	11.9009	0.2548	11.2793	12.9316	11.8503	11.9515

Table 41 Average carrying time in the main warehouse

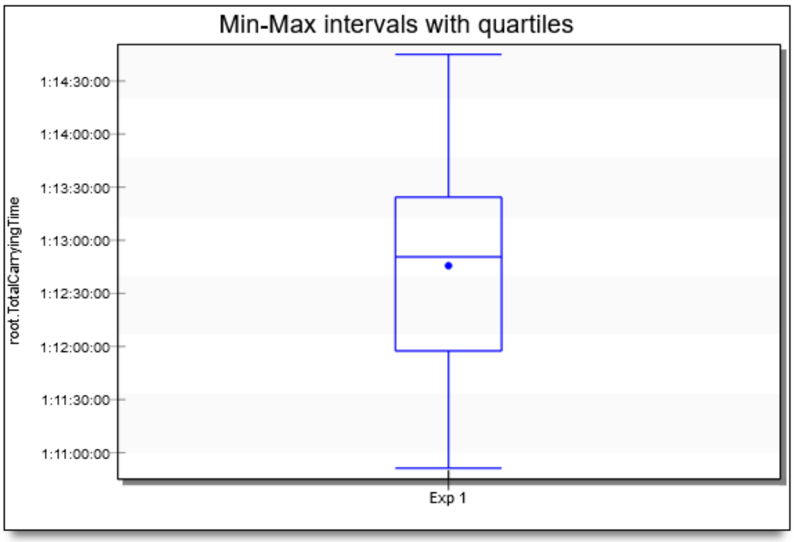

Figure 64 Box plot of the total carrying time in the main warehouse

Experiment	root.TotalCarryingTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	1:12:45:35.6915	51:18.5289	1:10:51:10.4601	1:14:44:55.6907	1:12:35:24.7058	1:12:55:46.6772

Table 42 Total carrying time in the main warehouse

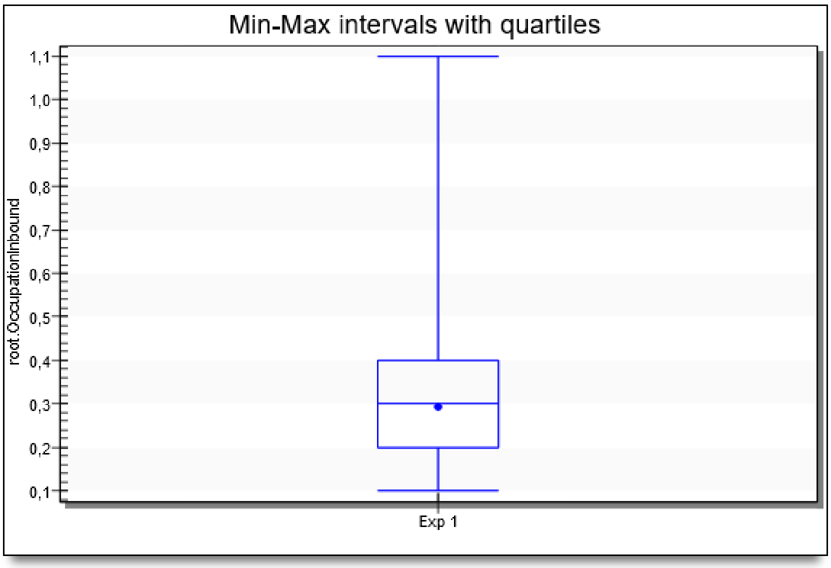

Figure 65 Box plot of the inbound occupation in the main warehouse

Experiment	root.OccupationInbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.292	0.167982683090197	0.1	1.1	0.258661017578828	0.325338982421173

