OPTIMIZING THE CONSOLIDATION POINT OF COMPANY X

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Preface

Dear Reader,

The report you are about to read is about optimising a Consolidation Point of Company X. It marks the end of the three-year lasting bachelor Industrial Engineering and Management at the University of Twente.

Firstly, I would like to express my gratitude to my supervisor at the company for providing me with the opportunity to undertake an engaging and challenging graduation assignment at Company X. I also wish to thank the company supervisor for its assistance in clarifying the processes of Company X when they were unclear and for connecting me with the appropriate colleagues to obtain the necessary information. Additionally, I extend my thanks to my colleagues at the company for their willingness to make time free to help me in the data collection process and for making me feel welcome and integrated within the Process Engineering Department.

I would also like to thank my supervisor at the University of Twente, Dr. Lin Xie and Dr. Amin Asadi, for their valuable feedback. Their expertise and ideas allowed me to look at the research from a different perspective and to increase the quality of this research. A special thanks to Dr. Lin Xie for visiting the warehouse of Company X and showing interest in the process of the consolidation point.

Enjoy reading this bachelor’s thesis.

Thijs van Rossum

Enschede, September 2024

Management Summary

The research for this graduation project was conducted at Company X. Due to the confidential nature of the study, the actual name of the company has been withheld, and it is referred to as Company X. Additionally, the data utilized in this research have been modified from the original figures. However, the methods employed in the study remain unchanged, and the research approach and conclusions are unaffected. Only specific data, such as expected growth and processing times, have been altered for confidentiality purposes.

Company X is a manufacturer in the transportation industry and has production facilities all over the world. The logistics department of the company is responsible for delivering production components to the right places at the right time. If this does not happen correctly, the production facilities are on hold, and Company X will face a backlog in products produced.

The logistics department of Company X has a crossdocking warehouse (referred to as Logistics Building X: LBX) that functions as a consolidation point (CP); it receives goods from international suppliers, and it dispatches the goods to countries overseas. The destinations that Company X currently delivers goods to are its production facilities in India and Peru, and a production factory of Company Y in Mexico[1]. Starting from 2025, the consolidation point of Company X will also receive and dispatch goods to a new production factory in Japan. This means that the throughput, the number of goods handled per time period, in the warehouse will increase. The problem that arises with this expansion, is that the company is unsure if the capacity of LBX is sufficient enough to accommodate this increase in throughput. To analyse the problem of Company X, the main research question addressed in this research is as follows:

Is the consolidation process in Logistics Building X (LBX) able to handle the expected growth in throughput? And if not, what changes have to be made to the processes and layout of LBX to be able to handle the expected growth in volume?

The approach to this this research question is by means of a simulation model. A simulation model was created to represent the situation in LBX. The company's warehouse management system, SAP, was used to collect input data for the simulation model. The missing data was collected by conducting an interview with a supervisor of the warehouse.

Experiments in the simulation model led to a table of output KPIs that show if the current layout and processes of LBX has a sufficient capacity to handle the increase in throughput. After increasing the arrival rate of the handling units (HUs) in the simulation model to the expected future arrival rate of HUs, we can conclude that the capacity is sufficient enough. This conclusion was based on the percentage of HUs that exceed the maximum length of stay of 24 hours. This percentage should be within reasonable boundaries. And since the percentage did not increase compared to the current situation, we concluded that the capacity of LBX is sufficient enough to handle the expected growth in throughput.

A literature review has been performed to search for existing theories to improve and optimize crossdocking warehouses. The literature review resulted in a list of possible solutions to increase the capacity of the warehouse.

After experimenting, we found that the solutions as found by the literature review resulted in a decrease in length of stay of the handling units at the warehouse. The first solution, the removal of the stickering process, reduces the average length of stay in the warehouse by 8,0%. The second solution, the removal of the cargo release step, resulted in a 5,0% reduction in the average length of stay of the

[1] The countries are made up because of confidentiality issues.

handling units. And finally, the third solution, the implementation of the inbound dock allocation model, reduced the average length of stay in the warehouse by 5,1%.

The three solutions were also combined and tested with different combinations of solutions. The experiments resulted in a maximum decrease of 18.4% in the average length of stay of the handling units in the warehouse. This decrease was achieved by implementing all three solutions. Furthermore, the percentage of handling units that exceed the maximum length of stay of 24 hours, decreased compared to the current situation.

These results demonstrate that the current situation in LBX can handle the anticipated growth in throughput. Although the existing capacity of the warehouse is sufficient to accommodate the expected growth, it is still recommended to implement the proposed solutions. The experiments have also demonstrated the value of implementing the three solutions at Company X's LBX. Implementing these solutions significantly decreases the length of stay, thereby increasing the warehouse's capacity. In cases of peak deliveries in handling units or an error in the forecasted volume growth for Japan, the implemented solutions could mean the difference between sufficient and insufficient capacity.

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List of Abbreviations

CP	Consolidation Point
LBX	Logistics Building X
HU	Handling Unit
TU	Transporting Unit
WMS	Warehouse Management System
IBD	Inbound Delivery
ASN	Advanced Shipping Notification
CMR	Contract for the International Carriage of Goods by Road
LMA	Local Material Administration
KPI	Key Performance Indicator
IT	Inbound Truck
ID	Inbound Dock
OT	Outbound Truck
OD	Outbound Dock
OB	Outbound Bin

1. Introduction

Company X is a manufacturer of products for the transportation sector all over the world. The company is divided into production and logistics. The logistics department has different locations, one of the locations consists of a warehouse called LBX (Logistics Building X). One of the activities performed in the LBX warehouse is the consolidation point (CP). The CP process is responsible for receiving, restacking and dispatching internationally-produced goods to the company's assembly plants overseas. Next to being a consolidation point, LBX also includes a Process S. This is meant for products that have a final destination within the country where LBX is located. However, Process S has its own dedicated area in the warehouse and does not interrupt the processes of the CP area.

LBX is a cross-docking warehouse. This means that the products arrive at the building, get sorted based on the destination country and are shipped again after sorting. The whole process between arrival and departure is quick and should be finished within 24 hours.

Currently, the CP process in LBX is responsible for consolidating goods with destinations in India, Peru and Company Y (Mexico). Starting from 2025, Japan will be added to this list of destinations. Company X is building a new production factory in Japan, and the CP will be responsible for the consolidation of the European-made goods destined for this production factory. This means that the volumes to be handled in the CP will increase.

Currently, Company X processes around 4200 handling units (HUs) per day. The expectation is that the volume will be 60% more by 2029. This means that the future demand for the CP will be $160\% \times 4200 = 6720$ HUs per day. The result of this change is that there is a difference between the norm (what is the wanted throughput[2] per day) and reality (what is the current throughput per day). This helps us define the action problem related to the situation of Company X:

The throughput of the Consolidation Point in LBX should be increased by 60% (from 4200 HUs per day to 6720 HUs per day) for Company X

Company X wants to find out if it is able to handle this increase in throughput. Using a problem cluster, as shown in Appendix A, one can find out what the potential core problem of this action problem is. After the elaboration on the core problem in Appendix B, the core problem can be described as: "The problems whose solution will make a real difference." (Heerkens & Winden, 2021, p. 41). This resulted in a list of 5 potential core problems. After analysing the potential core problems and eliminating the problems that are either outside of the research scope or caused by external factors, we are left with one core problem: *"Inefficient layout and process of CP"*. This core problem could result in Company X not being able to handle the expected growth. Therefore, the research question of this report can be formulated and is as follows:

Is the consolidation process in Logistic Building X (LBX) able to handle the expected growth in throughput? And if not, what changes have to be made to the processes and layout of LBX to be able to handle the expected growth in volume?

This research question will help solve the core problem of Company X, which eventually leads to the solution of the company's action problem.

The approach of this research is to make a simulation model that recreates the processes in the warehouse. The advantages of using simulation models instead of performing experiments in reality are that it is faster, it is easier and better for optimisation and it is useful for validation. The downsides of simulation models, however, are that it is time-consuming, data-hungry and reality is complex, so it is hard to recreate the reality in every detail. Since we want to check the capacity of the warehouse

[2] "Warehouse throughput refers to the number of units that are processed and moved through your building." (A-Lined, 2019)

and see the effects of changes in the warehouse processes and layout, a simulation model is a suitable way of seeing the effects of the changes on the capacity. This simulation model will give us an insight into the capacity of the consolidation point and the effects of certain changes in the processes and layout of the warehouse.

1.1 Research Design

To solve the research question mentioned in the previous section, a set of 6 knowledge questions is defined. Appendix C provides a more detailed description of the knowledge questions.

1. *What does the current layout and process of the CP look like?*

An insight into the current situation is needed to be able to know what the simulation model should look like. It also helps us in finding possible points of improvement in the processes and layout. We need these points of improvement to increase the capacity of the warehouse if the capacity seems too low for the expected volumes.

This knowledge question results in a map of the current layout and a flowchart of the processes going on in the current CP. The way to achieve this is by using literature review and observation. Company X currently has some process maps available which can be used in this research. The application of observation provides us with additional information on the CP which is not included in Company X's existing process maps.

2. *How do we set up the simulation study for the CP process?*

Before we can start simulating the warehouse processes, we need to define the different parts of a simulation study. This knowledge question includes the description of the conceptual model, the computer model, the steps we took for the verification & validation of the computer model and the experimental design of our simulation model. The result of this is a working simulation model that describes the real world as well as possible. This working simulation model can be used to perform experiments and test the effects of the solutions as described by knowledge question 6. The background of the information in this knowledge question is 'Simulation: The Practice of Model Development and Use', a book by Robinson (2014).

3. *What are the bottlenecks in the current layout and processes of the CP?*

After performing experiments in the simulation model, we analysed the results to see if we achieved the goal of the research. If we did not achieve the wanted throughput, we could find the bottlenecks in the current layout and processes at the CP based on the output of the simulation experiments. The KPIs clarified in the previous research question help us find those bottlenecks. Existing theories, as described by knowledge question 5, help us find a solution to these bottlenecks. This research question results in a list of bottlenecks in the current layout and processes.

4. *Which theories related to warehouse optimisation can be applied in improving the layout and processes of the CP?*

To increase the capacity, it is necessary to find a more efficient layout and to organize the processes more efficiently. Literature research on warehouse optimisation can help us find solutions towards a more efficient CP. In academic databases like Scopus, there are a lot of journals, books or other scientific papers available that cover these theories. Useful theories can therefore be found if the right search queries are used. The theories used, are related to the frequently occurring problems in warehousing. The theories should help us solve our bottlenecks as well and increase the capacity of the warehouse if necessary.

5. *What is the effect of the solutions on the CP process?*

The effect of the solutions described by Knowledge Question 5 on the KPIs can be tested again by implementing the solution into the simulation model and analysing the results. If the results show a positive impact on the output, the solution can be seen as successful. The result of this question is a list of successful solutions. The solution list should result in a more efficient layout and/or process at the CP. It also includes a conclusion if the CP can handle the expected growth or not.

6. *How can the improved layout and processes be implemented in the CP?*

The final step in the research is the making of an implementation plan for the improved layout and processes of the CP. This implementation plan will help Company X use the research effectively. Achieving an effective implementation plan can be done by conducting interviews. An interview with the supervisor at Company X can indicate what's possible and how to implement the new layout and processes as fast or cheaply as possible. After the solution is implemented effectively, Company X should be able to handle the gradual increase in volume at the CP.

2. Current Situation

To make a simulation model and find the bottlenecks in the current process layout of LBX, it is necessary to have a clear insight into the current processes and current layout. This chapter is focused on the third step in the managerial problem-solving method, the problem analysis. It answers the question: *What does the current layout and process of the CP look like?* It contains a flowchart, a description of the flowchart of processes and a map of the layout of the warehouse, which is related to knowledge question one. Furthermore, it gives a description of the future situation because of the new production factory in Japan.

2.1 Flowchart of Current Process

The process at Company X's consolidation point is concerned with receiving goods from international suppliers and distributing them overseas to India, Peru and Mexico. The whole process from receiving to dispatching is built up with different teams with their responsibilities. This section explains the process from start to end. This is done by making a process flowchart. A process flowchart is a picture that shows and describes the steps of a process in a sequential order (Rodríguez-Pérez, 2024). There are multiple notations possible to make a flowchart. This research uses the theory of Business Process Modelling Notation (BPMN). This is an understandable standard graphical representation of business processes (Object Management Group, 2024). Appendix D provides a flowchart of the CP process.

The first team in the process is the portocabin. This team is responsible for the arrival of the trucks and assigning a docking station to each truck. The arrival is registered in Software Y, which is software that contains information about the delivery, such as the pallets that the truck should contain. Based on the information in Software Y, the portocabin determines the docking station to unload the trailer. This decision is based on the content of the trailer since trailers containing HUs for the Process S are unloaded at the last four docking stations, while the other stations are used for the trailers with HUs for the consolidation point.

After arrival at the docking station, the unloading team is responsible for the unloading of the truck by using forklifts. The pallets are placed in the lane to the corresponding unloading dock. Each individual pallet, also called a handling unit (HU), is scanned using SAP, which is a Warehouse Management System (WMS) that Company X uses. After the employees empty the truck, an employee of the sticker team will place a new label on each pallet. This label is necessary for the tracking of the pallet internally at Company X. The scanned pallets are compared to the delivery list, which is a list of the pallets that should've been in the truck. At the comparison, it might happen that too many or too few pallets arrived compared to the delivery list. In the first case, new stickers must be printed and stuck on the remaining pallets. In the case of too few pallets, mutations will be made in SAP, so the missing pallets are known. The "Goods Receipt" department (GO LBX) is responsible for receiving the goods and processing the goods in SAP and the "Goods Administration" department (GA LBX) is responsible for the creation of the new stickers.

Once all the pallets have a sticker, the GO department will check all the HUs for their foreign customs permit for transport to the country of destination. It might happen that an HU does not have permission to be transported overseas because the foreign customs have not given a permit for transportation yet. The HUs that do not have permission, have to wait for permission before they can be processed. These products are temporarily stored in a dedicated hold area in the warehouse while the Local Material Administration (LMA) discusses the problem with the country of destination.

The HUs that do have a permit to be transported overseas are divided into two groups: restack and no-restack. Some pallets that arrive at the warehouse contain blue boxes with smaller parts like bolts and nuts. These pallets undergo a restacking process since the pallets might contain empty boxes. Therefore, the restack process reduces the transport of empty boxes overseas. An employee at the goods receipt department checks if the lane contains restack pallets. A forklift moves these pallets to the restack area where each individual blue box receives a sticker as well. With that sticker, the boxes can be seen tracked in SAP as well. Once all the blue boxes have been appropriately labelled, the cargo is considered released. This indicates that the pallets stored in the lane, from which these boxes originated, are now cleared for transportation to the outbound area of the warehouse.

At the restack area, the boxes are stacked on a new pallet until a complete pallet is filled. Once a pallet is filled, a new HU is created for the pallet. An employee “drags” the HUs of the boxes to the newly created HU in SAP. Because of this step, the new HU contains all the boxes that are stacked on the pallet. The next steps in the process only use the new HU that was created for the pallet and not the HUs for the individual boxes. The final step of the restacking is adding straps to the pallet to ensure that no boxes fall off the pallet during transportation.

As mentioned before, the ‘Cargo Release’ step can only be completed once all the blue boxes that arrived in that specific lane are handled at the restack area. With the release of cargo being completed, the forklifts are notified about the HUs that can be transported. A dashboard in the forklift informs the employee which pallet to pick up and where to place it. One of the destinations might be the “Air” area in the CP. Transportation by air is much more expensive than by sea, therefore, only the pallets with a high priority are transported by air. These prioritized pallets are weighed before they can be transported. This weight step is confirmed in a software called Packcenter.

The next step (steps 6.3 and 10.3 in Figure D.1) is the same for both prioritized and normal pallets, and it’s about placing the pallets in the mirrorbox (also called bin), scanning the pallets and checking the number of pallets in system and physical. The bins are areas at the outbound of LBX indicated by yellow lines on the floor. A bin recreates the area of the sea container and helps order the pallets in the right order, such that most pallets fit in a sea container. The employee can decide for himself how he wants to stack the pallets. The only criterion is that the height can’t be more than 14 layers, where 1 layer is between 15 and 20 cm. So, the maximum height of the stacked pallets is 2,6 m.

After scanning the pallets in the mirrorbox, a Transporting Unit (TU) is created. This is a unit that contains all the pallets in the corresponding mirrorbox. This also includes a request to Company Z for the delivery of an empty sea container, or a trailer.

After the arrival of either a sea container or trailer, employees at the CP will place the pallets from the mirrorbox in the right container or trailer. A sea container has to be sealed before being transported overseas. Then Company Z receives a notification that the container is full and it can be shipped. The final step in the process is transferring the information of the shipment to the Post Goods Issue. This is the confirmation of the process at the CP and a notification to the country of destination that the goods are shipped.

2.2 Map of Consolidation Point

Most warehouses use one of three common design types for warehouse layouts: U-shaped, I-shaped and L-shaped (Jenkins, 2023). Company X’s Consolidation Point makes use of the I-shaped warehouse layout. This means that one side of the warehouse is dedicated to receiving goods, the middle of the warehouse is for storage and the other side of the warehouse is responsible for dispatching goods. Figure 2.1 provides a schematic representation of an I-shaped warehouse.

Company X transformed this shape layout into its processes and came up with its own version of the layout. Appendix E provides the layout that Company X uses.

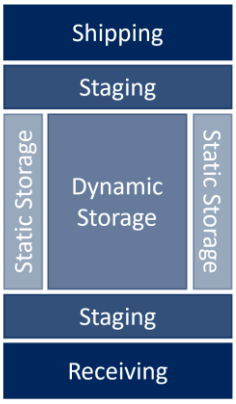


Figure 2-1: I-shape Design of Warehouse Layout

The first area of LBX is the inbound area on the south side of the building. This is the place where the trucks arrive and park the trailer at the unloading docks. The pallets are unloaded and temporarily stored in the lanes at the inbound area (light blue area). The pallets that contain blue boxes go through restack (pink area) before they can go to the outbound area (purple area). Forklifts transport the pallets from either the inbound or the restack area to the bins in the outbound area. This outbound area consists of mirrorboxes as explained before. The outbound area is divided into the different destinations: India, Company Y (Mexico), Peru, Air and Process S. There is also a dedicated area for products that do not have permission from foreign customs yet, that is the hold area (pink/purple area on the map). Once a mirrorbox in the outbound area is completely filled, forklifts load the pallets into a sea container or a trailer, depending on their urgency. The pallets will leave the building on the north side of the building.

The right side of the building is dedicated to a few different processes. The first one is storage for maintenance parts for the warehouse itself and for external companies working in the warehouse, think of the ICT maintenance company. Next is a workplace for the process supervisor. Furthermore, products that did not meet the quality check (performed in the orange area) and need extra time to be fixed will be stored in the “Andon” area. The “Flex” area is meant to be flexible and is used for unforeseen storage needs of all buildings in the city of LBX. Products will only be stored there in emergencies. And finally, the “Fragility Flow” area is used for the storage of fragile components. The fragile products cannot be stored together with the regular pallets because of local laws.

The right side also has a loading and unloading area where trucks can enter the building and load and unload inside the building. However, because of legislation where diesel trucks are not allowed inside buildings, these areas are no longer used for loading and unloading trucks.

The forklifts in LBX are electric vehicles and need to be charged. That’s what the “Charging Station” is for in the top left corner of the building. Next to the charging station, a meeting area for supervisors is located. Next to that is the “Pump Room” where water is pumped out of the water tank outside the building (pink circle). This water is used to extinguish fire if a fire occurs in the building.

2.3 Future Situation

As explained before, the new situation will be that the consolidation point in LBX should also supply the new production factory in Japan with products. This means that the volumes at LBX will increase compared to the current situation. Table 2.1 shows the expected increase in volume for Japan. The distribution of the volume over the years is however not known, so we do not know how many containers will leave LBX per day. To determine this, we will assume a linear increase in volume over the years. Since it's our goal to make LBX future-proof till at least 2026, we will prepare the building for the highest demand in that period. According to Table F.1 in Appendix F the demand is the highest in the last three months of 2026, with 85 containers leaving the building per month, which is 5 containers per day. This is a 15,3% increase in volume compared to the current number of containers leaving for India and Peru (30,5 + 2,2 = 32,7).

Year	Number of Containers
2025	172
2026	683
2027	1187
2028	1966
2029	2188

Table 2.1: Expected Yearly Demand for Japan

The products that will be shipped from LBX to Japan are the same type of products that Company X is currently handling in the CP. Some pallets will go through restack and others will not. A difference with the current situation is however, that the pallets can be transported directly from inbound to outbound without the need to temporarily store them at inbound. Currently, the pallets have to be stored in the inbound area first until the 'Release of Cargo' happens, this will not be the case for the pallets from Japan. Direct shipments eliminate double handling and the wasted action of "pallet touching the floor". This reduces throughput time, which is the time between the arrival and departure of a Handling Unit.

3. Literature Review

A crucial part of doing research is searching and evaluating existing theories and available literature that apply to the research. This section is dedicated to the literature review of this research. It answers the research question '*Which theories related to warehouse optimisation can be applied in improving the layout and processes of the CP?'*. Section 3.1 is focused on the studies that have been conducted for crossdocking optimizations, and the approaches that were used in those studies. The main focus of Section 3.2 is the analysis of advancements and improvements within cross-docking warehouses.

3.1 Crossdocking Optimization Studies

Various approaches have been developed for optimizing cross-docking operations, including the asynchronous multimodal approach, queueing systems, and simulation studies. A review of the literature on these approaches will help in identifying the most suitable method for our research.

The application of the multimodal approach for cross-docking operations has shown to be effective in the context of transportation networks (Hoel, Heng, & Honeycutt, 2005). Other applications of this approach is "…identifying and simplifying optimization of cross-docking terminals" (Pawlewski, 2015).