Table 43 Inbound occupation in the main warehouse

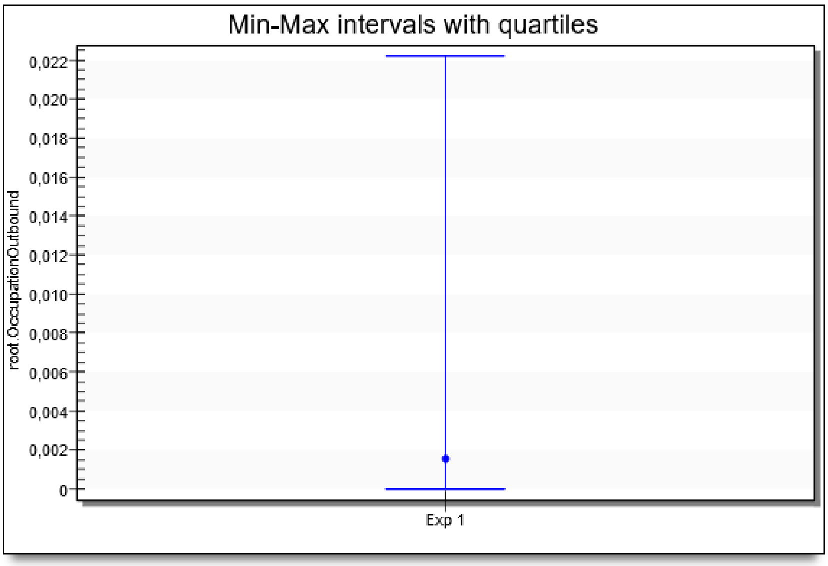

Figure 66 Box plot of the outbound occupation in the main warehouse

Experiment	root.OccupationOutbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.00155555555555556	0.00569849777724984	0	0.0222222222222222	0.000424593043658935	0.00268651806745218

Table 44 Outbound occupation in the main warehouse

Experiment	root.NProductsAisles	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0	0				

Table 45 Number of products in the aisles in the main warehouse

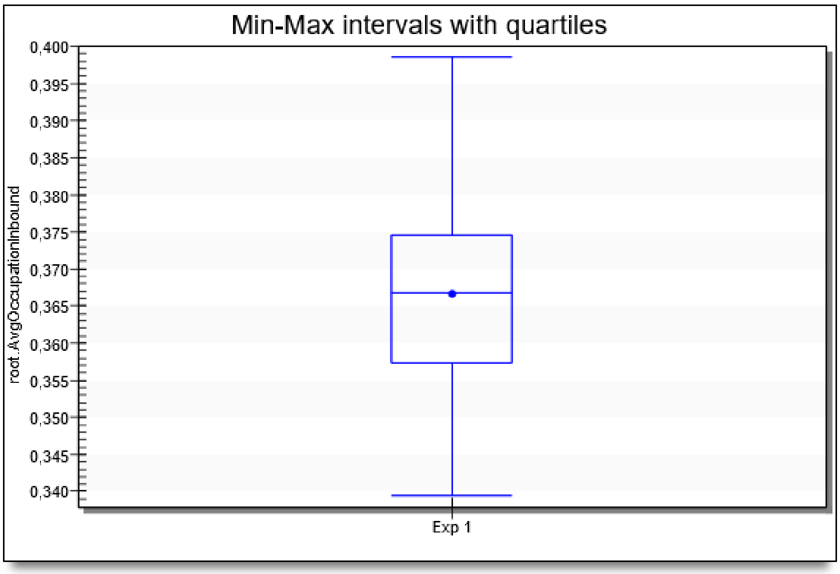

Figure 67 Box plot of the average inbound occupation in the main warehouse

Experiment	root.AvgOccupationInbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.366672288080027	0.0124991567100924	0.339423070007354	0.39861614108469	0.364191620679248	0.369152955480806

Table 46 Average inbound occupation in the main warehouse

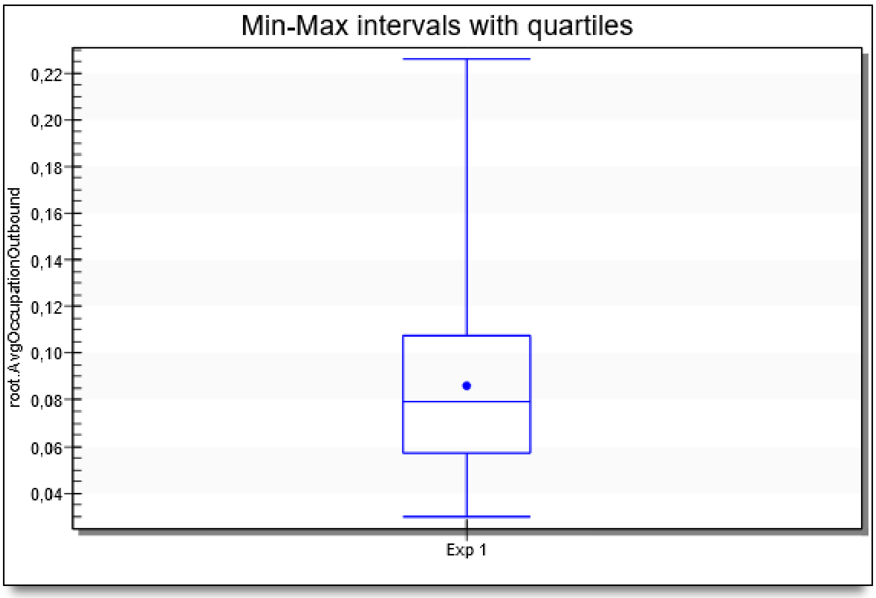

Figure 68 Box plot of the average outbound occupation of the main warehouse

Experiment	root.AvgOccupationOutbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.0859624836136141	0.0410525408265326	0.0297737796857053	0.226219073005282	0.0778149179730216	0.0941100492542067

Table 47 Average outbound occupation in the main warehouse

Experiment	root.nCarry	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	11125.39	233.639188934712	10543	11745	11079.0203821948	11171.7596178052

Table 48 Number of carrying operations in the main warehouse

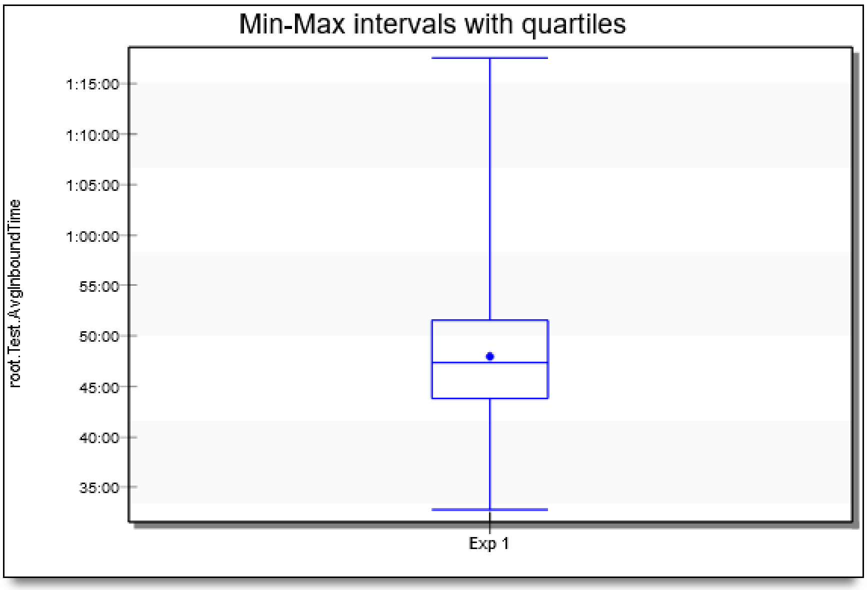

Figure 69 Box plot of the average inbound time in the new warehouse

Experiment	root.Test.AvgInboundTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	47:58.9272	6:43.8900	32:45.8488	1:17:32.7137	46:38.7684	49:19.0859

Table 49 Average inbound time in the new warehouse

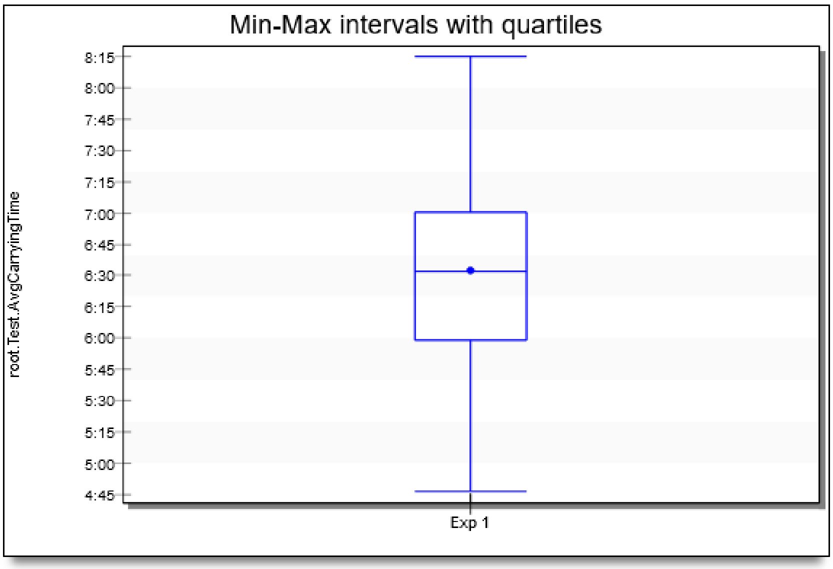

Figure 70 Box plot of the average carrying time in the new warehouse

Experiment	root.Test.AvgCarryingTime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	6:32.6924	42.9020	4:46.4554	8:15.1524	6:24.1778	6:41.2070