Studies applying queueing theory to cross-docking operations have shown the use of this approach in finding the most optimal number of inbound and outbound doors (A. & M., 2018). Another application of queueing systems is for minimizing the waiting times for the assignment of trucks to inbound docks (Shahram fard & Vahdani, 2019).

Several studies have shown the success of using simulation study in cross-docking operations. The application of simulation study has been used to optimize the performance of a cross-docking warehouse (Adwunmi & Aickelin, 2008). Another study showed that simulation can also be proposed to optimize multiple performance measures, such as total throughput and average operation time (Shi, Liu, & Liu, 2013).

After reviewing the different methods, it seems that a simulation study is the most suitable for our research. This is because simulation studies focus on improving the efficiency of the warehouse and evaluating the performance of the crossdock. On the other hand, the main focus of other methods is on transportation schedules or dock allocation models. Since our goal is to optimize the warehouse itself, a simulation study is the best fit for our research. The remainder of this section will therefore be focused on simulation study itself, and what to consider when performing a simulation study.

3.1.1 Simulation Study

An advantage of using simulation study instead of other design techniques, is that it can provide additional insight since it is virtual (Rohrer, 1995). This helps project team members better understand the current and future operations.

A useful simulation model must provide output that can be used to compare different scenarios. According to Rohrer (1995), the time spent between receiving to shipping is an important measure to analyse how the crossdocking system is performing. The time that a truck spends loading and unloading at a dock is also an important performing metric according to Rohrer (1995). And finally, we should look at the material handling equipment utilization, this shows how often certain stations are occupied. This metric provides valuable insights into the overall efficiency and effectiveness of the operation.

In addition to the metrics highlighted by Rohrer (1995), Ghazi et al. (2005) emphasize the importance of incorporating several other key performance indicators. These include the percentage of products exceeding the cycle time threshold, the ratio between inbound and outbound trailers, the number of delayed outbound trailers, and the percentage of trailers departing with less than a full truckload, measured in terms of both weight and volume.

Looking at the goal of our research, we can make a selection of useful KPIs. The output of the simulation model is determined by the selected KPIs. Since we want to know the capacity of the warehouse, we need to know the percentage of products exceeding the cycle time threshold, which is 24 hours in our case. To calculate this, we also need to know the time spent between receiving and shipping, the throughput time. And finally, to see the real occupation of the warehouse, we have to look at the utilization of the stations, such as the restack area.

3.2 Layout Improvements

One of the main focussed of this research is to find the most optimal layout for the operation that Company X performs in LBX. The warehouse layout is concerned with the arrangement of the space within a facility, such as the arrangement of the different processes within the warehouse (Jenkins, 2023). We want to have the most efficient layout to minimize travel distance and congestion and maximize the capacity of LBX.

3.2.1 Warehouse Shape

As explained in Section 2.2, Company X currently makes use of an I-shape cross-docking layout. This means that the goods arrive at one side of the building and leave on the other side. The most used warehouse design shapes besides the I-shape, are U-shaped and L-shaped warehouses. Every warehouse design shape has its advantages and disadvantages.

The I-shape is a straight warehouse design where all goods move in a single direction like an assembly line, as shown in Figure 3.1. Because of this straightforward design, this warehouse shape can be useful for warehouses that deal with high-volume orders (Jenkins, 2023). For this reason, this shape is an efficient shape for Company X's activities in LBX. Also, according to Bartholdi & Gue (2004), an I-shape warehouse design is the most efficient for docks of fewer than about 150 doors. Since LBX has 58 loading and unloading docks in use, the I-shape is the best shape for our warehouse according to Bartholdi & Gue.

A drawback of this warehouse design shape is, that both sides of the warehouse need loading/unloading docks. However, the warehouse of Company X already has loading docks on both sides since it is already using the I-shape design. Another disadvantage of the I-shape design is that the goods need to travel the entire length of the warehouse. In our situation, this is not a problem, however, since the loading/unloading docks are placed along the long sides of the warehouse. Therefore, the distance between the receiving and dispatching areas is minimized.

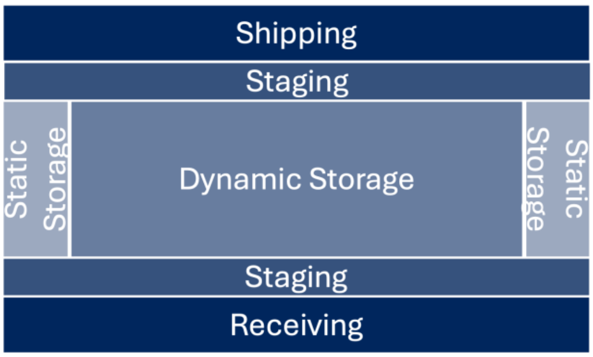


Figure 3-1: I-Shape Warehouse Layout Design (CIN7, 2023)

Next, the inventory of a U-shaped warehouse design is arranged in a "U" shaped semicircle. Figure 3.2 shows that both ends of the "U" are used as receiving and shipping docks. The advantage is that both docks are located next to one another, offering shared utilization of dock resources such as personnel and material handling products (REB Storage Systems International, 2024). The storage area of the warehouse is located in the middle portion (the bend of the "U"). If the shipping and receiving docks are too close to each other, congestion can occur, especially at high volumes. Since Company X deals with an average of 35 arriving trucks and 35 departing containers per day and only has space for 32 loading/unloading docks on one side, the chance of congestion and waiting trucks is high. Another disadvantage of the U-shaped warehouse design is that the storage area consists of a big static storage area and a relatively small dynamic storage area. The difference is that the static storage area is the place where the overflow of product is stored, or in our case, the pallets that do not have a foreign customs permit and need to wait in the hold area. The U-shaped warehouse design is therefore less suitable for businesses that cross-dock.

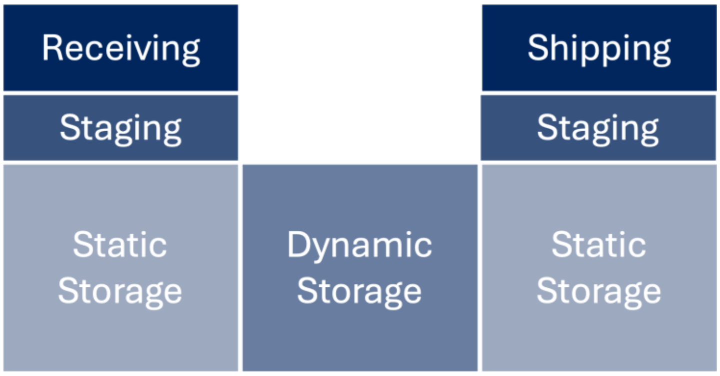


Figure 3-2: U-Shape Warehouse Layout Design (CIN7, 2023)

The third warehouse design is the L-shape warehouse, shown in Figure 3.3. For L-shaped layouts, the receiving and unloading areas are on both ends of the "L". The remaining space is designated for both static and dynamic storage. The advantage of an L-shaped warehouse layout is that it reduces back-and-forth movement, since the goods arrive at one side of the building and leave at another side of the building. However, the L-shaped layout is often used to fit an L-shaped building. This makes it less useful for Company X's LBX since this warehouse is shaped like a rectangle. In Figure 3.3 one can see that the travel distance between receiving and shipping increases compared to the I-shaped warehouse layout. We cannot use the entire south side of the building for receiving goods, as this will increase the chances of congestion. The issue arises because the receipt and issue of goods will be adjacent to each other on the right side of the building. Therefore, we cannot utilize the right half of the south side of the warehouse. Since the receiving docks are located on the left side of the building and the shipping docks on the right side, the travel distance will be greater compared to the current warehouse layout.

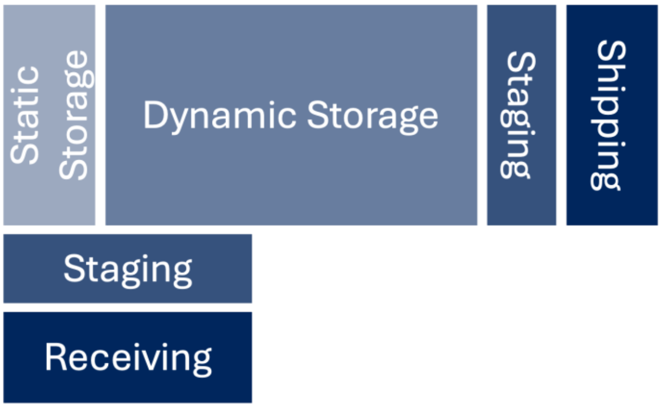


Figure 3-3: L-Shape Warehouse Layout Design (CIN7, 2023)

Furthermore, if we decide to implement the L-shape layout design in the rectangular shape of the warehouse, we need to use the short side of the building as either a receiving or shipping dock. This means that we can only use a maximum of 13 loading/unloading docks on one side of the building instead of the 28 or 30 loading docks Company X is currently using for receiving and shipping goods respectively.

Looking at the advantages and disadvantages of the three warehouse designs, we can conclude that the I-shaped warehouse design is most suitable for Company X's LBX. This has to do with the activities that Company X performs at this warehouse and the volumes that it deals with. Another important point is the shape of the building. It has a rectangular shape with the width being 3 times as long as the length. This makes the L-shaped warehouse design less suitable for the current building. So, concerning the warehouse design, we will stick to the current warehouse layout.

3.2.2 Pallet Racks

The pallets that arrive at LBX have to be stored somewhere. Currently, all the storage in the warehouse is floor storage. Another type of pallet storage is by using pallet racks. According to Bartholdi and Hackman (2019), one of the advantages of pallet racks is their potential to create additional pallet positions by taking advantage of vertical space. Compared to floor storage, such as the current setup in LBX, pallet racks can store pallets at greater heights. Floor storage in Company X's warehouse is limited to a maximum height of 2.60 meters. If we decide to install pallet racks, the maximum height could be increased to 6 meters, effectively doubling the storage capacity within the same area.

However, cases where pallet racks do not create additional pallet positions occur when the maximum height of floor storage is already close to the ceiling (Bartholdi & Hackman, 2019). In such instances, adding pallet racks might even reduce the number of pallet positions, as each layer of pallet racks requires more space than a layer of floor storage.

Furthermore, pallet racks can create a cramped workspace if there is insufficient room for manoeuvring (Bair, 2022). Installing a pallet rack in the inbound area can restrict the movement of unloading forklifts, which slows down the process of unloading.

Additionally, a cross-docking warehouse like LBX typically has high throughput, meaning goods are stored for only short periods. Therefore, unless the pallets are uneven on top and pallet racks reduce labour by facilitating easier storage and retrieval of goods, as noted by Bartholdi and Hackman (2019), it is not advantageous to install pallet racks in a cross-docking warehouse.

Also, it is not advantageous to place pallet racks at the outbound bins in the warehouse, as these bins serve as representations of the sea containers. By arranging the pallets in the correct order within the warehouse, time is saved during the loading process of the sea containers. Installing pallet racks at the outbound bins would prevent us from effectively arranging the pallets within the warehouse.

Taking these points into account, the only place in the warehouse where a pallet rack might be beneficial is the hold area. Since there is not much movement of unloading of trailers or loading of sea containers happening that might be hindered by pallet racks. Also, the pallets stored at the hold area, generally stay there for 24 hours or more, so the throughput time of those pallets is lower.

3.3 Process Improvements

Besides layout improvements, one can also look at the processes performed at the warehouse. Are there unnecessary steps involved in the process? Can different process steps be combined? Answering these types of questions will help us find process improvements and increase the capacity at LBX.

Looking at the results from the experiments of the simulation of the current processes and layout, one can see a couple of interesting things.

3.3.1 Dock Allocation

Travel time inside the warehouse is a big factor in the throughput time of the pallets. A lower travel time inside the facility results in a lower throughput time, which increases the capacity of the warehouse. The dock where a trailer is unloaded and a sea container is loaded, influences the travel time of the pallets. Hence, we look at the most optimal dock allocation for unloading and loading, to minimize travel distance in increase the warehouse capacity.

Zhang et al. (2010) consider three objectives in the dock allocation problem: minimizing the total starting and handling times of arriving trucks at inbound docks, minimizing the total weighted travel distance of pallets within the facility, and minimizing the total departure time of outbound trucks at the outbound docks.

The first objective calculates a different unloading time for different data sets. This unloading time varies depending on the unloading dock. Since we assume that the handling time for unloading depends on the number of pallets in the trailer and not on the inbound dock, we can ignore this objective in our calculations.

The second objective examines the distance between the unloading dock and the destination within the facility, multiplying this distance by the number of pallets designated for that destination to determine the total travel distance. This objective is relevant to our research, as we have knowledge of the pallets' destinations upon arrival as well as their destinations within the warehouse. To determine the most efficient unloading dock, we employ the mathematical model developed by Zhang et al. (2010). The mathematical model can be modified according to our situation, this results in the model as shown below:

Index

i	Index for all inbound docks, $i \in \{1, 2, \dots, I\}$
j	Index for all outbound bins, $j \in \{1, 2, \dots, J\}$
k	Index for all pallets in inbound truck, $k \in \{1, 2, \dots, K\}$
o	Set of unoccupied inbound docks, $o \in \{O_1, O_2, \dots, O_n\}$

Parameters

C_k	Current outbound bin for pallet k, $C_k \in j$
$T_{i,j}$	Travel time between inbound dock i and outbound bin j

Decision Variables

x_i	Binary decision variable indicating whether inbound dock i is chosen (1 if chosen, 0 otherwise). Here, x_i should be defined for $i \in o$ (unoccupied docks).

Objective Function

$$\min \sum_{i \in O} x_i \cdot \left(\sum_{k=1}^{K} T_{i,C_k} \right)$$

Constraints

$$\sum_{i \in O} x_i = 1$$

Explanation

The objective function finds the inbound dock i that has the lowest travel time for all the pallets in the inbound truck. If an inbound dock is already occupied by another inbound truck, $i \notin O$, that means that that dock cannot be assigned as the unloading docks. The constraint makes sure that one inbound dock gets assigned per arriving trailer.

The third and final objective minimizes the total departure time of the outbound trucks. Zhang et al. (2010) consider the loading time of an outbound truck as a parameter that depends on the outbound truck and the outbound dock. Similar to the handling time of unloading an inbound truck, we assume that the handling time depends on the number of pallets to load in the outbound truck and not on the inbound dock. So, we will ignore this objective in our calculations.

In summary, we only consider the travel time between the inbound dock and the outbound dock when determining the optimal inbound dock. The inbound dock with the shortest travel time to the outbound dock, according to the mathematical model of Zhang et al. (2010), is deemed the most efficient unloading dock, and thus, the inbound trailer will be allocated to this dock.

3.3.2 Staging Protocol

Staging of pallets near a loading/unloading dock causes several problems. Two significant problems are the increased chance of congestion and delays, as well as the need for additional space for staging (Bartholdi et al, 2007). Both problems have an effect on the throughput in the warehouse. Therefore it is necessary to consider different staging protocols for the warehouse.

There are different staging protocols that affect not only the efficiency of the material flow but also the efficiency with which containers are loaded. Some staging protocols allow us to achieve higher load factors: the percentage volume filled of a departing container (Bartholdi et al, 2007).

Company X makes use of a *two-stage* protocol, as shown in Figure 3.4. A team of workers puts pallets in lanes corresponding to the receiving doors, a second team sorts the pallets based on destination country into the shipping lanes, and a final team loads the pallets into the outbound containers. According to Bartholdi et al (2007), The advantage of a multi-stage protocol is that it is easier for the outbound workers to pack the trailer tightly and the disadvantage is that pallets are handled multiple times.

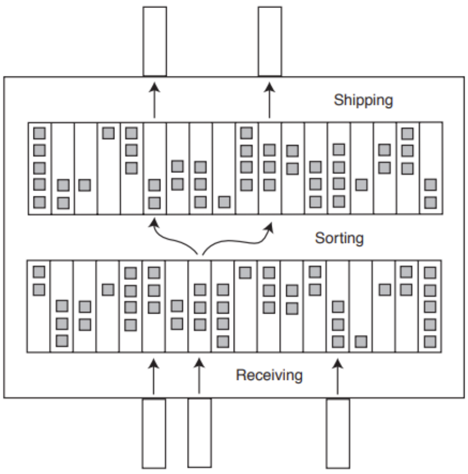


Figure 3-4: A two-stage crossdock (Bartholdi et al, 2007)

Simulation research by Bartholdi et al. (2007) concluded that a single-stage system has a significantly higher throughput than a two-stage system. There are three protocols to organize a single-stage system: sort-at-shipping, sort-at-receiving or double-sort protocol. The protocols are shown in Figures 3.5, 3.6 and 3.7 respectively.

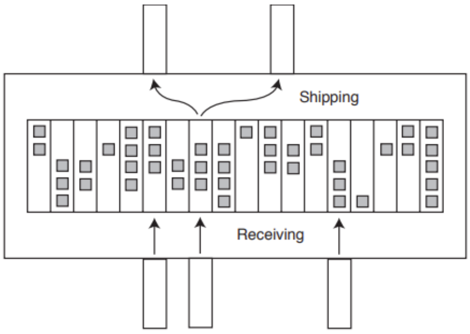


Figure 3-5: Sort-at-Shipping Protocol

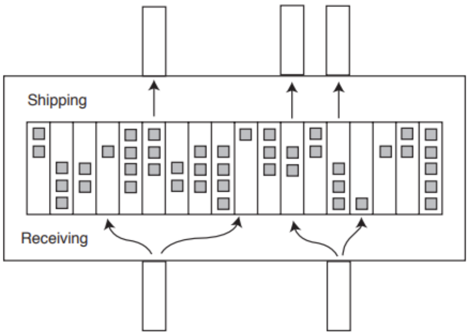


Figure 3-6: Sort-at-Receiving Protocol

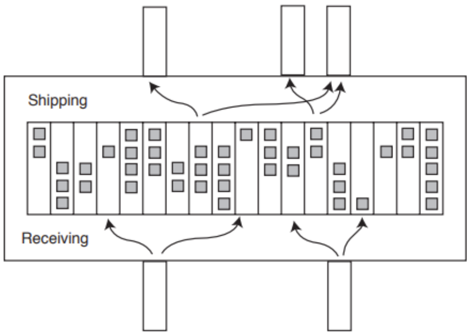


Figure 3-7: Double-Sort Protocol

In the single-stage, sort-at-shipping (SaS) protocol, workers at the shipping area pull pallets out of the lanes where they were delivered and deliver them in the appropriate outbound container. The advantage of the SaS protocol is that the destination of a pallet need not be known when the pallet is unloaded from the trailer, since the worker places the freight in the lane corresponding to the unloading dock. One of the big problems of the SaS protocol is the load factor. Because the workers at shipping load the containers on delivery, there is no opportunity to select pallets for an efficient arrangement of the sea container.

The advantage of the single-stage, sort-at-receiving (SaR) protocol is that the load factor of the sea containers can be higher (Bartholdi et al., 2007). This means that transportation costs are reduced in the long run, and the space needed at the staging area is less. This protocol is only possible if the destination of the pallet is known at arrival, which is the case for Company X.

The third protocol, the double-sort (DS) protocol, is not a protocol that is often used in practice, but it might be applicable to operations that do not prioritize the load factor. Since we want to achieve a throughput, a high load factor is important to us, so this protocol is not desirable to our operation.

Single stage-systems have in general a higher throughput than a double-stage system (Bartholdi et al., 2007). Since we want to increase the throughput of LBX, this seems to be a solution to our problem. However, single-stage systems are less beneficial for value-added services, such as the restacking process in LBX. However, by combining the two-stage and the single-stage system, a benefit can be achieved compared to the current protocol. The two systems can be combined by making a separation between the goods that need value-added services (restack pallets) and goods that don't need value-added services (normal pallets). The restack pallets can be staged at the inbound area until the restack area becomes available, while the normal pallets can be transported directly from inbound to outbound and follow a SAR protocol.

It is important to consider the "release of cargo" step in the process because this step currently does not allow us to move the pallets from inbound to outbound unless the restack pallets have been processed at restack. Thus, we need to remove the "release of cargo" step in the process, as explained in Section 2.1.

3.3.3 Release of Cargo

To implement the SaR protocol, we need to remove the release of cargo step in the process. Release of cargo does not allow us to transport the normal pallets from inbound to outbound unless all the blue boxes from the same lane are processed at the restack area. This means that normal pallets are waiting for transportation, although there might be forklifts available. This waiting time increases the throughput time of the pallets, which decreases the maximum throughput of the warehouse. So, by removing this step in the process, the pallets can be transferred directly from inbound to outbound, without the need to wait for the restack pallets. The release of cargo step can be removed by changing the warehouse management system used in LBX. By changing the software of SAP, this step can be removed from the consolidation process.

To summarize, there are different approaches to warehouse layout and process improvement. Concerning Company X's warehouse design in LBX, it is most efficient to stay with the I-shape that it is currently using. Next, pallet racks can be applied in the hold area of LBX, this increases the storage area and possibly increases the throughput. Furthermore, we can apply a mathematical model to calculate the most efficient inbound dock for the incoming trailer. This can reduce travel distance inside the warehouse. Then, a combination of a single- and double-stage protocol can be applied in the warehouse to decrease the throughput time of the Hus. However, this is only possible if the release of cargo step in the process is removed. In Chapter 6 we check the effects of each of these possible improvements.

4. Simulation Study

A simulation study consists of various deliverables (Robinson, 2014). This chapter outlines the four steps involved in a simulation study, and it answers our knowledge question: *How do we set up the simulation study for the CP process?* The stages of the simulation study are based on the book of Robinson (2014), as shown in Figure 4.1. Chapter 2 provides a detailed description of the current situation, representing the real world in simulation studies. Section 4.1 explains the conceptual model to be developed. Next, Section 4.2 presents and elaborates on the developed computer model. Finally, Section 4.3 discusses the experimentation setup of the computer model. The final step of the simulation study, implementation, is covered in Chapter 6.

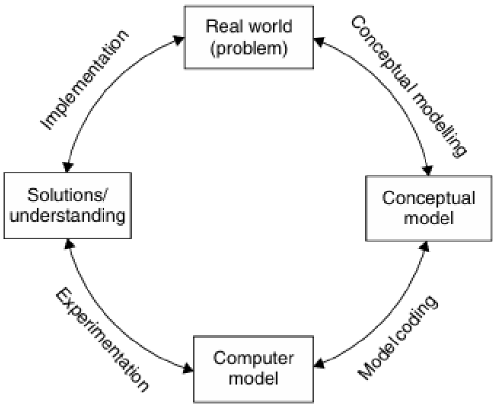


Figure 4-1: Simulation Studies: Key Stages and Processes (Robinson, 2014)

4.1 Conceptual Model

The advantages of using simulation models instead of performing experiments in reality are that it is faster, it is easier and better for optimisation and it is useful for validation. The downsides of simulation models, however, are that it is time-consuming, data-hungry and reality is complex, so it is hard to recreate the reality in every detail. Therefore, we create a conceptual model to identify the objective, the input & output data and the content of the simulation model.

Different types of simulation are used. The type of simulation used in this research is discrete event simulation. *"Discrete-event simulation, or DES, is intended to simulate systems where events occur at specific, separable instances in time*" (Software Solutions Studio, 2022). The event is seen as a state change of the simulation, such as the arrival of goods. This happens at a specific time in the simulation, and the simulation only considers the points in time at which the state changes. This is also the case in LBX, where the state of the warehouse only changes if a certain event occurs, such as the arrival of a trailer, or the movement of a pallet. The software used to model this discrete event is Tecnomatix Plant Simulation 16.1.

4.1.1 Objectives

As discussed in Chapter 1, Company X anticipates an increase in throughput in the coming years. The critical question is whether the current consolidation process at LBX can accommodate this expected growth. The simulation model developed in this research will determine if Company X can manage the projected volume increase. If the current process proves insufficient, the simulation model will provide insights into the effects of potential changes to the layout and process of the consolidation process (CP).

The restriction to keep in mind during the simulation study is that the throughput times of the handling units should be within 24 hours. This means that the maximum time between arrival and departure is 24 hours. Furthermore, some pallets require an extra step in the process, the restacking process. The restack pallets should go through the restack process and cannot be transported directly to the outbound area. Finally, the pallets that don't have permission from foreign customs, have to wait at the hold area until permission is granted.

4.1.2 Input Data

A crucial component of a simulation study is defining the input of the simulation model. The input manages and sustains the simulation. The input of the simulation model consists of random variables, so we can describe the real world more precisely. The real-life input data is tested for its distribution to describe the variability of the data in the simulation best.

There are various approaches to specify random input data based on a data set from the past. We will fit a theoretical distribution function to the data by means of a statistical analysis that consists of three steps (Robinson, 2014, p. 113). We first select a statistical distribution. We do this by creating a histogram of the data set from the past. According to the shape of the histogram, we find the theoretical statistical distribution that fits the shape. Next, we determine the parameters of the data from the past. Depending on the statistical distribution the parameters differ. For a normal distribution, the parameters are for example the *mean* and *standard deviation*. The parameters allow us to do a goodness-of-fit test in the final step of the statistical distribution fitting. With this goodness-of-fit test, we determine if the sample is likely to follow the predetermined statistical distribution with the predetermined parameters. We can calculate the test statistic of the statistical distribution by comparing the observed frequencies with the expected frequencies (according to the predetermined parameters). If the test statistic is lower than the critical value from the Chi-Square distribution (with 5% probability and $n - 1$ degrees of freedom, with n, being the number of data points), we fail to reject that the data from the past follows the predetermined statistical distribution with the predetermined parameters.

In the absence of data, there are other approximate distributions that provide a useful approximation of a distribution. The simplest form is the uniform distribution with a minimum and maximum value. But a slightly more sophisticated approximation than the uniform distribution is the triangular distribution since it includes the most likely value, the *mode* (Robinson, 2014, p. 107). For the input data that we do not have data from the past, we will use the triangular distribution. To get the minimum, mode, and maximum, we use the expertise of an expert in the field, which is a supervisor at LBX in our case.

In the CP process, different steps have their own processing time. Steps, such as stickering time of the HUs, take a certain amount of time to complete. Next to processing time, we also have to include data types such as arrival rates of the HUs within the warehouse. Table 4.1 shows the different input data types and their corresponding distribution. Appendix G and H show the histograms and tables with the parameters and goodness-of-fit tests for the data types that do not follow a triangle distribution. The data types that do follow a triangle distribution are based on the recommendation of a supervisor in LBX, as mentioned before.

AREA IN LBX	DATA TYPE	DISTRIBUTION
INBOUND	Arrival Rate HUs	$Sea \sim (1+x) * N(3218, 854), Air \sim (1+x) * N(40, 20), Restack \sim (1+x) * N(1513, 454), Company\ Y \sim N(54, 23)$ Where x is the increase percentage of the arrival rate, because of the goods for Japan
	Number of Boxes per Pallet	$\sim Exp(4{,}8)$
	Number of Pallets per Trailer	$\sim Triangular(8, 70, 230)$
	Pallet Type Distribution	Tables in Appendix G.4

	Trailer Unloading Time	$= 00{:}27{:}52 + 00{:}00{:}16 * \#Pallets\ in\ Trailer$
	Sticker Time per Pallet	$\sim Triangular(00{:}00{:}04, 00{:}00{:}15, 00{:}01{:}00)$
RESTACK	Sticker Time per Box	$Blue\ Boxes \sim Triangular(00{:}00{:}10, 00{:}00{:}25, 00{:}01{:}00)$
	Pallet Completion Time	$\sim 5\ minutes$
OUTBOUND	Container Fill Rate	$\sim N(56{,}9;\ 2{,}9)$
	Arrival Time of Empty Container	$\sim Exp(20{,}5)$
	Loading Time per Pallet	$\sim Exp(23577{,}5)$
	Departure Time of Full Container	$\sim Exp(21{,}3)$
OTHER	Number of HU for Hold	$\sim 0{,}0011 * Arrival\ Rate\ Sea$
	Number of Forklifts in use	Unloading: 5, Restack: 1, Picking: 5, Dispatching: 8, Outside: 3
	Transportation Time	Tables in Appendix H.5

Table 4.1: Input Data and their Distribution

4.1.3 Output Data

The output data of our simulation model consists of key performance indicators (KPIs). The output KPIs should be formulated in a way that we can use them to analyse the performance of our simulation model. We do this by keeping the goal of this research in mind when defining the output KPIs.

The goal of the simulation model is to find out if Company X's consolidation point can handle the expected growth in volume. Therefore, it is important to define the output data in a way that makes us able to draw conclusions about this matter. This includes not only the capacity of the warehouse but also the waiting time for different processes in the warehouse. These waiting times will help us find the bottlenecks in the processes and increase the capacity if necessary.

The most important KPI is the capacity of the warehouse. This is the number of HUs that it can handle per day. It is important that the HUs have a throughput time of fewer than 24 hours. That means that the time of goods between arrival and departure has to be less than 24 hours. As soon as the throughput time is higher than 24 hours, the warehouse can no longer handle the volumes and the maximum capacity has been reached. The percentage of HUs that exceed the 24-hour throughput time is therefore also a KPI in the simulation model.

As mentioned before, the waiting times at the different processes have to be included as well. Company X wants to know if the current layout and processes can handle the expected growth, if the maximum capacity shows that this is not the case, we need to be able to determine what the bottlenecks in the current layout and processes are. The waiting times will help us find those bottlenecks because we can look for the processes that take the most time. We can implement solutions to those bottlenecks and see the effects of the solutions on the waiting times and the capacity.

Furthermore, we include data about the number of pallets per arriving trailer and the number of pallets loaded per departing sea container. We can compare this number to the number of pallets arriving and departing in reality. This comparison helps us validate the reliability of the simulation model. If the output of the simulation model and the output in reality are equal, the simulation model is considered reliable and valid. And so, the improvements in the simulation model should provide a good picture of the effects in reality.

4.1.4 Content

For Company X, we only model the Logistics Building X. Within this building, two processes are located, the consolidation process and Process S. In our model, we only include the consolidation process, since both processes are separated and the problem only has an effect on the consolidation process.

The model does not describe the real world in every detail. Section 4.1.2 provides the analysis of the data input. We had to make assumptions for some processes to keep the simulation model running, as described in Section 4.1.5. Furthermore, the data input is based on the real world and is therefore a good representation of reality. However, we cannot include every detail in the simulation model. Variables such as employee mistakes are not included. Section 4.1.6 explains the limitations of these variables missing in the model.

4.1.5 Assumptions

The simulation model is based on the processes and layout described in Chapter 2 of this paper. It uses data from Company X's warehouse management systems as described in Section 4.1.2 of this paper. But next to this, some data is still missing to make the simulation model. Therefore, we have to make some assumptions for the simulation model. The assumptions we made are the following:

- There are enough employees available at the warehouse to perform all the tasks;
- The simulation model makes use of a shift calendar that represents the working hours of the employees in the warehouse;
- The processing time for stacking boxes onto pallets at the assembly station in the restack frame begins once a sufficient number of boxes are available to fill one pallet;
- Forklifts can only transport one pallet at a time;
- There are no blue boxes that go to the hold area, only pallets go to hold;
- There are no blue boxes that are transported by air, only pallets are transported by air;
- HUs for air transportation are picked up every morning at the beginning of the morning shift;
- Pallets with priority do not have to wait for transport if they are ready for pickup. Pallets that get transported by sea require a sea container.

4.1.6 Limitations

One of the downsides of a simulation model is that it can never completely imitate the real world. There will always be unforeseen events in the real world that are impossible to recreate in a simulation model, and that applies to our model too.

One of the limitations of the simulation model used in this research is that it does not take the chances of congestion into account. In the real world, if multiple forklifts are operating in the same area in the warehouse, congestion will increase because of the abundance of forklifts. This simulation, however, only looks at the number of forklifts in the system and not the location of those forklifts. Therefore, congestion is not considered in this simulation model. That's why this simulation cannot calculate the effect on the capacity of the warehouse if more forklifts are used.

Another limitation of our simulation model is the exclusion of human errors. Warehouse employees may make mistakes while performing their tasks, but our processes do not account for these errors. Consequently, the actual outcomes may differ from the results of our simulation model due to these errors.

The final limitation of the model is the omission of the weight of arriving pallets and boxes. The capacity of a departing container is constrained not only by its volume but also by its maximum allowable load weight. Consequently, the weights of the pallets are also a factor in determining the maximum number of pallets in practice. However, due to significant variations in pallet weights and the lack of available data on pallet weights, we opted not to include this factor in the simulation model.

4.2 Computer Model

Appendix I shows the simulation model of LBX. The main simulation frame consists of two components. The grey part, shown in Figure 4.2 contains variables, tables and methods that make sure that the simulation works the way it does. Appendix J contains logic flow charts that describe the main methods of the simulation model. Sections 4.2.1 and 4.2.2 describe the methods and the connection between the methods shortly. The other area of the simulation frame is the warehouse itself with the different components that are located in the warehouse, this is explained in Section 4.2.3

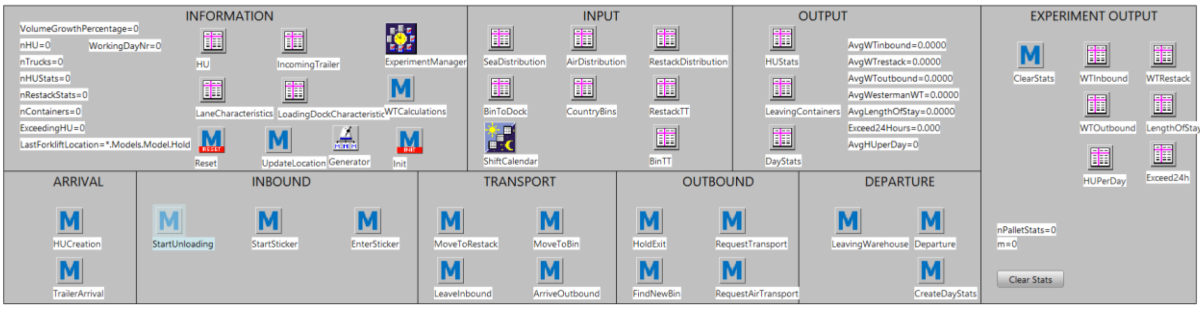


Figure 4-2: Operating Components in Simulation Model

4.2.1 Variables and KPI's Storage

The 'Information' box is responsible for the storage of changing variables during the simulation, for example, the last forklift location. It also contains tables that are updated according to the handling units in the system and the status of the inbound lanes and the outbound docks. Furthermore, it contains a generator that is activated at the end of every day. This generator is called the 'RequestAirTransport' method, which creates a transporting unit for the pallets in the air bins.

The 'Input' box in the grey area includes tables that contain data about the processes in the simulation model. The 'SeaDistribution', 'AirDistribution' and 'RestackDistribution' tables are the same tables as shown in Appendix G.4: Distribution of Pallet Types. The tables are used as distribution tables for the sources of the simulation model. They describe the distribution of the different pallet types for each source. The 'BinToDock' and 'CountryBins' show the travel distance between the bins and the docks, and the bin numbers dedicated for each country respectively. The 'ShiftCalendar' makes sure that the processing stations only work during the working hours of Company X, which is explained in Section 4.2.4. Finally, 'RestackTT' and 'BinTT' are tables that contain the travel time for each possible combination of locations at the warehouse. This could be, for example, from restack to a departure bin, or from an arrival lane to restack.

The 'Output' box consists of output KPIs as described in Section 4.1.3. The KPIs are stored in tables or variables. These KPIs are used to make conclusions about the efficiency of the warehouse and to find the points for improvement.

Next, the 'Experiment Output' box involves methods and tables to store data when performing experiments with the 'ExperimentManager'. The output KPIs are stored in the tables for further analysis.

4.2.2 Process Methods

The methods in the lower area of the grey box are concerned with the usage and calculation of the pre-described information and input data/variables.

The ‘HUCreation’ method in the ‘Arrival’ box determines the characteristics of the incoming goods. For example, it determines the destination country for the HU and it determines if an HU has permission from the foreign customs or not. The other method in the ‘Arrival’ box, the ‘TrailerArrival’ method, determines the unloading dock to unload the arriving truck.

The methods in the ’Inbound’ box in the grey area are responsible for the unloading of the arriving trailers and the stickering of the HUs. The methods make sure that the stickering starts as soon as all the pallets are unloaded from the trailer. Furthermore, the pallets can only continue to their next destination as soon as all the pallets are stickered.

The ‘MoveToRestack’ method in the ‘Transport’ box then makes sure that the restack pallets are filtered out of the lane and transported to restack. Once all the restack pallets are processed at restack, the normal pallets from that lane are allowed to be transported as well and placed in the transportation queue. When the pallets arrive at the transporting station, the ‘LeaveInbound’ method is called. This method calls the method ‘MoveToBin’, which calculates the bin to transport the pallet to, based on the country of destination of that pallet. The ‘LeaveInbound’ method then uses the calculated bin to determine the travel time from the lane to the bin. It uses the ‘BinTT’ table to find the travel time. At the end of the travel time, the HU arrives at the bin and the ‘ArriveOutbound’ method is called. This method places the HU into the bin in the simulation model.

When a bin reaches its maximum volume, the ‘MoveToBin’ method calls the ’RequestTransport’ and ‘FindNewBin’ methods in the ‘Outbound’ box in the grey area. These methods calculate the most efficient dock to load the sea container and the most efficient new bin to place the pallet. The ‘RequestAirTransport’ is called every morning at the beginning of the shift and is responsible for the dispatch of the pallets destined for air transport. Furthermore, the ‘HoldExit’ method is called when a pallet leaves the hold area.

The last box in the grey part is the ‘Departure box. The first method in this box is the ‘LeavingWarehouse’ method and it stores the departure data of the leaving HUs, such as departure time and departure container. It also opens the bin and loading dock again for new HUs to arrive. The ‘Departure’ and ‘CreateDayStats’ store the data and statistics of the leaving HUs in the tables and variables in the ‘Output’ box in the grey area.

4.2.3 Warehouse Design

As one can see in Appendix I, the simulation design of the warehouse consists of four main components: the HU sources, inbound (blue area), restack (green area), and outbound (orange area).

The HU source area is where the Handling Units (pallets and boxes) are created according to a pre-determined arrival rate, described in Section 4.1.2. The four sources create HUs that have a specific destination within the warehouse according to the source that created it. The sources use the pallet distribution tables in the ‘Input’ box in the grey area to determine what handling unit types to create. The created HUs move to the ‘StackAtSupplier’ frame first. The blue boxes are stacked upon an empty pallet according to the distribution described in Section 4.1.2. The normal pallets and the restack pallets then move to the ‘CreateTrailer’ frame. This is where the trailers are created. Each trailer gets a pallet capacity assigned according to the distribution described in Section 4.1.2. The trailers are filled with the created HUs. If the trailer is completely filled, it moves to the trailer buffer where it gets assigned to a loading dock.

The trailer arrives at a 'Dock' station. The 'Unloading' station, as shown in Figure 4.3, contains stations that dismantle the pallets from the pre-assembled truck. The assembled truck enters the frame at the entry and moves to the 'DismantleStation'. The 'DismantleStation' separates the pallets from the truck and it deletes the truck from the system by moving it to the 'Drain'. The pallets are sent to the 'Unloading' station, where the pallets are processed for a specific time, to represent the unloading time of the trailer. The pallets are then moved to the exit, where they enter the warehouse frame again.

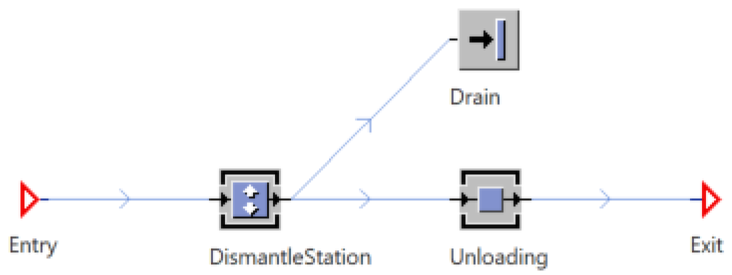


Figure 4-3: Unloading Frame of Simulation Model

If the trailer is completely unloaded and all the pallets are moved through the steps in the 'Unloading' frame and are stored in the right lane, the HUs move through the sticker station. After stickering all the pallets, the restack pallets are filtered out and transported to the 'RestackTransportBuffer'.

The 'RestackTransportBuffer' is the queue for the restack pallets that are ready to be transported to the restack area. If there is a place free in the 'RestackTransport' station, it means that there is a forklift available and that the first pallet in the queue can be transported to restack. For the processing time, the station looks at the lane where the pallet is from and it looks up the travel time in the 'RestackTT' table. The pallets start in the queue at the restack area. If there is a place free, the pallet enters the 'Restack' frame. It arrives at the 'Entry' in the 'Restack' frame and moves to the 'RemoveHUFromPallet' dismantle station, as shown in Figure 4.4. As the name of the station suggests, the boxes are separated from the pallets and both the pallets and the boxes move along a conveyor belt. Several empty pallets are stored, so there are empty pallets available at all times. The abundance of pallets is deleted from the system by the 'PalletDrain'. At the end of the box conveyor belt (Conveyor1), the 'CountrySorter' method places the boxes in a queue according to their destination country.

Since there are three different box types, the maximum number of boxes on a pallet can differ. The maximum number of boxes per pallet for a small box is 40, while the maximum number for a medium box is 20, and for a big box only 10. The maximum capacity of a pallet is therefore 40, and the volume of a small box can be seen as 1, a medium has a volume of 2 and a big box has a volume of 4. Based on these volumes the simulation model fills the queue for a country. If the next box does not fit on the pallet anymore, the queue of that country moves on to one of the 'QueueRestack' buffer, where the boxes wait until one of the two 'HUOnPallet' assembly stations becomes available.

The 'HUOnPallet' assembly station is the place where an empty pallet and the blue boxes come together and are stacked upon each other, they are "assembled" to each other. After filling up the pallet, the filled pallet moves on to the 'Finishing' station. This is the station where the straps are added to the pallet and the administrative work is done. After finishing the pallet up, the pallet with the boxes moves to the 'Exit' where it enters the warehouse frame again.

The 'CargoRelease' method in the restack frame enables the pallets from inbound to move on to outbound. The method is called by the exit of Conveyor1, which means that after all the boxes from a lane are removed from their original pallet, the 'CargoRelease' step is completed. After completion of this step, all HUs from a specific lane are allowed to move on to outbound. The 'CargoRelease' method therefore moves the pallets from inbound to the 'BinTransportBuffer' queue. The HUs in this queue are ready for transport outbound and wait for a free place in the 'BinTransport' station. If a place becomes available, it means that a forklift becomes available to transport the pallet from inbound or restack to outbound. At outbound, the HUs are placed in the bin that is determined by the 'MoveToBin' method described earlier. The bins for each country are outlined and marked with the country of destination.