Table 50 Average carrying time in the new warehouse

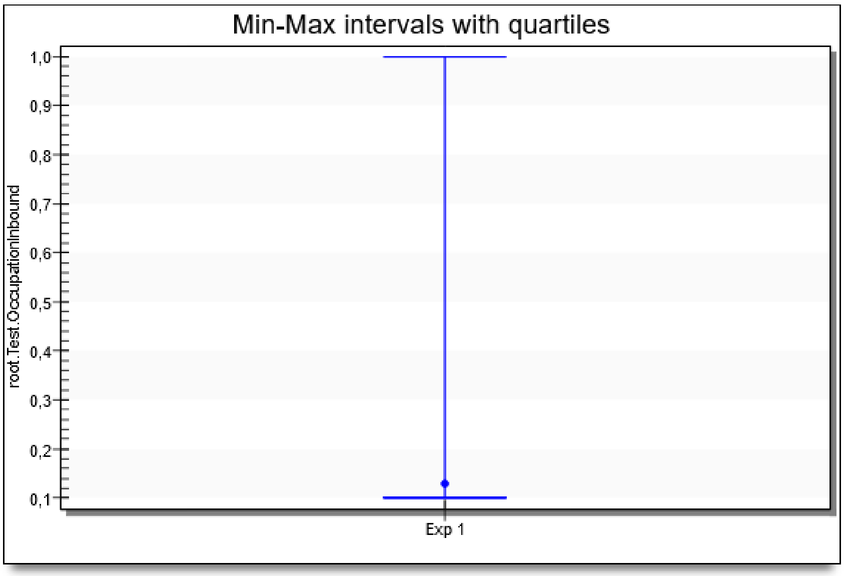

Figure 71 Plot of the Inbound occupation of the new warehouse

Experiment	root.Test.OccupationInbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.13	0.108711461300922	0.1	1	0.10842438618899	0.15157561381101

Table 51 Inbound occupation in the new warehouse

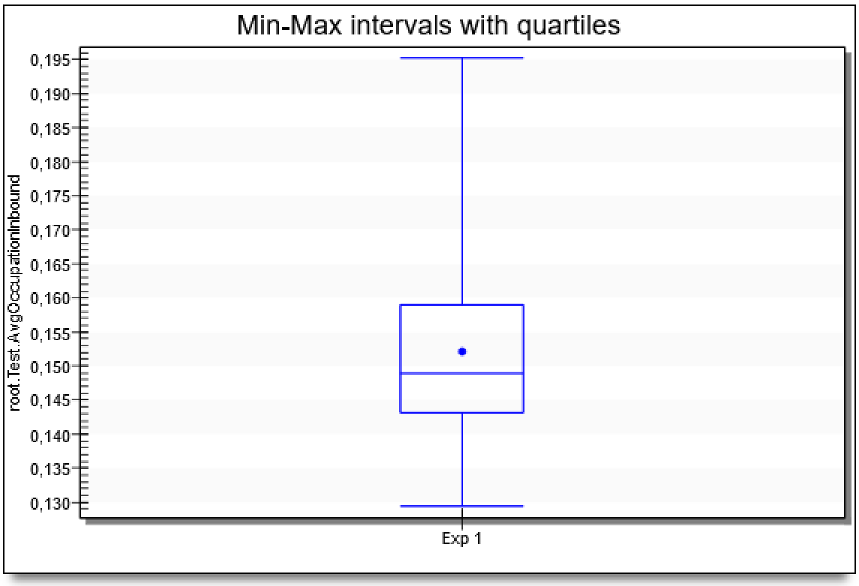

Figure 72 Box plot of the average inbound occupation in the new warehouse

Experiment	root.Test.AvgOccupationInbound	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.152123952036157	0.012369015643453	0.12940146295126	0.195245023536331	0.149669113313984	0.154578790758329

Table 55 Average inbound occupation in the new warehouse