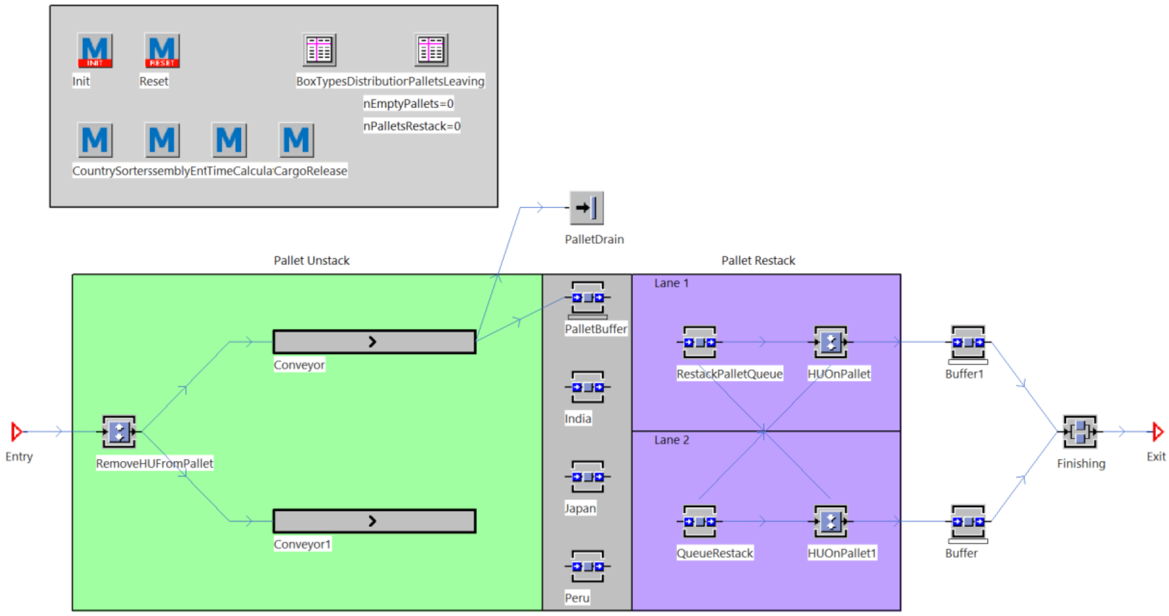


Figure 4-4: Restack Frame of Simulation Model

A fraction of the arriving pallets do not have permission from the foreign customs yet. The 'BinTransport' station moves those pallets to the 'Hold' queue first. The pallets in hold move through the 'PermissionRequest' station, where they wait for the permission of the foreign customs. At the exit of this station, the HUs move back to the 'BinTransportBuffer' queue where they wait for an available forklift that transports them to the right bin.

All the HUs wait in the bin until the bin is filled based on the volume of the HUs in that bin. Every bin gets assigned a volume capacity. Every pallet has its own volume, therefore it varies how many pallets cause the bin to be completely filled. The pallets in a filled bin move to the 'DockQueue' buffer, where they wait for the arrival of a sea container. After the arrival of the sea container, the pallets move to the 'ContainerLoading' frame, as shown in Figure 4.5. The pallets enter the frame at the 'Entry' and are moved to the 'PalletBuffer' where they wait until there is a place free at the 'Loading' station, which means that a forklift becomes available to transport the pallet to the sea container. At the 'ContainerLoading' assembly station, the pallets are attached to the sea container (which is created at the 'ContainerSource' source). If all the pallets are "assembled" in the sea container, the sea container moves to the 'ContainerSealing' station, where the final steps are taking place to finish the container for transportation. After finishing up the sea container, it moves to the 'Exit' where it enters the warehouse frame again.

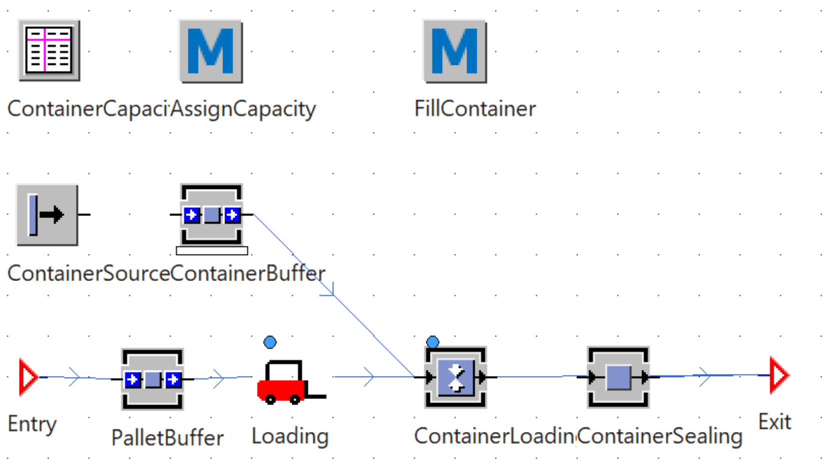


Figure 4-5: ContainerLoading Frame of Simulation Model

The finished sea container arrives at the 'ContainerDeparture' station. This station calls the 'LeavingWarehouse' method, which calculates the KPIs of the pallets and boxes within the sea container. The method also takes the waiting time for Company Z to come to pick up the filled sea container into account. After this waiting time, the container moves to the 'Drain'. The 'Drain' calls the 'Departure' method which stores the data of the sea container and the pallets in the sea container in the tables of the 'Output' box.

The simulation layout outlines Process S at the bottom of the simulation model. The unloading docks, lanes, bins and loading docks in this area are not used by the simulation model, since they are dedicated to Process S and they do not process any of the arriving HUs in our model.

4.3 Experimental Design

For the analysis of the simulation model, we conduct multiple experiments. It is essential to define the length of the warm-up period, as it helps eliminate the initialization bias. We must also determine the number of replications needed to achieve valid and reliable results, as well as the appropriate run length for our experiments. Finally, it is necessary to verify whether the computer model accurately represents reality, thereby ensuring the validity of our simulation. These four factors are explained in this section.

4.3.1 Warm-Up Period

Our simulation starts without any pallets or boxes in the system. However, in reality, this is never the case. The initial conditions of our simulation are therefore unrealistic, and that contaminates the output of the simulation model, this is known as the initialization bias (Robinson, 2014, pp. 138 - 140). The input of the simulation varies according to a fixed distribution, and that is why the output of the simulation also varies according to a fixed distribution (the steady state distribution). The output data will become steady over time, and the output data in this steady state is what can be used for the performance measurement of the model. Therefore, we divide the simulation into two phases, the warm-up phase and the steady-state phase. The warm-up phase is the period that it takes until the simulation output is independent of the initial conditions in the simulation.

Since the model will not reach an empty condition, the time period under investigation does not complete and the input data does not complete, this is a non-terminating simulation model. This means that the simulation does not have a natural end point, and it could go on indefinitely with no statistical change in behaviour (Robinson, 2014, p. 138).

To determine the length of the warm-up period, we can use the Marginal Standard Error Rule (MSER). Let $\hat{d}(n)$ denote the amount of data points to ignore after having collected the data points $Y_0, \ldots, Y_{n-1}$. The MSER for a non-terminating simulation as proposed by (Wang & Glynn, 2016):

$$\hat{d}(n) = \underset{0 \le k \le n-2}{\arg\min}\, g_n(k)$$

Where

$$g_n(k) \triangleq \frac{1}{(n-k)^2} \sum_{j=k}^{n-1} (Y_j - \bar{Y}_{n,k})^2$$

In this formula, n is the number of observations from the output data and $\bar{Y}_{n,k}$ is the mean value of data points $Y_k, \dots, Y_{n-1}$.

To test the length of the warm-up period, we perform several replications of the standard model configuration. The average value of the replications is used for the calculations w.r.t the warm-up period. Appendix K contains the MSER graph of the output KPI "Length of Stay". This is the output KPI with the longest warm-up period of all KPIs, so that is the warm-up period that we will use in the simulation. To determine the length of the warm-up period, we use a tool created by Robinson (2014). The calculations show that we have to ignore a total of 2 data points before the simulation output is in steady-state. This leads us to a warm-up period length of 15 hours. This is because the first data point is stored at hour 14 since that is the first hour that HUs leave the warehouse.

4.3.2 Number of Replications

The random variables and distributions that we use in the model, allow us to describe the real world more precisely. However, we have the problem that we cannot compare the performance of different experiment configurations because their performance depends on chance. To solve this problem, we have to treat the performance of a configuration as a random variable as well. We do this by creating multiple replications of each model configuration.

To determine the number of replications that we have to perform, we use a confidence interval. We keep performing replications of the same configuration until the width of the confidence interval relative to the average of the replications, is sufficiently small. According to Robinson (2014), we calculate n*, which is the smallest number of replications (i) for which the estimated relative error is smaller than d (0,05 in our case):

$$n^* = \min\left\{ i \ge n : \frac{t_{i-1,1-\frac{\alpha}{2}}\sqrt{\frac{S_n^2}{i}}}{|\bar{X}_n|} \le 0{,}05 \right\}$$

Appendix K also shows the table that includes the calculations with respect to the determination of the number of replications. The output data for the "Waiting Time at Inbound" results in the highest number of replications, so that is what we will use for the experiments we will perform. As can be seen in the table, at replication 4, the error is below 0,05 so we can assume that we need 4 replications for each simulation configuration.

4.3.3 Run Length

To determine the run length for a single long-run simulation of our simulation model, we follow Robinson's (1995) method. Initially, we perform three replications and we can calculate the cumulative means for each replication. As the run length increases, the cumulative means of the three replications should converge. The level of convergence is calculated as follows:

$$C_i = \frac{Max(\bar{Y}_{i1}, \bar{Y}_{i2}, \bar{Y}_{i3}) - Min(\bar{Y}_{i1}, \bar{Y}_{i2}, \bar{Y}_{i3})}{Min(\bar{Y}_{i1}, \bar{Y}_{i2}, \bar{Y}_{i3})}$$

Where,

$C_i = convergence\ at\ period\ i$

$\bar{Y}_{ij} = cumulative\ mean\ of\ output\ data\ at\ period\ i\ for\ replication\ j$

The run-length is selected at the point where the convergence is seen as acceptable, which is typically at a level of less than 5%. A tool created by Robinson (2014) was used to calculate the convergence. We used the daily average length of stay of the departing HU. In our case, the convergence dropped below 5% on day 32 but rose again before stabilizing below 5% from day 55 onward. This suggests a run length of at least 55 days is needed.

4.3.4 Simulation Validation

Before we can start analysing the results from the simulation model, we need to validate the model. We do this by comparing the output data from our simulation model to data from the real world. Performing a paired t-test on the difference between two data sets shows if the simulation model is valid or not.

The data sets that we use for the validation of the model are about the average waiting time at the inbound area per day. The simulation was run for 139 days, which resulted in 93 data points (since weekends are not included in the data points), this is equal to the number of data points available from Company X's WMS. The data from the real world was retrieved from Company X's warehouse management system, SAP. The first step of the paired t-test is calculating the difference between the two observations on each data point (Shier, 2004). Table L.1 in Appendix L shows the data sets and the difference between the data sets. The next step is to calculate the mean value ($\bar{d}$) and the standard deviation of the differences between the data sets. We can then use the standard deviation to calculate the standard error of the mean difference, $SE(\bar{d}) = \frac{s_d}{\sqrt{n}}$.

According to Shier (2004), we can then calculate the t-statistic given by $T = \frac{\bar{d}}{SE(\bar{d})}$. We use this t-statistic to test it against the t_{n-1} distribution with 92 (n -1) degrees of (Pezzulo, 2024). Table L.2 in Appendix L shows the parameters of the paired t-test as mentioned in this section.

Since the p-value is greater than the level of significance of 5%, we fail to reject the null hypothesis (H_0). This means that there is no significant difference between the means of the two data sets. Therefore, we will assume that our simulation model is valid and that its output can be used to draw conclusions about the changes in the warehouse.

5. Solution Experimentation

This Chapter helps us answer the research question *What is the effect of the solutions on the CP process?* Section 5.1 analyses the results of the base model, so we can compare the solutions to the current situation. The other sections cover the possible layout and process improvements as discussed in Chapter 3 and explain the effects of the changes on the output KPIs.

5.1 Unchanged Situation

This section continues on the current situation at LBX. The simulation model used in this section shows no changes to the layout or processes compared to the current situation. The experiments we perform, demonstrate the anticipated effects of the future scenario on the CP process. Chapter 2.3 outlines this future scenario, concluding that to ensure LBX is future-proof, it must handle an expected volume growth of 15.3%. Consequently, we will experiment with an increased arrival rate of handling units at the warehouse.

Chapter 4.2 addresses the computer model of our simulation. Within this model, we have a variable named 'VolumeGrowthPercentage,' which adjusts the arrival rate of handling units (HUs) by a specified percentage. In our experiments, we vary this percentage to observe the impact of higher volumes on the CP process and our output KPIs. We increment the volume growth by 5% for each experiment, up to a maximum of 30%. The reason for stopping at 30% is that the number of outbound containers for Japan is expected to reach 9 containers per day in 2029, representing an approximately 30% increase over the current volume. Thus, our experiments will determine the point at which LBX's capacity remains sufficient enough to manage the forecasted volume growth.

VOLUME INCREASE	AvgWT Inbound	AvgWT Restack	AvgWT Outbound	AvgWT Company Z	Avg Lengthofstay	Exceed24hours	Avg HUperDay
0%	01:43:29	00:28:48	03:09:14	02:12:43	03:15:10	0,45%	4072,75
5%	01:45:03	00:33:50	03:24:07	02:12:45	03:33:58	0,43%	4274,25
10%	01:46:44	00:33:28	03:21:11	02:13:26	03:33:31	0,42%	4469,5
15.3%	01:47:28	00:32:55	03:19:09	02:13:22	03:32:00	0,42%	4679
20%	01:47:51	00:32:04	03:15:03	02:12:31	03:29:19	0,40%	4872,75
25%	01:48:40	00:31:48	03:13:10	02:12:58	03:28:46	0,37%	5071,5
30%	01:50:34	00:31:13	03:10:58	02:12:38	03:28:12	0,36%	5278,25

Table 5-1: Output KPIs - Base Model

Table 5.1 shows the results of the experiments in the base model. As illustrated in the table, the average processing time at the inbound area increases with the number of arriving handling units (HUs). This increase is caused by two factors.

First, we can see in Table 5.2 that there is an increase in waiting time for transportation by forklifts. With more pallets in the system and a constant number of forklifts, pallets must wait longer to be transported to their next destination. Second, the pallets in the lane experience longer waiting times for cargo release. These two factors cause the observed increase in the average processing time in the inbound area.

VOLUME INCREASE	AvgForkliftWT	AvgCargoReleaseWT
0%	00:47:11	00:13:21
5%	00:50:55	00:13:33
10%	00:55:45	00:13:59
15.3%	00:57:13	00:13:58
20%	01:02:47	00:13:56
25%	00:55:55	00:14:07
30%	01:03:13	00:14:24

Table 5-2: Output Base Model

Furthermore, we can see that the average processing time at restack increases in the first experiment (5% volume growth) and decreases from there on. With a greater arrival rate for restack pallets, the waiting time for transportation to the restack area increases. Furthermore, the pallets have to wait in line at the restack area longer because more pallets arrive at the restack area. The decrease in processing time can be explained by the fact that the pallets are only filled as soon as there are enough boxes available to fill a pallet. With a greater arrival rate for the boxes, the capacity of the pallet is reached sooner, so the waiting time for the boxes decreases. From 10% the time saved is greater than the extra waiting time, and that results in a decrease in overall processing time.

The same reasoning applies to the processing time in the outbound area. The pallets have to wait in the outbound bin until sufficient pallets are in the bin to fill a sea container. With a higher arrival rate for the pallets, the maximum volume of the sea container is reached sooner, so we can request a sea container sooner too. On the other hand, the waiting times for transportation increases because of the increase in arrival rate. But from 10%, the decrease in waiting time at the outside bin is more than the extra waiting time for transportation, so the average processing time decreases from that point on.

Due to changes in processing times at inbound, restack, and outbound, the average length of stay for handling units initially increases at a 5% arrival rate but then decreases from 10% onward. However, if we examine the percentage of HUs that do not achieve a length of stay under 24 hours, we see that this percentage remains constant. This constancy is because the number of HUs exceeding the maximum length of stay in the base model does not change with an increased arrival rate. The increased arrival rate consists solely of HUs with Japan as their destination, and because of the high arrival rate for Japan pallets, these pallets do generally not exceed the 24-hour mark. The 0.46% of HUs that exceed the maximum length of stay are slow-moving goods destined for Mexico and the pallets for Hold. Since sea containers do not depart daily for Mexico, pallets arriving on day n and leaving on day n + 1 have a higher likelihood of exceeding the maximum length of stay. Therefore, as the total number of HUs in the system increases but the number of HUs exceeding the maximum length of stay remains almost unchanged, the percentage of HUs exceeding the 24-hour mark decreases.

5.2 Bottlenecks in Current Situation

The results of the base model help us find the bottlenecks in the current situation. This section therefore answers the knowledge question: *What are the bottlenecks in the current layout and processes of the CP?*

If we look at the output data of the current situation, we can see that two steps in the process take a lot of time compared to the other processes. The first bottleneck is the waiting time at inbound. The whole process at inbound consists of only two steps: unloading and stickering. Both steps take at most a minute to complete. The reason for the high processing time at inbound is the time that the HUs are waiting to be processed. Typically, pallets are unloaded from the inbound trailer, stored in the lane, and then stickering begins once all pallets are unloaded. After stickering, the pallets must wait again until all pallets are stickered. Thus, the pallets experience two waiting periods during the stickering process. This decreases the throughput since the inbound dock is occupied for a longer period.

The second bottleneck identified from the simulation model is the waiting time at the outbound bin. At outbound, pallets wait in a bin until it is completely filled, after which they are loaded into a sea container and dispatched from the warehouse. Before loading, a sea container is requested from Company Z. Once the container is filled and sealed, another request is made to Company Z for transport. As mentioned in Section 4.1.2, it takes 01:10:21 and 01:07:42 for Company Z to deliver and pick up a sea container, respectively. The time taken by Company Z to deliver an empty sea container is the time during which the bin in the outbound area cannot be used. Similarly, the time taken to pick up a filled sea container renders the dock unavailable during that period. On average, the pallets have to wait for 02:12:43 for Company Z.

5.3 Layout Improvements

Layout adjustments can create a higher throughput for the warehouse. Section 4.1.1 elaborates on the shape of the warehouse. After an analysis of existing literature about warehouse design shapes, we concluded that the I-shape is the most optimal shape for our warehouse and the processes we perform in the warehouse.

Next to the design shape, in Section 3.2.2 we did research on the advantages and disadvantages of placing pallet racks in the warehouse. The only place in the warehouse where pallet racks would be more optimal than floor storage is the hold area. This is because of the lower throughput time of the hold pallets, and the location of the hold area in the warehouse. However, when we look at the maximum number of contents of the Hold process in the simulation model, we can see that it only contains a maximum of 9 pallets at a 30% volume increase. The floor storage at the hold area is sufficient enough to store 32 euro-sized pallets[3]. Therefore, it is not necessary to invest in pallet racks, since the additional pallet places it creates, are not needed.

Another change to the layout could be to add another restacking station. Currently, LBX has two restacking stations where the boxes move along to be stacked on an empty pallet. Adding a restacking station increases the capacity of the restack area and that could reduce the throughput time of the HUs and increase the capacity of the warehouse. However, if we run the simulation in the base model, we can see that the capacity of the restacking stations is not the bottleneck in the restack process. The step that takes the longest is the waiting for enough boxes to fill a pallet. Once sufficient boxes are gathered, they experience little to no waiting time for an available restacking station. Therefore, adding an extra restacking station will not reduce throughput time or increase the capacity of LBX.

5.4 Process Improvements

Next to layout improvements, there are also possible improvement possibilities in the processes of the consolidation process. The theories from Chapter 3 are used to determine the points of improvement.

5.4.1 Remove Sticker Process

Part of the inbound process is the stickering of the pallets. Each pallet that arrives at the warehouse receives a sticker that makes it possible for the employees to scan and track the pallet in the warehouse. However, at receival, the pallet already contains a sticker with the characteristics of the pallet, such as the destination country. If Company X uses this sticker instead of the one it prints and sticks on the pallet, time could be saved. This would require a modification in Company X's WMS since Company X no longer prints its own labels and barcodes.

VOLUME INCREASE	AvgWT Inbound	AvgWT Restack	AvgWT Outbound	Avgwt Company Z	Avg Lengthofstay	Exceed24hours	Avg HUperDay
0%	00:40:03	00:28:18	03:09:40	02:13:00	03:00:27	0,46%	4081,5
5%	00:41:02	00:33:37	03:25:12	02:13:19	03:19:19	0,43%	4279
10%	00:42:04	00:33:06	03:21:31	02:13:16	03:17:30	0,41%	4486,5
15.3%	00:43:01	00:32:31	03:18:16	02:13:02	03:15:04	0,39%	4695
20%	00:43:45	00:31:46	03:15:28	02:13:11	03:13:32	0,37%	4885,75
25%	00:44:38	00:31:12	03:13:42	02:13:31	03:12:31	0,37%	5089,25
30%	00:45:32	00:30:54	03:11:28	02:13:11	03:11:14	0,35%	5294,25

Table 5-3: Output KPIs - Removal of Stickering Process

In Table 5.3 one can observe the significant effect on the inbound processing time following the removal of the stickering process. The waiting time decreases by over an hour due to the elimination of waiting periods associated with the stickering process and the time for stickering itself. By removing

[3] The bin has a floor area of 31,3 M^2, and a euro pallet has an area of 0,96 M^2, so the floor capacity is $\frac{31,3}{0,96} = 32$ euro pallets maximum.

the stickering step, pallets only wait until unloading is complete, and the blue boxes are processed at restack (cargo release). Subsequently, forklifts can transport the restack pallets directly to restack, thereby saving waiting time.

The restack and outbound process times are minimally affected by this process change. The length of stay is however reduced by 16 minutes (8.0%) compared to the base model for a volume increase of 15.3%. The reason the effect on the length of stay is significantly less than on the inbound process time is that, in the revised model, the HU is detected in the system immediately after unloading. In contrast, the base model detects the HU when the stickering process begins. Therefore, in the new model, the length of stay includes the waiting time in the inbound lane. Although the HU is detected in the system sooner, the effect of the change is still significant.

5.4.2 Release of Cargo

As discussed in Section 3.2.3, the cargo release step in the process results in a lower throughput than possible, as it increases the waiting times of pallets in the inbound lanes. Theoretically, removing this step from the process could reduce the length of stay for the pallets. To see the expected effects of this change, we will adjust our base model remove the cargo release step and perform experiments with the adjusted model.

VOLUME INCREASE	AvgWT Inbound	AvgWT Restack	AvgWT Outbound	AvgWT Company Z	Avg Lengthofstay	Exceed24hours	Avg HUperDay
0%	01:30:27	00:28:49	03:12:03	02:13:07	03:04:29	0,43%	4073,25
5%	01:32:42	00:34:11	03:26:39	02:12:54	03:23:30	0,44%	4277,75
10%	01:33:09	00:33:35	03:24:30	02:13:17	03:22:57	0,41%	4467,5
15.3%	01:34:27	00:33:00	03:21:06	02:14:05	03:20:55	0,39%	4682,5
20%	01:35:40	00:32:25	03:17:15	02:12:30	03:20:17	0,38%	4872,25
25%	01:36:25	00:32:04	03:14:30	02:13:18	03:18:11	0,37%	5075,75
30%	01:37:39	00:31:22	03:12:05	02:12:40	03:17:07	0,35%	5282,25

Table 5-4: Output KPIs - Removal of Cargo Release

Table 5.4 shows the results of the adjusted model. Looking at the results from the inbound area, we can conclude that the processing time decreased compared to the base model. The time saved in processing time is about 13 minutes, which is quite significant compared to the total processing time. That is a saving of $\frac{00:13:36}{01:47:28} = 12{,}6\%$ at a volume increase of 15,3%.

The effect of the adjustment on the restack processing time is almost zero, while the effect on the outbound processing time is an increase of about 3 minutes. That is an extra processing time of $\frac{00:03:19}{03:19:09} = 1{,}7\%$ at a volume increase of 15,3%.

The overall effect of the removal of the cargo release step on the length of stay is a decrease of about 10 minutes. That is a saving of $\frac{00:10:34}{03:32:00} = 5{,}0\%$ on the length of stay of the HUs. To conclude, the removal of the release in cargo is an adjustment to the process that decreases the throughput time and therefore increases the capacity of the CP process.

5.4.3 Inbound Dock Allocation

The base model determines the Inbound Dock (ID) by assigning a random number between an interval. This interval is based on the distribution of destination countries within the trailer. The mathematical dock allocation model described in Section 3.2.1 looks at the travel time of the pallets within the warehouse. It compares each ID by the active Outbound Dock (OD) for the pallets within the trailer, and it finds the ID with the lowest travel time between the ID and the active ODs.

VOLUME INCREASE	AvgWT Inbound	AvgWT Restack	AvgWT Outbound	AvgWT Company Z	Avg Lengthofstay	Exceed24hours	Avg HUperDay
0%	01:39:12	00:28:28	03:08:15	02:11:49	03:09:12	0,45%	4076
5%	01:41:19	00:34:17	03:24:07	02:12:20	03:28:35	0,45%	4274
10%	01:39:07	00:33:17	03:20:48	02:11:44	03:23:16	0,41%	4474
15.3%	01:39:43	00:32:41	03:17:33	02:11:23	03:21:05	0,40%	4687
20%	01:41:25	00:32:21	03:14:59	02:12:18	03:20:31	0,38%	4871
25%	01:41:04	00:31:46	03:13:18	02:12:14	03:17:37	0,37%	5078
30%	01:41:41	00:31:10	03:10:52	02:12:16	03:16:31	0,35%	5284

Table 5-5: Output KPIs - Inbound Dock Allocation

Table 5.5 shows that the mathematical model decreased the length of stay by almost 11 minutes at a volume increase of 15,3%, which is a 5,1% decrease compared to the base model. The decrease in length of stay can be explained by the decrease in transportation time. Instead of assigning an Inbound Trailer (IT) to a random dock, the most efficient dock is calculated to be the dock with the lowest travel time inside the warehouse.

5.4.4 Number of Servers

In the simulation model, we can also vary in the number of servers for a station. For example, we can add servers to the transportation stations to resemble an increase in forklifts in the warehouse. This will reduce the HU's waiting time for transportation. Therefore, the more forklifts the better. However, in reality, this is not the case, since an increase in the number of forklifts also increases the chances for congestion. As explained in Section 4.1.6, one of the limitations of our simulation model is that we do not include the congestion of forklifts. So, increasing the number of servers for the transporting stations will not result in a valid outcome of our KPIs.

5.4.5 Improvement Combinations

The three points of improvement related to the consolidation process can also be combined, potentially leading to even greater improvements. Therefore, we have created a new model where each of the three improvements can be activated or deactivated. This results in eight possible combinations, as shown in Table M.1 in Appendix M. For each combination, we will also vary the volume growth rate. We will limit the volume growth rates to 0%, 15.3%, and 30% to reduce experimentation run time, resulting in 24 experiments (8 combinations × 3 growth rates). These selected volume growth rates are the most critical to examine, as they represent the warehouse's current and projected future volumes.

The output shown in Appendix M indicates that the most efficient combination is to activate all three improvements. For the expected growth rate of 15.3% for 2026, the average length of stay of the handling units (HUs) decreased by 18.4%. Additionally, the percentage of HUs with a throughput time exceeding 24 hours decreased compared to the basic model. Therefore, we can conclude that implementing all three process improvements described in Sections 5.4.1, 5.4.2, and 5.4.3 positively impacts the process at LBX.

5.5 Occupation Rate

Next to the processing times and percentage of HU's exceeding the 24 hours throughput, in Section 3.1 we also concluded that we need to look at the occupation rate of the different stations. Table 5.6 shows the occupation rate of the forklift and the restack area for the different experiments we performed. From this table we can conclude that the restack occupation does not rise above 25% and the forklift occupation does not rise above 75%. An interesting thing to notice is that the forklift occupation with the dock allocation model, does not rise above 56%. This has to do with the fact that the inbound dock allocation model is focused on finding the inbound dock that minimizes the total distance between inbound and outbound. That means that the forklifts have to travel a shorter distance and can therefore transport more pallets in the same time.

	Base Model		Without Stickering		Without Release of Cargo		With Dock Allocation	
	Restack Occupation	Forklift Occupation	Restack Occupation	Forklift Occupation	Restack Occupation	Forklift Occupation	Restack Occupation	Forklift Occupation
0%	19,8%	50,1%	19,8%	50,4%	19,8%	49,7%	19,8%	38,6%
5%	20,8%	54,2%	20,8%	56,5%	20,8%	55,2%	20,8%	46,2%
10%	21,8%	59,3%	21,8%	59,4%	21,8%	60,1%	21,8%	45,7%
15.3%	22,8%	63,8%	22,8%	63,6%	22,8%	63,0%	22,8%	45,9%
20%	23,8%	67,4%	23,8%	66,5%	23,7%	66,6%	23,8%	50,4%
25%	24,8%	69,8%	24,8%	69,7%	24,7%	70,4%	24,7%	49,6%
30%	25,7%	73,7%	25,8%	73,5%	25,7%	73,0%	25,7%	56,4%

Table 5-6: Occupation Rate

6. Solution Implementation

The solutions as described in Chapter 5 improve the throughput of the warehouse. However, just knowing what the problems and their solutions are, won't help Company X in improving the CP process. Therefore, this chapter is dedicated to answering the knowledge question: *How can the improved layout and processes be implemented in the CP?* Appendix N shows the BPMN process flows that are the result of the changes as described in this Chapter.

6.1 Remove Sticker Process

Removing the sticker process from the consolidation process requires a change in Company X's warehouse management system. Company X's IT team should modify Company X's WMS to recognise and process existing stickers instead of needing to print new stickers. The employees who perform tasks that require the new stickers can carry a handy scanner with them, that they can use to scan the existing stickers on the pallets and read the data about the pallets. This action is only needed if the existing sticker does not show the information that the employee has to know for his task.

Depending on the implementation of the solution in the WMS, the employees might need to be trained to learn how to operate the new process. If the steps in the WMS change a lot compared to the current situation, it is important that the employees are well-educated about the new scanning process.

The sticker process in the current situation is also for identifying the pallets that arrived in the warehouse and the pallets that were supposed to arrive but are still missing. To identify the shortage or surplus of the arriving pallets, we still need to scan the pallets. If we have a shortage of pallets, the missing pallets should be automatically mutated in SAP. If we have a surplus of pallets, steps 2.8, 2.9, 4.5, 5.1 and 5.2 can be skipped and the extra pallets are identified in SAP by scanning the existing label.

6.2 Release of Cargo

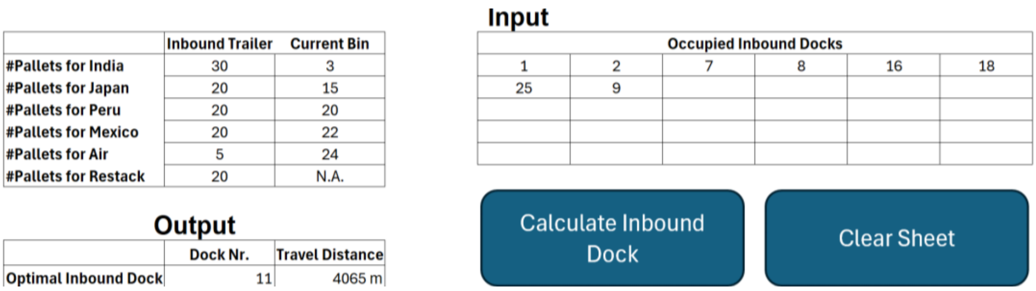
The removal of the release of cargo step in the process also requires a change in Company X's WMS. Currently, SAP is programmed such that the pallets in a lane are allowed to be transported to the outside area once all the boxes from that lane have been processed at restack. By removing the release of cargo step, SAP should add the pallets to the transportation list of the forklifts as soon as they are stickered.

For the employees, this change does not require different handling steps than in the current situation. It is purely software-based that the forklifts are only notified about the transport of the pallets when the WMS adds the pallets to the forklift dashboard. And since the drivers of the forklifts only transport the pallets on the dashboard, nothing will change for the employees.

6.3 Inbound Dock Allocation

The mathematical model described in Section 3.2.1 determines the most optimal inbound docking station to reduce the total travel time of the HU in the warehouse. It does this by comparing each inbound dock (ID) to the active outbound bin (OB) for the pallets in the inbound trailer. It finds the ID with the lowest total travel time between the ID and the active OB for the pallets in the inbound trailer (IT).

To help Company X make most of this mathematical model, a tool was created by means of Visual Basic for Applications (VBA) in Microsoft Excel. The dashboard of the tool is shown in Figure 6.1. Input for this tool is the same as the input for the mathematical model, which is: the number of pallets for each destination within the warehouse, the current OB for each destination country, the occupied IDs and the transportation distance between the IDs and ODs (as shown on a different sheet in the workbook). Pressing the "Calculate Inbound Dock" button will calculate the most efficient ID and the output is the ID with the lowest total travel distance between the ID and the active ODs, and the distance that has to be travelled in total from that inbound dock.


Input

	Occupied Inbound Docks				
1	2	7	8	16	18
25	9				

	Inbound Trailer	Current Bin
#Pallets for India	30	3
#Pallets for Japan	20	15
#Pallets for Peru	20	20
#Pallets for Mexico	20	22
#Pallets for Air	5	24
#Pallets for Restack	20	N.A.

Output

	Dock Nr.	Travel Distance
Optimal Inbound Dock	11	4065 m

Figure 6-1: Inbound Dock Allocation Tool

The tool will be used by the portocabin. The employee at the portocabin looks in Software Y what the content of the inbound trailer is, the employee fills this in in the tool, and the tool calculates the best ID to unload the IT. Then, the employee sends the driver of the trailer to that ID and the trailer can be unloaded. Since there are no changes in the process steps that change the flowchart of the current situation the flowchart for the implementation of this solution is the same as the flowchart of the current situation.

For this approach to be effective, the portacabin must be well-informed of any changes in the warehouse. The tool should be updated when an ID becomes available for a new trailer and when the active OD is changed for a country. The tool becomes inefficient if the data from Software Y does not accurately reflect the actual contents of the trailer or if the tool is not updated correctly. Therefore, effective communication between the warehouse employees and the portacabin personnel is essential to ensure the tool is kept up to date, thereby enhancing its efficiency.

7. Conclusions, Recommendations, and Future Research

Through this thesis, a simulation model has been designed, created, and tested for the consolidation point of Company X. Looking at the results from the simulation model, we can draw conclusions about the future situation of Company X's warehouse. The results from the simulation model allow us to answer the main research question:

Is the consolidation process in Company X*'s Logistics Building X (LBX) able to handle the expected growth in throughput? And if not, what changes have to be made to the processes and layout of LBX to be able to handle the expected growth in volume?*

Section 7.1 is focused on answering this research question. In Section 7.2, we explain the recommendations towards Company X, and in Section 7.3, we state suggestions for future research.

7.1 Conclusions

Throughout this report, various knowledge questions have been addressed and answered to help us answer the main research question. The conceptual model in Section 3.1 helped us create a simulation model of Company X's warehouse. By looking at existing theories and methods, we managed to find some interesting and useful theories on how to improve the process at the consolidation point. We described this literature review in Chapter 3 and tested the theories in Sections 5.2 and 5.3.

Section 6.1 focused on the current situation and the capacity of the consolidation process, aiming to address the first part of the main research question: *Is the consolidation process in Company X's Logistics Building X (LBX) able to handle the expected growth in throughput?* Based on the output KPIs from the simulation model, we can conclude that the current capacity is sufficient to manage the expected growth until at least 2029. This conclusion was reached while adhering to the throughput time restriction. The percentage of handling units exceeding the maximum throughput time of 24 hours remains constant throughout the experiments. Therefore, we can conclude that Company X's Logistics Building X can handle the anticipated growth in throughput.

Since the outcome of the first part of the research question indicates that Company X can handle the expected growth, it is unnecessary to address the second part of the question. However, after analysing the output KPIs from the simulation model, it is evident that several factors can be optimized for greater efficiency. The experiments in Section 5.4 demonstrated that the average throughput time of the handling units can be reduced by 18.4% as a result of which the capacity of the warehouse increases by 22.5%. This increases in capacity can be achieved by removing the sticker process, eliminating the 'Cargo Release' step, and applying the mathematical model described in Section 3.2.1 for the inbound trailer's dock allocation.

And finally, the output data showed that a significant part of the waiting time of the HUs is caused by the waiting time for Company Z. The time that the pallets are stationary, is the time that the area of the pallet's location cannot be used. This decreases the overall capacity of the warehouse.

7.2 Recommendations

Based on the observations from the simulation model and the knowledge that was gained during this research, a few recommendations are in place for Company X.

First of all, Company X should establish clear agreements with Company Z regarding the delivery and pickup of sea containers at the outbound area of the warehouse. As indicated by the output data from the simulation model, the average waiting time for Company Z exceeds 2 hours. During this period, either an outbound bin or outbound dock remains unavailable. By making agreements with Company Z to reduce the time that it takes to deliver and pick up a sea container, Company X can further increase the capacity of the warehouse.

Next, it is recommended that employees expand their skill sets to enable their deployment across multiple areas within the warehouse. Observations in the warehouse and conversations with Company X employees revealed an imbalance in workload distribution: some personnel had insufficient tasks, while others were overwhelmed with work. By broadening the skill sets of employees, those with fewer tasks can assist their coworkers who are struggling to manage their workload. This also increases the capacity of the warehouse, since there is less time wasted by the employees. Instead of one person working on a task, it could be two people working on it.

A final recommendation for Company X is to maximize the capabilities of the warehouse management system (WMS). Company X's WMS, SAP, is currently used to manage the flow of goods within the warehouse. However, SAP offers functionalities beyond mere product flow management. The data collected by SAP can for example also be utilized to assess employee performance and provide insights into trends within the warehouse, such as increases in the arrival of specific products.

7.3 Future Research & Limitations

The main limitation of this research was the missing input data for the simulation model. As can be seen in Section 4.1.2 there are quite a few data types that follow a triangular distribution. A triangular distribution is less accurate than other distribution types, such as normal distribution. Using a more accurate distribution type increases the accuracy of the simulation model too.

A future study that follows on from this study and the results of this study could focus on the implementation of the solutions. As mentioned in Chapter 6, two of the suggested solutions require a modification of Company X's warehouse management system. However, it is unclear how the modification should be implemented into the WMS. A future research could therefore find out how to implement the solutions into the warehouse management system SAP.

Furthermore, a future study could develop a more sophisticated simulation model that includes the chances of congestion within the warehouse. This model could adjust the number of servers for a transport station to represent the number of forklifts operating in the warehouse. An increased number of operating forklifts would decrease the waiting time for a pallet to be picked up but would also increase the likelihood of congestion. Therefore, a more complex simulation model could evaluate the effects on the warehouse capacity of a variable number of forklifts in use.

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Appendices

Appendix A - Problem Cluster

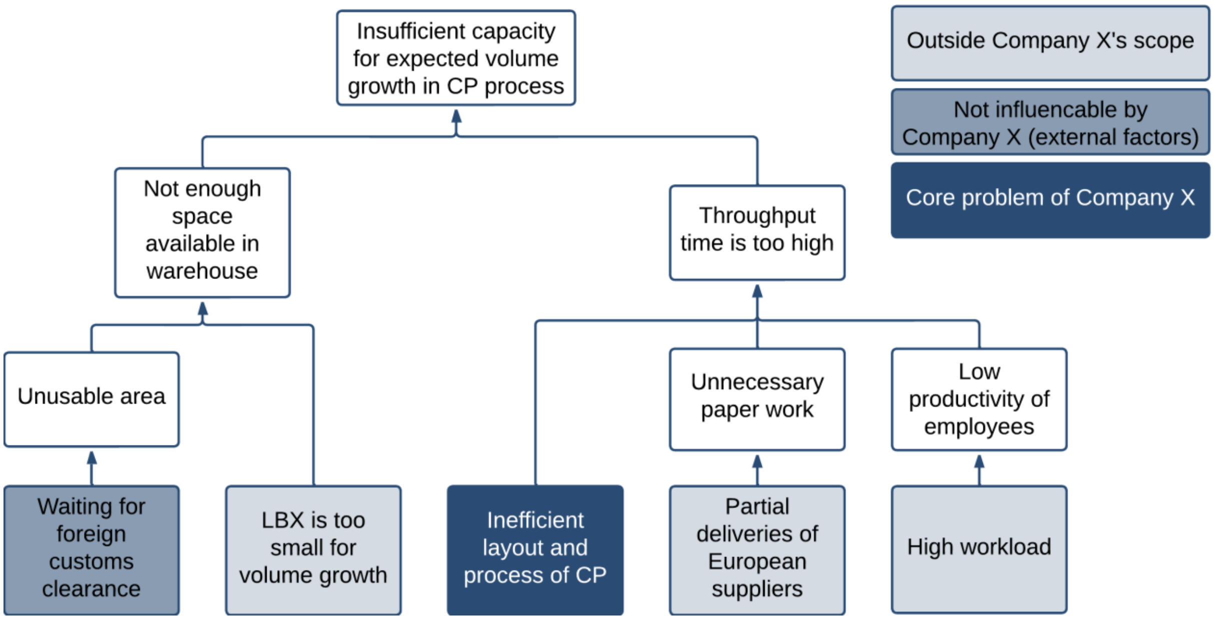

Figure A.1: Problem Cluster of Company X's Action Problem

Appendix B - Elaboration on the Core Problem

The problem cluster starts with the action problem defined in the introduction, which is the insufficient capacity for expected volume growth in LBX. The two reasons that the capacity is not sufficient enough are the lack of space in the warehouse and the throughput time being too high.

<u>Lack of Space</u>

A small part of this lack of space is caused by an unusable area. This unusable area is caused by products that are not allowed to be shipped yet and that causes a build-up of goods. The reason that some goods cannot be shipped yet has to do with customs clearance. For some shipments, this clearance can take longer than for other shipments. As long as there is no clearance for a handling unit, the HU cannot leave the CP and this causes unwanted stock. The space that this stock uses can therefore not be used for the preparation of the other HUs.

The processes performed at the warehouse, such as the receival, restacking and dispatching of the goods, all need a certain amount of space in the warehouse. With an increasing throughput, the area needed for these processes might increase too. However, the size of the warehouse stays the same, so this might cause a lack of space.

<u>High Throughput Time</u>

Throughput time can be seen as the total time between the arrival and departure of a handling unit at the warehouse (Lauri, 2020). Minimizing the throughput time will increase the capacity because we can handle more handling units per time unit. The high throughput time has three different causes.

The first cause is the inefficient layout and processes of the CP building. For example, within the CP there is a lot of traffic going on from forklifts. If the distances that these forklifts travel can be reduced, time will be saved and that means that the amount of goods handled will increase. This can, for example, be achieved by relocating certain process components closer to the area where they're most needed. It might also be more efficient to transport the incoming goods directly to outbound goods instead of storing them temporarily, which is what Company X is doing now. This would result in a change in the current process, but it might also cause a lower throughput time.

The second reason for a higher throughput time is unnecessary paperwork. It might happen that goods from the same order list are delivered in different trucks. This means that one order might arrive at different times. The sea containers are loaded based on an order list. If only a fraction of that order shows up, the order list cannot be completely checked. To still be able to fill a sea container with a partial delivery, a new order list should be made for the remaining part of the initial order lists. This costs time and will increase throughput time. The partial deliveries are caused by international cross-docks that load the truck because they don't look at the order list of Company X while loading the trucks. They load the trucks as full as possible and then only a part of the order might fit in that truck.

Another cause for a high throughput time is the low productivity of employees. This means that the employees have a high handling time of the incoming goods, which results in a higher throughput time. This low productivity is caused by a high workload of the employees. There are a lot of goods that need to be handled in a short amount of time. The goods must be prepared for overseas shipping within 24 hours. This makes the employee's job harder and that causes a lot of stress for the employees. The high workload reduces the motivation of the employees and they are therefore less willing to work harder.

Core Problem

Working backwards in the problem cluster in Appendix A will help find the roots of the action problem, also called the core problem. This results in a list of five potential core problems which cause the action problem. The potential core problems are:

- Waiting for foreign customs clearance
- LBX is too small for volume growth
- Inefficient layout/process of CP building
- Partial deliveries of international suppliers
- High workload

Starting with the waiting for foreign customs clearance, this is not a problem that can be influenced by Company X and can therefore be ignored as a core problem. Solving this problem is the responsibility of the Company X facility of the receiving country or of the customs of that country. It is therefore not up to Company X to solve that problem.

The second potential core problem to be discussed is the partial deliveries of international suppliers. The problem can be solved by Company X. This can be done by making clear agreements with the international cross-docks about the loading of the trucks. It is Company X's responsibility to have these conversations with the international cross-docks and to find a solution to this problem. It is however the responsibility of the 'Transport Management' department and therefore not within the scope of this research.

The high workload is the third potential core problem to address. Just like the second potential core problem, this is a problem that can be influenced by Company X. However, it is not related to the scope of the assignment. If Company X wants to lower the workload, it can simply hire new people. Instead, Company X wants to focus on the process and the warehouse. Therefore, this problem will also be ignored as the core problem.

The two potential core problems that remain are related to the size and the layout/process of the warehouse. Currently, LBX is located in a logistically favourable location. It is surrounded by Company Z and it is located next to an important river which allows for easy access to international waters. This means that the sea containers can be transported quickly and easily to the sea, from where they can be shipped intercontinental. But its location does not give the possibility to expand the building easily. Company X is surrounded by Company Y which doesn't allow for expansion. That is why the optional core problem related to the warehouse being too small for volume growth is not a desirable problem to solve. Furthermore, the increase in volume will be gradual, so this gives the option for a gradual increase in capacity too. The capacity increase by making the layout and processes of the CP process in LBX more efficient should be enough to handle the increase in volume in the beginning.

The potential core problem that therefore remains is the inefficiency of the layout of the CP process. This problem can be influenced by Company X and is the preferred problem to solve by the company. This means that the core problem is:

The inefficient layout and processes of the CP process in LBX

Appendix C - Research Design

Research question: *Is the consolidation process in Company X 's Logistics Building X (LBX) able to handle the expected growth in throughput? And if not, what changes have to be made to the processes and layout of LBX to be able to handle the expected growth in volume?*

Knowledge question	MPSM Phase	Simulation Studies Stage	Research Type	Research Population	Research Strategy	Data Gathering Method(s)	Presentation of Outcome	Activity Plan
What does the current layout and process of the CP look like?	3	1	Descriptive	Literature, LBX warehouse	Qualitative	Literature review, observation	A map of the current layout of CP and a flowchart of the processes going on in the CP	Observing the process at CP, look at process maps already available at Company X
How do we set up the simulation study for the CP process?	2	1, 2 ,3 , 4	Explanatory	Literature, Expert in LBX	Qualitative	Literature review, Testing, interview	A description of different components of simulation study	Look at the book of Robinson (2014) of all components of simulation study, apply these components to the situation in LBX
What are the bottlenecks in the current layout and processes of the CP?	3	3&4	Explanatory	Literature, Simulation model	Qualitative	Experimentation	A list of the bottlenecks in the CP that cause a lower capacity	Look at the results of the simulation experiments, and find the bottlenecks according to the simulation model
Which theories related to warehouse optimisation can be applied in improving the layout and processes of the CP?	4&5	4	Descriptive	Literature	Qualitative	Literature review	A List of theories that are useful for improving the bottlenecks in the CP process	Search for available improvement theories for frequent occurring warehouse problems
What is the effect of the solutions on the CP process?	6&7	4	Descriptive	Simulation model	Qualitative	Experimentation	Tables showing the effect of the solutions on the simulation KPIs	New models are created with the solutions implemented, the models are run, and the results

								are analysed to see the effect on the process
How can the improved layout and processes be implemented in the CP?	6&7	None	Descriptive	Employees at CP, Process engineers at Company X	Qualitative	Literature review, interviews	An implementation plan of the new (improved) layout and processes for Company X	Conduct interviews with employees at CP and process engineers for possibilities of implementation plan

Appendix D - Flowchart of CP Process

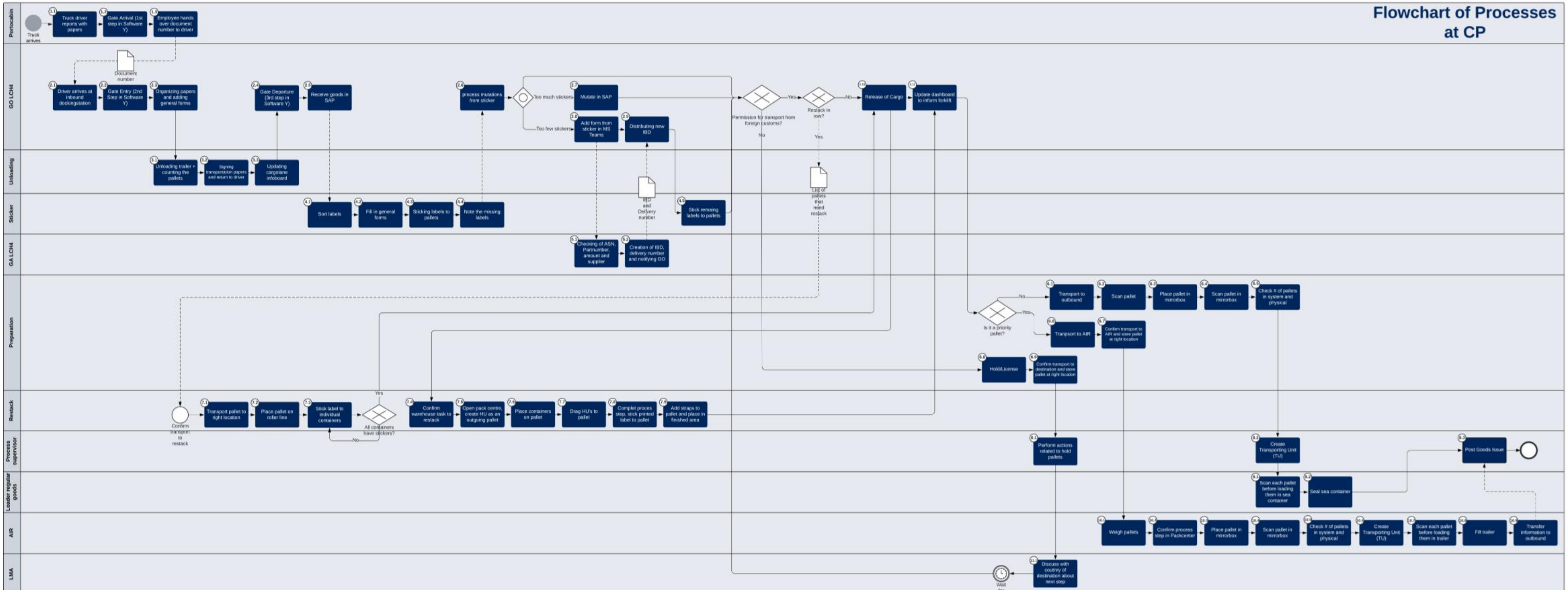

Figure D.1: Flowchart of Processes at LBX

Appendix E - Map of Logistics Building X

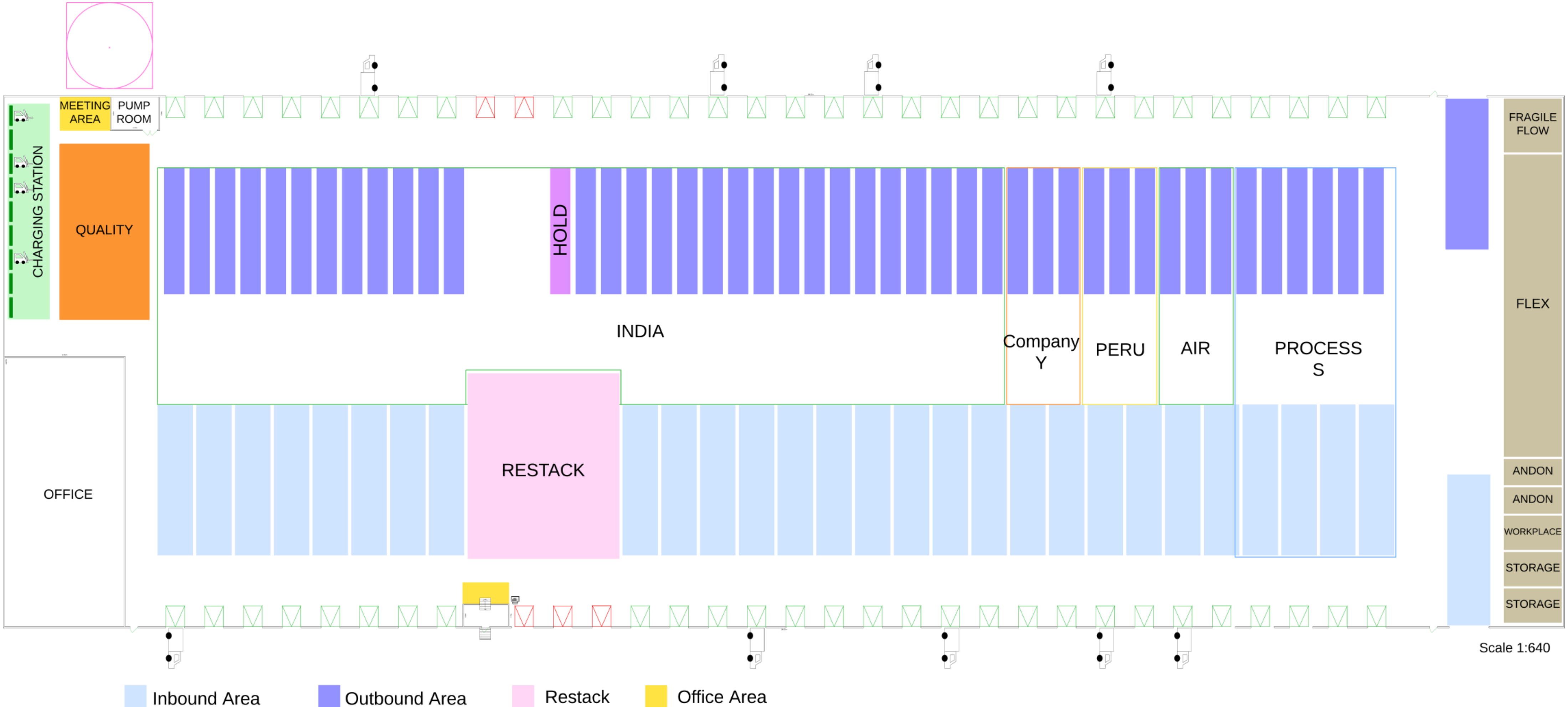

Figure E.1: Map of Logistics Building X

Appendix F - Expected Demand Japan

	Month and Year	Containers per Month	Containers per Day[4]
Q1 - 2025	Jan-25	0	0
	Feb-25	3	1
	Mar-25	5	1
Q2 - 2025	Apr-25	8	1
	May-25	11	1
	Jun-25	13	1
Q3 - 2025	Jul-25	15	1
	Aug-25	18	1
	Sep-25	21	1
Q4 - 2025	Oct-25	23	1
	Nov-25	26	2
	Dec-25	29	2
Q1 - 2026	Jan-26	29	2
	Feb-26	35	2
	Mar-26	39	2
Q2 - 2026	Apr-26	44	3
	May-26	49	3
	Jun-26	54	3
Q3 - 2026	Jul-26	59	3
	Aug-26	65	3
	Sep-26	70	4
Q4 - 2026	Oct-26	74	4
	Nov-26	80	4
	Dec-26	85	5
Q1 - 2027	Jan-27	85	5
	Feb-27	88	5
	Mar-27	90	5
Q2 - 2027	Apr-27	93	5
	May-27	95	5
	Jun-27	97	5
Q3 - 2027	Jul-27	100	5
	Aug-27	102	5
	Sep-27	103	5
Q4 - 2027	Oct-27	108	5
	Nov-27	112	5
	Dec-27	114	5

Table F.0.1: Expected Demand for Japan

[4] When determining the number of containers leaving LBX per day, holidays and weekends were left out. Therefore, this number is based on the number of working days per month. Furthermore, the result was rounded up to full container loads.

Appendix G - Goodness-Of-Fit Tests Inbound Data

Appendix G.1 - Number of HU Arrivals

Company X makes use of SAP, which is a warehouse management system (WMS) which tracks the handling units within the CP. In SAP, every HU has its own unique code, called a 'Source Handling Unit'. By counting the number of source handling units per day, one can determine the distribution of the number of HU arriving per day, with arrival rate λ. A division was made in the destination of the HUs within the warehouse. This can be either, sea (normal pallets that go directly to outbound), air (priority pallets that are transported by air) or restack (blue boxes that need to go through restack). Data points from January 2nd 2024 till May 15th 2024 from SAP were used to determine this distribution.

Looking at the graphs of the data from the past we can see that the normal distribution is the statistical distribution that fits the data points the best. For each destination, we can determine the parameters of the past data points as shown in Table G.1.

DESTINATION WITHIN LBX	$\boldsymbol{Sample\ mean}: \overline{X}$	$\boldsymbol{Sample\ standard\ deviation}: \sigma$
SEA	$2791\ HU\ per\ day$	$741\ HU\ per\ day$
AIR	$35\ HU\ per\ day$	$17\ HU\ per\ day$
RESTACK	$1312\ HU\ per\ day$	$394\ HU\ per\ day$

Table G.1: Mean and Standard Deviation of Arrival Rate

In Tables G.2, G.3 and G.4, we can see that sum of errors for all three cases is less than the critical value (117,6), therefore we do not reject the null hypothesis that the number of arriving HUs with a specific destination within the warehouse follows a normal distribution with means and standard deviations as shown in Table G.1. So, for the simulation, we assume that our null hypothesis is true and that,

$$\#Arriving\ Sea\ HU\ per\ day \sim N(2791{,}741)$$

$$\#Arriving\ Air\ HU\ per\ day \sim N(35{,}17)$$

$$\#Arriving\ Restack\ HU\ per\ day \sim N(1312{,}394)$$

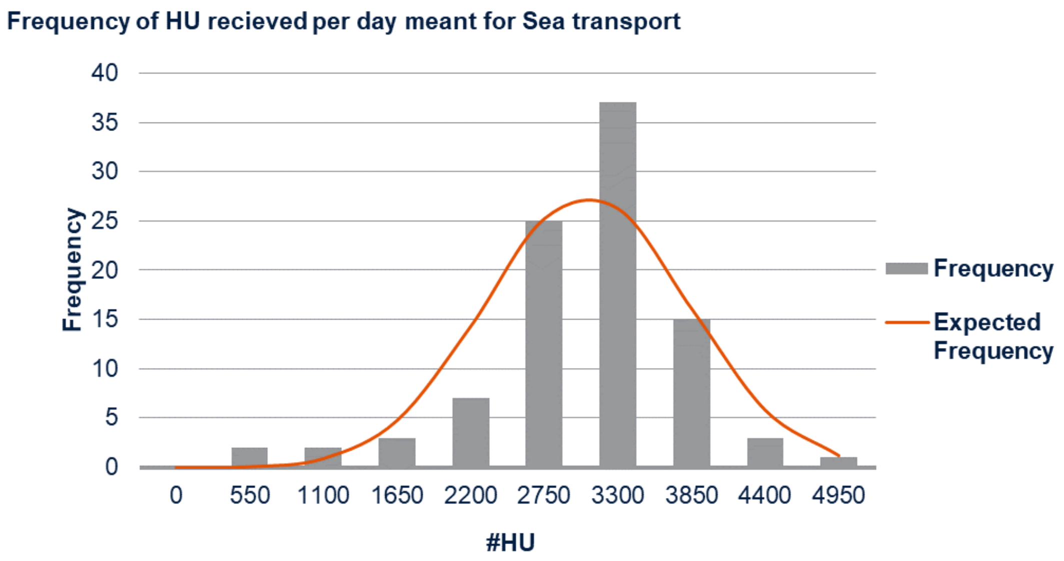

Figure G.1: Frequency of Number of Handling Units Arriving per Day for Sea

Bin	Observed Frequency (f)	CDF P(t<=T)	Expected Frequency (f')	Error $\chi^2 = \frac{(f-f')^2}{f'}$
0	0	0,00	0,01	0,01
550	2	0,00	0,11	32,42
1100	2	0,01	0,95	1,17
1650	3	0,06	4,80	0,67
2200	7	0,21	14,32	3,74
2750	25	0,48	25,22	0,00
3300	37	0,75	26,23	4,43
3850	15	0,92	16,11	0,08
4400	3	0,99	5,84	1,38
4950	1	1,00	1,25	0,05
			Error:	43,95
			Critical Value	117,63

Table G.2: Goodness-Of-Fit Test for Number of HU Arrivals per Day for Sea

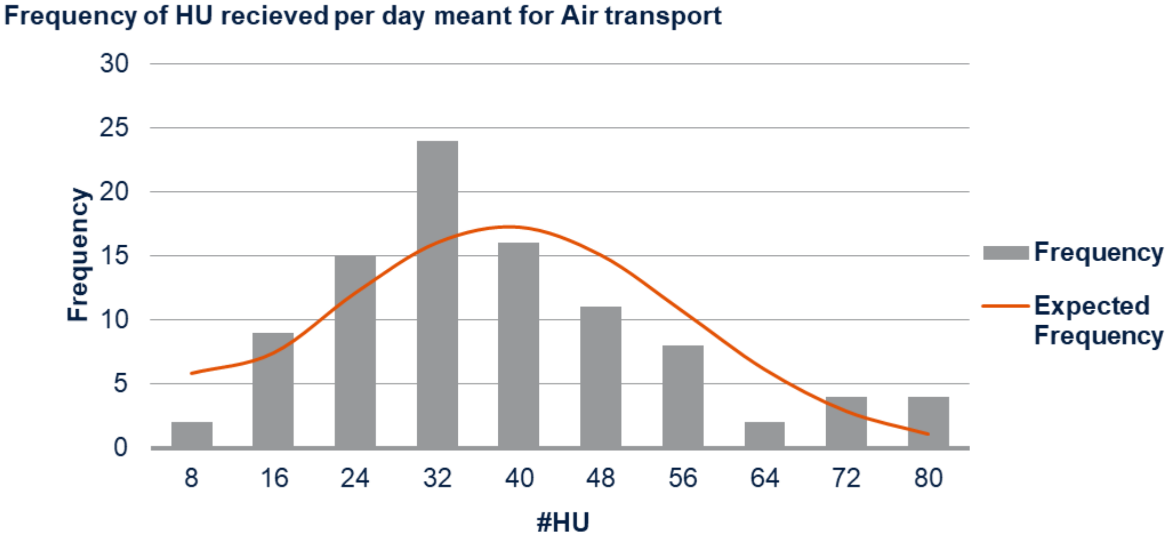

Figure G.2: Frequency of Number of Handling Units Arriving per Day for Air

Bin	Observed Frequency (f)	CDF P(t<=T)	Expected Frequency (f')	Error $\chi^2 = \frac{(f-f')^2}{f'}$
8	2	0,06	5,84	2,53
16	9	0,14	7,42	0,33
24	15	0,27	12,11	0,69
32	24	0,44	16,04	3,95
40	16	0,62	17,26	0,09
48	11	0,78	15,07	1,10
56	8	0,89	10,69	0,68
64	2	0,95	6,15	2,80
72	4	0,98	2,88	0,44
80	4	1,00	1,09	7,74
			Error:	20,35
			Critical Value	117,63

Table G.3: Goodness-Of-Fit Test for Number of HU Arrivals per Day for Air

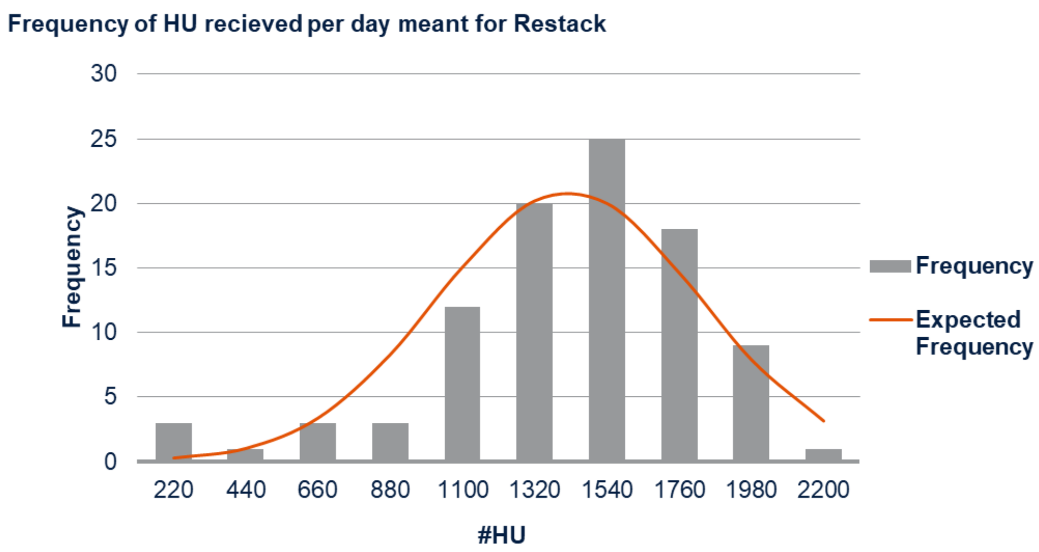

Figure G.3: Frequency of Number of Handling Units Arriving per Day for Restack

Bin	***Observed Frequency (f)***	***CDF P(t<=T)***	***Expected Frequency (f')***	***Error*** $\chi^2 = \frac{(f-f')^2}{f'}$
220	3	0,00	0,27	28,20
440	1	0,01	1,01	0,00
660	3	0,05	3,37	0,04
880	3	0,14	8,30	3,39
1100	12	0,30	15,07	0,63
1320	20	0,51	20,21	0,00
1540	25	0,72	19,99	1,25
1760	18	0,87	14,61	0,79
1980	9	0,95	7,88	0,16
2200	1	0,99	3,13	1,45
			Error:	35,91
			Critical Value	117,63

Table G.4: Goodness-Of-Fit Test for Number of HU Arrivals per Day for Restack

Appendix G.2 - Number of HU Arrivals for Company Y

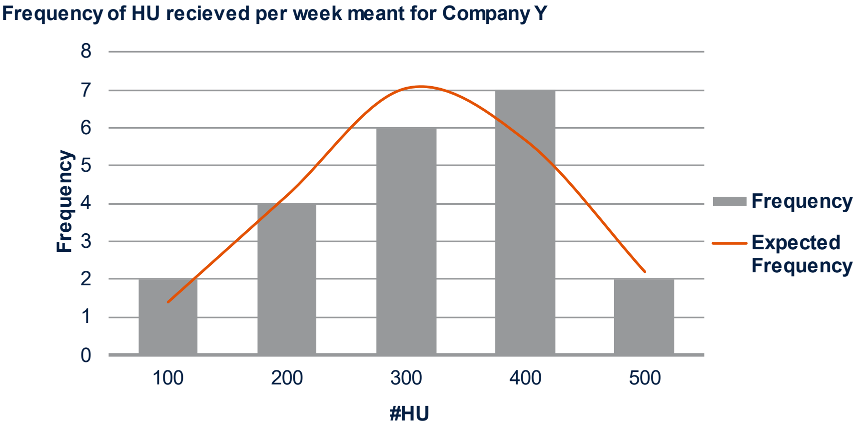

Figure G.4: Frequency of Number of Handling Units Arriving per Week for Company Y

Bin	Observed Frequency (f)	CDF P(t<=T)	Expected Frequency (f')	Error $\chi^2 = \frac{(f - f')^2}{f'}$
100	2	0,07	1,39	0,27
200	4	0,27	4,22	0,01
300	6	0,60	7,06	0,16
400	7	0,87	5,68	0,31
500	2	0,98	2,20	0,02
			Error:	0,76
			Critical Value	31,4

Table G.5: Goodness-Of-Fit Test for Number of HU Arrivals per Week for Company Y

Appendix G.3 - Number of Blue Boxes per Pallet at Arrival

Some pallets that go through restack contain more blue boxes than other pallets at arrival at LBX. Therefore, it is important to analyse how many boxes a pallet contains because this influences the number of pallets that arrive at the warehouse and how much storage is needed in the inbound area. A data set of over 12.000 data points provides us with the number of boxes per pallet. Looking at the shape of Graph G.5, we can assume a negative exponential distribution. After determining the expected frequency and comparing it to the observed frequency, we can see that the sum of errors is smaller than the critical value. Therefore, we cannot reject the null hypothesis that the number of boxes per pallet at arrival is negative exponentially distribution with an average of 4,8 boxes per pallet.

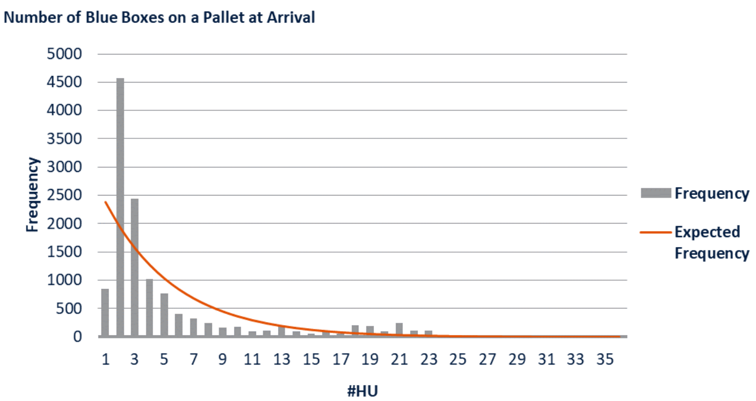

Figure G.5: Frequency Graph for Number of Blue Boxes per Pallet

Bin	*Observed Frequency (f)*	*CDF P(t<=T)*	*Expected Frequency (f')*	*Error* $\chi^2 = \frac{(f-f')^2}{f'}$
1	843	0,19	2374,17	987,49
2	4568	0,34	1928,93	3610,63
3	2436	0,46	1567,19	481,64
4	1021	0,56	1273,29	49,99
5	764	0,65	1034,51	70,73
6	405	0,71	840,50	225,66
7	319	0,77	682,88	193,90
8	241	0,81	554,82	177,50
9	159	0,85	450,77	188,86
10	175	0,87	366,24	99,86
11	101	0,90	297,56	129,84
12	107	0,92	241,75	75,11
13	189	0,93	196,42	0,28
14	94	0,95	159,58	26,95
15	60	0,96	129,66	37,42
16	81	0,96	105,34	5,62
17	61	0,97	85,59	7,06
18	210	0,98	69,54	283,74
19	185	0,98	56,50	292,30
20	91	0,98	45,90	44,31
21	248	0,99	37,29	1190,51
22	107	0,99	30,30	194,16
23	108	0,99	24,62	282,43
24	30	0,99	20,00	5,00
25	0	0,99	16,25	16,25
26	24	1,00	13,20	8,83
27	3	1,00	10,73	5,57
28	3	1,00	8,71	3,75
29	7	1,00	7,08	0,00
30	9	1,00	5,75	1,83
31	3	1,00	4,67	0,60
32	0	1,00	3,80	3,80
33	3	1,00	3,09	0,00
34	0	1,00	2,51	2,51
35	0	1,00	2,04	2,04
36	5	1,00	1,65	6,76
			Error:	8712,9
			Critical Value	12921,9

Table G.6: Goodness-Of-Fit Test for Number of Blue Boxes per Pallet

Appendix G.4 - Distribution of Pallet Types

The HUs that arrive at the CP consist of a lot of different types of pallets or boxes. Each pallet and box type has its own volume. The box types are important to know to be able to determine how boxes fit on a pallet at restack. Bigger boxes need more space and therefore there are fewer of these boxes on a pallet. The distribution of the pallet types influences how many pallets fit in a container in the outbound area. Some pallets require more space than other pallets, and that has to be considered when filling the containers in the outbound area. For these two reasons, it is important to determine the distribution of the pallet and box types that arrive at the CP.

Each pallet and box type has its own code in SAP. In the period from January 2nd 2024 till May 15th 2024, a total of 64 different pallet types were handled in LBX. The distribution of the different pallet 27 and box types is determined for every destination within the CP (Air, Sea, Restack). But to limit the number of pallet types, we will only consider the pallet types that have a share of 1% or more, the others are left out. The distribution of the pallet types for each destination within the warehouse is provided in Tables G.7, G.8 and G-9. For Company Y, we assume the same pallet distribution as the pallets with internal destination sea. The reason for this assumption is that the pallets for Company Y follow the same path as the pallets for sea, and they also don't need restack.

This distribution is used by Plant Simulation to determine the HU type entering the warehouse. And the volume of the HUs is used to fill the containers at the outbound area of LBX.

Handling Unit Type	Frequency	Volume (M3)	Percentage of total	Name in Simulation
11	16858	0,36	7,11%	Euro1R
12	38336	0,56	16,17%	Euro2R
13	36462	0,76	15,38%	Euro3R
14	34311	0,96	14,47%	Euro4R
15	5694	1,16	2,40%	Euro5R
21	41225	0,17	17,39%	HalfEuro1R
22	25599	0,271	10,80%	HalfEuro2R
23	4608	0,373	1,94%	HalfEuro3R
90	3996	2,372	1,69%	DiversePallet
D1	12248	0,154	5,17%	Hpallet1R
D2	7291	0,217	3,08%	Hpallet2R
D3	4236	0,281	1,79%	Hpallet3R
D4	2810	0,344	1,19%	Hpallet4R
D5	3420	0,41	1,44%	Hpallet5R

Table G.7: Pallet Types and Distribution meant for Sea Transportation

Handling Unit Type	Frequency	Volume (M3)	Percentage of Total	Name in Simulation
11	106	0,36	6,4%	Euro1R
12	146	0,56	8,8%	Euro2R
13	153	0,76	9,2%	Euro3R
14	89	0,96	5,4%	Euro4R
15	58	1,16	3,5%	Euro5R
21	328	0,17	19,8%	HalfEuro1R
22	560	0,271	33,7%	HalfEuro2R
23	27	0,373	1,6%	HalfEuro3R
90	101	2,372	6,1%	DiversePallet
D1	35	0,154	2,1%	Hpallet1R
D2	57	0,217	3,4%	Hpallet2R

Table G.8: Pallet Types and Distribution meant for Air Transportation

Handling Unit Type	Frequency	Volume (M3)	Percentage of Total	Name in Simulation
B1	50136	0,008	43,0%	Box3
B2	35197	0,017	30,2%	Box2
B3	31311	0,034	26,8%	Box1

Table G.9: Box Types and Distribution meant for Restack

Appendix G.5 - Correlation between Number of Pallets in Trailer and its Unloading Time

For the simulation model, it is necessary to know how long it takes to unload a trailer. The Warehouse Management Systems of Company X do not have data with regards to the unloading time, since the HUs are scanned once unloaded, and that is when the HUs are imported in the WMS. Therefore, the opinion of an expert in the field is used, where the expert is again the supervisor of LBX. The expert gave the following data: the minimum unloading time is 00:30:00, the maximum unloading time is 01:30:00 and the most frequent unloading time is 00:45:00. So,

$$Trailer\ Unloading\ Time \sim Triangular(00:30:00, 00:45:00, 01:30:00)$$

However, the unloading time is dependent on the number of pallets in the corresponding trailer. Therefore, we will perform another analysis that shows the correlation between the number of pallets in the trailer and its unloading time.

If we split up the difference in minimum and maximum unloading time in the same number of data points as the number of pallets in a trailer, we can create a graph with the probabilities for both the number of pallets per trailer and the trailer unloading time, see Figure G.6. In this graph it can be seen that the two probability functions are almost the same and that there might be a correlation between the two. By performing a t-test we can determine if there is indeed a correlation or not.

The first step of the t-test is calculating the correlation coefficient (Bobbitt, 2021). This is a number between -1 and 1 that shows the correlation between two data sets. The correlation coefficient of the probability functions of the two data sets is 0,992. This means that there is a strong positive linear correlation between the probability functions of both data sets. The next step is to calculate the t-score, the formula used for this is:

$$t - score = r\sqrt{(n-2)(1-r^2)}$$

Where r is the correlation coefficient, and n is the sample size, which is 223 in our case. This results in a t-score of 14,6. Using a t-score to p-value calculator (Bobbitt, 2018), we can calculate the p-value which is 0,000. The p-value is smaller than our level of significance, which is 0,05. Therefore, we can conclude that the correlation between the two variables is statistically significant.

If we distribute the interval of the trailer unloading time into equal steps, we find out that for each extra pallet, we need 16 seconds of extra unloading time. But with 8 pallets in a trailer, we still need 30 minutes of unloading time, which means that we have a startup time of $00:30:00 - (8 * 00:00:16) = 00:27:52$. So, the unloading time per trailer can be determined with the following formula:

$$Trailer\ Unloading\ Time = 00:27:52 + 00:00:16 * \#Pallets\ in\ Trailer$$

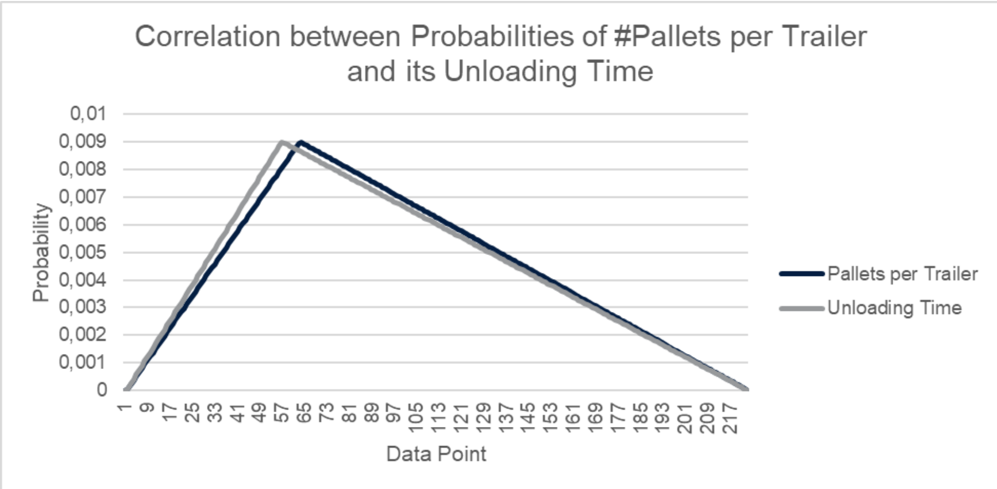

Figure G.6: Correlation between Probabilities of #Pallets per Trailer and its Unloading Time

Appendix H - Goodness-Of-Fit Tests Outbound Data

Appendix H.1 - Container Fill Rate

Before a container is requested at Company Z, a complete bin should be filled with pallets. Therefore, we need to know how many pallets fit in a sea container or truck such that it is completely filled. The data we need for this is the sizes of the different pallet types and the fill volume of a container.

Company X makes use of a lot of different pallets for the different products they transport. A table of the different HU types used at the warehouse and their volume is provided in Appendix G.4. Each HU type has its own volume (in M3), this volume will be used in the simulation to determine how many pallets fit in a container or trailer.

The number of pallets in a container is limited by the maximum volume of a sea container. The type of sea container used by Company X is a 40 ft. High Cube Container with a maximum volume of 76,4 M3 (Freightfinders.com, 2024). However, there will always be some empty space in the sea container. This has to do with the dimensions of the pallets, the margins on the sides of the container and the way the employee stacked the pallets.

Looking at data from past sea containers that left the warehouse, we can see that the average loading volume is 53,2 M3 . This means that there is an average void percentage of 27,6%. This is because the data set contains a lot of containers that are only filled for about 30%. This is caused by HU type 90. This is a pallet type that varies in size. SAP registers this pallet type according to a certain volume, but the volume of the pallet might be bigger. The containers with a low fill rate contain more of these pallets, and therefore the total volume loaded in the container is low. For this reason, we will consider those fill rates as outliers.

To determine the outliers in the data set, we make use of the interquartile range method (Bhandari, 2024). The interquartile range (IQR) is the interval between the first and third quartiles of the data set. All the data points that lie 1,5 * IQR below the first quartile or 1,5 * IQR above the third quartile, are considered outliers and not included in the statistical analysis.

From a data set of 4158 data points, we are left with 2976 container fill rates. By analysing these remaining data points, we can conclude that the filling volume of the departing sea containers follows a normal distribution with a mean value of 56,9 M3 and a standard deviation of 2,9 M3

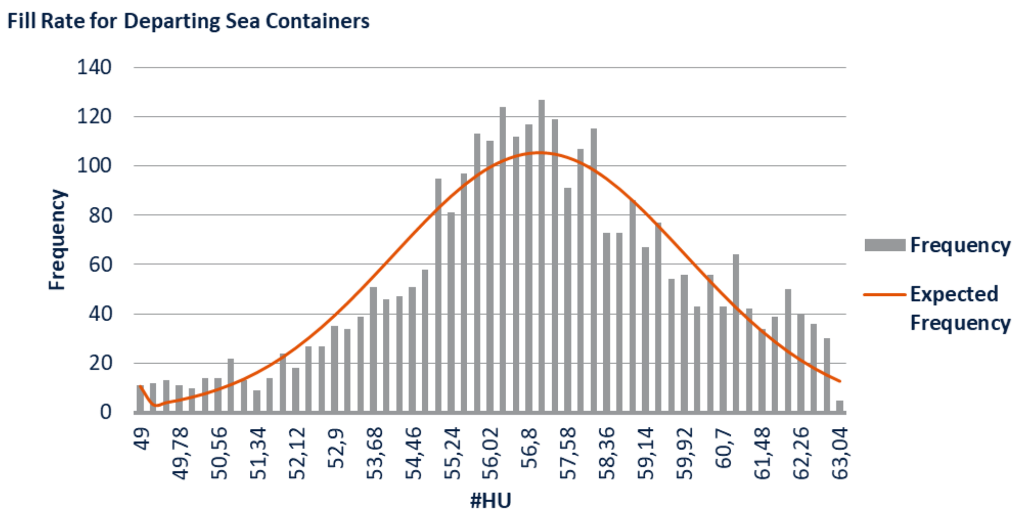

Figure H.1: Fill Rate Frequencies for Departing Sea Containers

Bin	*Observed Frequency (f)*	*CDF P(t<=T)*	*Expected Frequency (f')*	*Error* $\chi^2 = \frac{(f - f')^2}{f'}$
1	11	0,004	10,59	0,02
2	12	0,005	3,18	24,46
3	13	0,006	4,01	20,19
4	11	0,008	5,01	7,17
5	10	0,010	6,21	2,31
6	14	0,012	7,64	5,30
7	14	0,015	9,33	2,34
8	22	0,019	11,29	10,15
9	13	0,024	13,57	0,02
10	9	0,029	16,18	3,18
11	14	0,036	19,13	1,38
12	24	0,043	22,45	0,11
13	18	0,052	26,14	2,54
14	27	0,062	30,20	0,34
15	27	0,074	34,61	1,67
16	35	0,087	39,36	0,48
17	34	0,10	44,40	2,44
18	39	0,12	49,70	2,30
19	51	0,14	55,20	0,32
20	46	0,16	60,82	3,61
21	47	0,18	66,49	5,71
22	51	0,20	72,11	6,18
23	58	0,23	77,60	4,95
24	95	0,26	82,85	1,78
25	81	0,29	87,76	0,52
26	97	0,32	92,24	0,25
27	113	0,35	96,18	2,94
28	110	0,38	99,50	1,11
29	124	0,42	102,14	4,68
30	112	0,45	104,01	0,61
31	117	0,49	105,09	1,35
32	127	0,52	105,35	4,45
33	119	0,56	104,79	1,93
34	91	0,59	103,40	1,49
35	107	0,63	101,24	0,33
36	115	0,66	98,34	2,82
37	73	0,69	94,78	5,00
38	73	0,72	90,62	3,43
39	86	0,75	85,97	0,00
40	67	0,78	80,92	2,40
41	77	0,81	75,57	0,03
42	54	0,83	70,02	3,67
43	56	0,85	64,37	1,09
44	43	0,87	58,71	4,20
45	56	0,89	53,12	0,16

46	43	0,90	47,69	0,46
47	64	0,92	42,48	10,90
48	42	0,93	37,55	0,53
49	34	0,94	32,92	0,04
50	39	0,95	28,64	3,75
51	50	0,96	24,72	25,85
52	40	0,97	21,17	16,75
53	36	0,97	17,99	18,04
54	30	0,98	15,16	14,52
55	5	0,98	12,68	4,65
			Error:	246,9
			Critical Value	3103,0

Table H.1: Goodness-Of-Fit Test for Sea Container Fill Rate

Appendix H.2 - Arrival of Empty Container

The first step in fitting a statistical distribution is the selection of a statistical distribution. If we make a histogram of the times between request and arrival of an empty sea container, as shown in Figure H.2, one can see that the histogram has the shape of a negative exponential distribution: it starts with a high frequency and the frequency decreases exponentially if we increase the waiting time,

The next step is the determination of the parameters of the statistical distribution. We assumed that the distribution is negative exponential, so that means that we have to determine the lambda of the data set. Lambda is the number of occurrences per time unit in a given time unit (Newcastle University, 2024), which is the number of arrivals per time unit (days in our case). The mean of the data is 01:10:21, which is 0,0489 days. This resulted in the following parameter

$$lambda = \lambda = \frac{1}{0{,}0489} = 20{,}5\ arrivals\ per\ day$$

Now that the arrival rate is known, we can continue with the third step, which is the goodness-of-fit test. This begins with calculating the cumulative distribution function (P(t<=T)). Since we assume that the statistical distribution is exponential, we use the EXPON.DIST function in excel. The input for this function are *t* and lambda and the result is the probability that a value belongs to a specific bin. The CDF values can be used to determine the expected frequency, as Table H.2 shows. And by comparing the expected and observed frequency, we can determine the error. The sum of the errors is 67,16 which is smaller than the critical value of 800,2 (with 5% probability and 736 degrees of freedom). This means that we do not reject the null hypothesis that the time between request and arrival of an empty sea container is negative exponentially distributed with lambda = 20.5. As explained in before, if we fail to reject H_0, we assume that the null hypothesis is true, so

$$Time\ to\ request\ sea\ container \sim Exp(20{,}5)$$

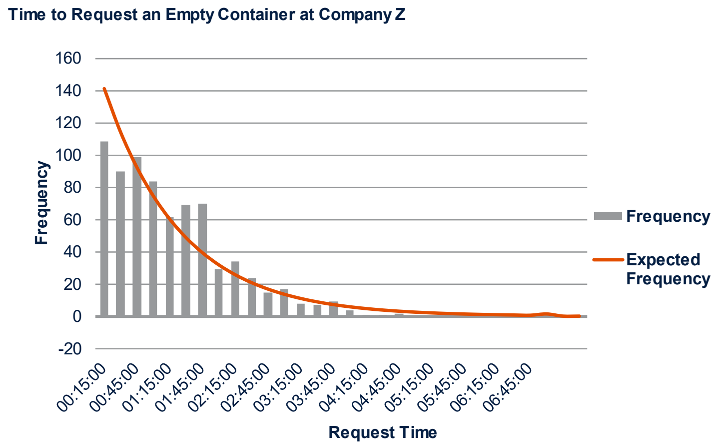

Figure H.2: Frequency for Request Time for Arrival of Empty Container

Bin (Waiting Time)	Observed Frequency (f)	CDF P(t<=T)	Expected Frequency (f')	Error $\chi^2 = \frac{(f-f')^2}{f'}$
00:15:00	109	0,19	141,53	7,48
00:30:00	90	0,35	114,35	5,18
00:45:00	99	0,47	92,39	0,47
01:00:00	84	0,57	74,65	1,17
01:15:00	62	0,66	60,31	0,05
01:30:00	69	0,72	48,73	8,43
01:45:00	70	0,78	39,37	23,82
02:00:00	29	0,82	31,81	0,25
02:15:00	34	0,85	25,70	2,68
02:30:00	24	0,88	20,77	0,50
02:45:00	15	0,90	16,78	0,19
03:00:00	17	0,92	13,56	0,87
03:15:00	8	0,94	10,95	0,80
03:30:00	7	0,95	8,85	0,39
03:45:00	9	0,96	7,15	0,48
04:00:00	4	0,97	5,78	0,55
04:15:00	1	0,97	4,67	2,88
04:30:00	1	0,98	3,77	2,04
04:45:00	2	0,98	3,05	0,36
05:00:00	0	0,99	2,46	2,46
05:15:00	0	0,99	1,99	1,99
05:30:00	1	0,99	1,61	0,23
05:45:00	0	0,99	1,30	1,30
06:00:00	0	0,99	1,05	1,05
06:15:00	0	1,00	0,85	0,85
06:30:00	1	1,00	0,69	0,14
06:45:00	0	1,00	0,55	0,55
			Error:	67,16
			Critical Value:	800,22

Table H.2: Goodness-Of-Fit Test for Time of Arrival of Empty Container

Appendix H.3 - Loading Time Sea Container

The loading time that was exported from SAP resulted in a list of 168 TU's, their unloading time and the number of pallets per TU. By dividing the unloading time by the number of pallets in a TU, we can determine the unloading timer per pallet. The frequency of the unloading times per pallet is provided in Figure H.3. The grey bars (representing the observed frequency) show the shape of a negative exponential distribution. That is why we will check for a negative exponential distribution in this data set.

First, we calculate the Cumulative Distribution Function for the negative exponential distribution with mean 4 seconds (or 0,0000424 days). Lambda is therefore $\frac{1}{0{,}0000424} = 23577{,}5$ pallets per day. By multiplying the CDF with the number of observations, we can calculate the expected frequency according to this distribution, as shown in Figure H.3. Next, we can calculate the error with the formula described before.

When summing all the errors and calculating the critical value (with 5% probability and 167 degrees of freedom), one can see in Table H.3 that the error is smaller than the critical value. For this reason, we do not reject H_0 where the loading time per pallet follows a negative exponential distribution with lambda 23577,48 pallets per day. And as mentioned before, we will assume that H_0 is true and that,

$$Loading\ Time\ per\ Pallet\ {\sim}Exp(23577{,}5)$$

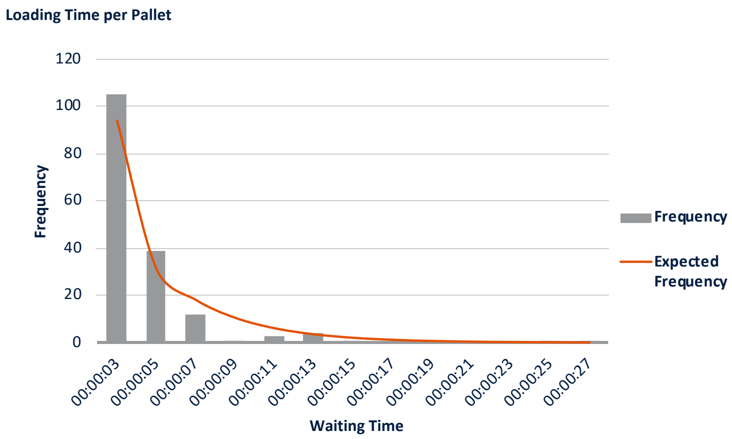

Figure H.3: Frequency for the Unloading Time per Pallet

Bin (Waiting Time)	**Observed Frequency (f)**	**CDF P(t<=T)**	**Expected Frequency (f')**	**Error** $\chi^2 = \frac{(f-f')^2}{f'}$
00:00:03	00:00:03	105	0,56	93,91
00:00:05	00:00:05	39	0,74	31,16
00:00:07	00:00:07	12	0,85	18,06
00:00:09	00:00:09	1	0,91	10,46
00:00:11	00:00:11	3	0,95	6,06
00:00:13	00:00:13	4	0,97	3,51
00:00:15	00:00:15	1	0,98	2,03
00:00:17	00:00:17	0	0,99	1,18
00:00:19	00:00:19	1	0,99	0,68
00:00:21	00:00:21	0	1,00	0,40
00:00:23	00:00:23	0	1,00	0,23
			Error	34,69
			Critical Value	198,15

Table H.3: Goodness-Of-Fit Test for Loading Time per Pallet

Appendix H.4 - Departure of Full Container

For the departure time of a full sea container, the same approach was applied as the arrival time of an empty sea container. The same statistical distribution seems to fit the data from the past. If we look at the error and critical value in Table H.4 we can conclude that we fail to reject the null hypothesis that the time between request and departure of a full sea container is negative exponentially distributed with lambda = 21,3. Therefore, for our simulation we assume that

$$Time\ for\ sea\ container\ to\ leave \sim Exp(21{,}3)$$

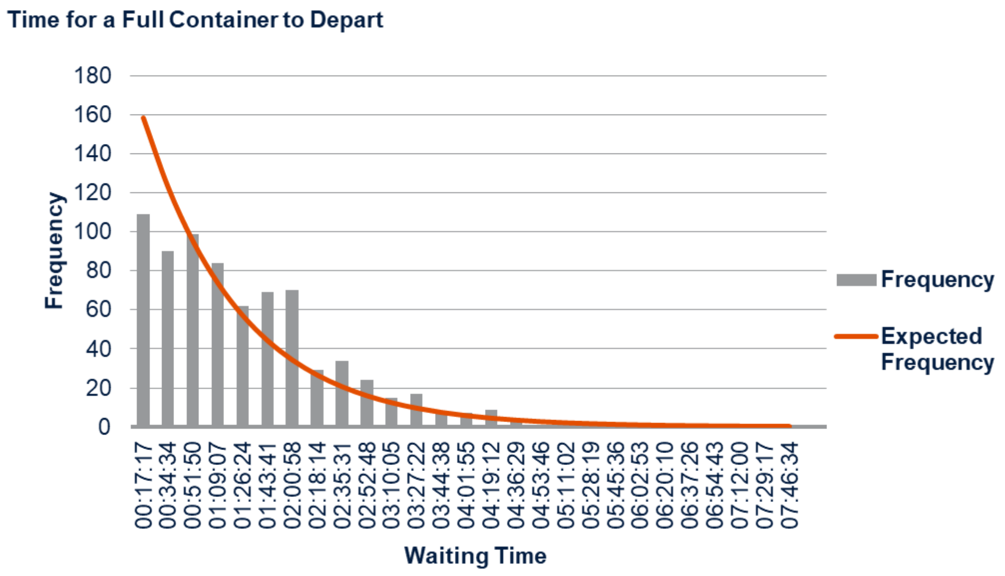

Figure H.4: Frequency for Request Time for Departure of Full Container

Bin (Waiting Time)	***Observed Frequency (f)***	***CDF P(t<=T)***	***Expected Frequency (f')***	***Error*** $\chi^2 = \frac{(f-f')^2}{f'}$
00:17:17	169	0,23	158,36	0,71
00:34:34	136	0,40	122,69	1,44
00:51:50	106	0,53	95,05	1,26
01:09:07	54	0,64	73,64	5,24
01:26:24	61	0,72	57,05	0,27
01:43:41	38	0,78	44,20	0,87
02:00:58	20	0,83	34,24	5,92
02:18:14	25	0,87	26,53	0,09
02:35:31	21	0,90	20,55	0,01
02:52:48	12	0,92	15,92	0,97
03:10:05	5	0,94	12,34	4,36
03:27:22	8	0,95	9,56	0,25
03:44:38	8	0,96	7,40	0,05
04:01:55	8	0,97	5,74	0,89
04:19:12	5	0,98	4,44	0,07
04:36:29	5	0,98	3,44	0,70
04:53:46	3	0,99	2,67	0,04
05:11:02	3	0,99	2,07	0,42
05:28:19	4	0,99	1,60	3,60
05:45:36	1	0,99	1,24	0,05
06:02:53	5	1,00	0,96	16,98
06:20:10	2	1,00	0,74	2,12
06:37:26	1	1,00	0,58	0,31
06:54:43	1	1,00	0,45	0,68
07:12:00	1	1,00	0,35	1,23
07:29:17	1	1,00	0,27	2,00
07:46:34	0	1,00	0,21	0,21
			Error:	50,75
			Critical Value:	764,75

Table H.4:Goodness-Of-Fit Test for Departure of Full Container

Appendix H.5 – Number of HU Hold

A fraction of the arriving handling units do not have permission from the foreign customs yet. These HUs are placed in the hold area of the warehouse. The number of HUs that go to hold can be determined by looking at a data set of incoming HUs in the CP. This data set contains over 400.000 HUs, of which only 450 went to the hold area. Only normal pallets meant for sea transport go to hold. Therefore, we will assume that 0,11% of the arrival rate for HUs designated for sea, do not have permission for intercontinental transportation, and will be placed in the designated hold area.

$$Arrival\ Rate\ Hold \sim 0{,}0011\ *\ Arrival\ Rate\ Sea\ HUs$$

Appendix H.6 - Transportation Times

The forklifts have to travel a certain distance in the warehouse to transport the pallets from point A to B. The distance between the destinations determines the amount of time that a forklift is occupied. The longer the forklift is occupied, the fewer pallets it can transport in the same amount of time. This decreases the throughput time of the pallets and that is why we will consider this transportation time in our simulation as well.

The transportation time is based on a few factors: forklift speed, distance to travel and time of picking a pallet up and putting it down. The forklifts are allowed to travel at a maximum speed of 8 km/h in the warehouse. However, the forklifts also have to accelerate, decelerate and account for other traffic in the warehouse. Therefore, we will assume that the forklift travels at an average speed of 5 km/h in the warehouse.

Furthermore, according to a forklift driver in Company X's warehouse, the average time to pick up a pallet is around 10 seconds. Therefore, we take 10 seconds into account for picking a pallet up and 10 seconds for placing it down.

The distances between the different locations in the warehouse are based on the map of the warehouse. This resulted in a table with the travel distances between points A and B, and the other way around.

Finally, the pallets that have priority and are transported by air, need to be weighed before they can be dispatched. We also included this in the transportation timetables. Based on the advice of an employee of LBX, this process of weighing a pallet and placing a sticker on it takes 45 seconds. So, we add an additional 45 seconds to the transportation time for the lanes designated for Air transportation.

By combining the four factors for the transportation time, we can make a table that covers the transportation time of the different routes in the warehouse. Table H.5 shows the travel time between each of the lanes at the outbound area and restack. We will use this for the restack pallets that are transported from inbound to the restack area. The second table, Table H.6, shows the travel time from the inbound area, including restack, to each of the bins in the outbound area.

LANE NUMBER	DISTANCE (IN M)	TRAVEL TIME
1	55	00:01:00
2	50,25	00:00:56
3	45,5	00:00:53
4	40,75	00:00:49
5	36	00:00:46
6	31,25	00:00:42
7	26,5	00:00:39
8	21,75	00:00:36
9	21,75	00:00:36
10	26,5	00:00:39
11	31,25	00:00:42
12	36	00:00:46
13	40,75	00:00:49
14	45,5	00:00:53
15	50,25	00:00:56
16	55	00:01:00
17	59,75	00:01:03
18	64,5	00:01:06
19	69,25	00:01:10
20	74	00:01:13
21	78,75	00:01:17
22	83,5	00:01:20
23	88,25	00:01:24
24	93	00:01:27
25	97,75	00:01:30
26	102,5	00:01:34
27	107,25	00:01:37
28	112	00:01:41

Table H.5: Travel Time from Lane x to Restack

Lane/Bin	Bin1	Bin2	Bin3	Bin4	Bin5	Bin6	Bin7	Bin8	Bin9	Bin10	Bin11	Bin12	Bin13	Bin14	Bin15	Bin16	Bin17	Bin18	Bin19	Bin20	Bin21	Bin22
Lane 1	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:01:04	00:01:06	00:01:08	00:01:10	00:01:13	00:01:15	00:01:17	00:01:19	00:01:21	00:01:23
Lane 2	00:00:32	00:00:29	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:01:00	00:01:02	00:01:04	00:01:06	00:01:08	00:01:10	00:01:13	00:01:15	00:01:17	00:01:19
Lane 3	00:00:36	00:00:34	00:00:32	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:00:57	00:01:00	00:01:02	00:01:04	00:01:06	00:01:08	00:01:10	00:01:13	00:01:15	00:01:17
Lane 4	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:04	00:01:06	00:01:08	00:01:10	00:01:13
Lane 5	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:04	00:01:06	00:01:08	00:01:10
Lane 6	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:29	00:00:32	00:00:34	00:00:36	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:04	00:01:06
Lane 7	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:32	00:00:34	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:04
Lane 8	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:29	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00
Lane 9	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:00:34	00:00:32	00:00:29	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42
Lane 10	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40
Lane 11	00:01:15	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:29	00:00:32	00:00:34	00:00:36
Lane 12	00:01:19	00:01:17	00:01:15	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:32	00:00:34
Lane 13	00:01:21	00:01:19	00:01:17	00:01:15	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:29
Lane 14	00:01:26	00:01:23	00:01:21	00:01:19	00:01:17	00:01:15	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32
Lane 15	00:01:28	00:01:26	00:01:23	00:01:21	00:01:19	00:01:17	00:01:15	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34
Lane 16	00:01:32	00:01:30	00:01:28	00:01:26	00:01:23	00:01:21	00:01:19	00:01:17	00:01:15	00:01:13	00:01:10	00:01:08	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38
Lane 17	00:01:34	00:01:32	00:01:30	00:01:28	00:01:26	00:01:23	00:01:21	00:01:19	00:01:17	00:01:15	00:01:13	00:01:10	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40
Lane 18	00:01:38	00:01:36	00:01:34	00:01:32	00:01:30	00:01:28	00:01:26	00:01:23	00:01:21	00:01:19	00:01:17	00:01:15	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44
Lane 19	00:01:41	00:01:38	00:01:36	00:01:34	00:01:32	00:01:30	00:01:28	00:01:26	00:01:23	00:01:21	00:01:19	00:01:17	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47
Lane 20	00:01:45	00:01:43	00:01:41	00:01:38	00:01:36	00:01:34	00:01:32	00:01:30	00:01:28	00:01:26	00:01:23	00:01:21	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51
Lane 21	00:01:47	00:01:45	00:01:43	00:01:41	00:01:38	00:01:36	00:01:34	00:01:32	00:01:30	00:01:28	00:01:26	00:01:23	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53
Lane 22	00:01:51	00:01:49	00:01:47	00:01:45	00:01:43	00:01:41	00:01:38	00:01:36	00:01:34	00:01:32	00:01:30	00:01:28	00:01:17	00:01:15	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57
Lane 23	00:01:54	00:01:51	00:01:49	00:01:47	00:01:45	00:01:43	00:01:41	00:01:38	00:01:36	00:01:34	00:01:32	00:01:30	00:01:19	00:01:17	00:01:15	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00
Lane 24	00:01:58	00:01:56	00:01:54	00:01:51	00:01:49	00:01:47	00:01:45	00:01:43	00:01:41	00:01:38	00:01:36	00:01:34	00:01:23	00:01:21	00:01:19	00:01:17	00:01:15	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04
Lane 25	00:02:00	00:01:58	00:01:56	00:01:54	00:01:51	00:01:49	00:01:47	00:01:45	00:01:43	00:01:41	00:01:38	00:01:36	00:01:26	00:01:23	00:01:21	00:01:19	00:01:17	00:01:15	00:01:13	00:01:10	00:01:08	00:01:06
Lane 26	00:02:04	00:02:02	00:02:00	00:01:58	00:01:56	00:01:54	00:01:51	00:01:49	00:01:47	00:01:45	00:01:43	00:01:41	00:01:30	00:01:28	00:01:26	00:01:23	00:01:21	00:01:19	00:01:17	00:01:15	00:01:13	00:01:10
Lane 27	00:02:09	00:02:07	00:02:04	00:02:02	00:02:00	00:01:58	00:01:56	00:01:54	00:01:51	00:01:49	00:01:47	00:01:45	00:01:34	00:01:32	00:01:30	00:01:28	00:01:26	00:01:23	00:01:21	00:01:19	00:01:17	00:01:15
Lane 28	00:02:11	00:02:09	00:02:07	00:02:04	00:02:02	00:02:00	00:01:58	00:01:56	00:01:54	00:01:51	00:01:49	00:01:47	00:01:36	00:01:34	00:01:32	00:01:30	00:01:28	00:01:26	00:01:23	00:01:21	00:01:19	00:01:17
Restack	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:29	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47
Hold	00:00:55	00:00:52	00:00:50	00:00:48	00:00:46	00:00:44	00:00:42	00:00:39	00:00:37	00:00:35	00:00:33	00:00:31	00:00:22	00:00:24	00:00:26	00:00:29	00:00:31	00:00:33	00:00:35	00:00:37	00:00:39	00:00:42

Lane/Bin	Bin23	Bin24	Bin25	Bin26	Bin27	Bin28	Bin29	Bin30	Bin31	Bin32	Bin33	Bin34	Bin35	Bin36	Bin37	Bin38	Bin39	Bin40	Bin41	Bin42	Bin43	Bin44	Hold
Lane 1	00:01:26	00:01:28	00:01:30	00:01:32	00:01:34	00:01:36	00:01:38	00:01:41	00:01:43	00:01:45	00:01:47	00:01:49	00:01:51	00:01:54	00:02:41	00:02:43	00:02:00	00:02:02	00:02:04	00:02:07	00:02:09	00:02:11	00:01:02
Lane 2	00:01:21	00:01:23	00:01:26	00:01:28	00:01:30	00:01:32	00:01:34	00:01:36	00:01:38	00:01:41	00:01:43	00:01:45	00:01:47	00:01:49	00:02:36	00:02:39	00:01:56	00:01:58	00:02:00	00:02:02	00:02:04	00:02:07	00:00:57
Lane 3	00:01:19	00:01:21	00:01:23	00:01:26	00:01:28	00:01:30	00:01:32	00:01:34	00:01:36	00:01:38	00:01:41	00:01:43	00:01:45	00:01:47	00:02:34	00:02:36	00:01:54	00:01:56	00:01:58	00:02:00	00:02:02	00:02:04	00:00:55
Lane 4	00:01:15	00:01:17	00:01:19	00:01:21	00:01:23	00:01:26	00:01:28	00:01:30	00:01:32	00:01:34	00:01:36	00:01:38	00:01:41	00:01:43	00:02:30	00:02:32	00:01:49	00:01:51	00:01:54	00:01:56	00:01:58	00:02:00	00:00:51
Lane 5	00:01:13	00:01:15	00:01:17	00:01:19	00:01:21	00:01:23	00:01:26	00:01:28	00:01:30	00:01:32	00:01:34	00:01:36	00:01:38	00:01:41	00:02:28	00:02:30	00:01:47	00:01:49	00:01:51	00:01:54	00:01:56	00:01:58	00:00:49
Lane 6	00:01:08	00:01:10	00:01:13	00:01:15	00:01:17	00:01:19	00:01:21	00:01:23	00:01:26	00:01:28	00:01:30	00:01:32	00:01:34	00:01:36	00:02:23	00:02:26	00:01:43	00:01:45	00:01:47	00:01:49	00:01:51	00:01:54	00:00:44
Lane 7	00:01:06	00:01:08	00:01:10	00:01:13	00:01:15	00:01:17	00:01:19	00:01:21	00:01:23	00:01:26	00:01:28	00:01:30	00:01:32	00:01:34	00:02:21	00:02:23	00:01:41	00:01:43	00:01:45	00:01:47	00:01:49	00:01:51	00:00:42
Lane 8	00:01:02	00:01:04	00:01:06	00:01:08	00:01:10	00:01:13	00:01:15	00:01:17	00:01:19	00:01:21	00:01:23	00:01:26	00:01:28	00:01:30	00:02:17	00:02:19	00:01:36	00:01:38	00:01:41	00:01:43	00:01:45	00:01:47	00:00:38
Lane 9	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:04	00:01:06	00:01:08	00:01:10	00:01:13	00:02:00	00:02:02	00:01:19	00:01:21	00:01:23	00:01:26	00:01:28	00:01:30	00:00:32
Lane 10	00:00:42	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:04	00:01:06	00:01:08	00:01:10	00:01:58	00:02:00	00:01:17	00:01:19	00:01:21	00:01:23	00:01:26	00:01:28	00:00:36
Lane 11	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:04	00:01:06	00:01:53	00:01:55	00:01:13	00:01:15	00:01:17	00:01:19	00:01:21	00:01:23	00:00:38
Lane 12	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:04	00:01:51	00:01:53	00:01:10	00:01:13	00:01:15	00:01:17	00:01:19	00:01:21	00:00:42
Lane 13	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00	00:01:47	00:01:49	00:01:06	00:01:08	00:01:10	00:01:13	00:01:15	00:01:17	00:00:44
Lane 14	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:45	00:01:47	00:01:04	00:01:06	00:01:08	00:01:10	00:01:13	00:01:15	00:00:49
Lane 15	00:00:32	00:00:29	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:01:40	00:01:42	00:01:00	00:01:02	00:01:04	00:01:06	00:01:08	00:01:10	00:00:51
Lane 16	00:00:36	00:00:34	00:00:32	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:00:51	00:01:38	00:01:40	00:00:57	00:01:00	00:01:02	00:01:04	00:01:06	00:01:08	00:00:55
Lane 17	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:01:34	00:01:36	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:04	00:00:57
Lane 18	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:01:32	00:01:34	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:02
Lane 19	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:01:27	00:01:29	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:04
Lane 20	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:01:25	00:01:27	00:00:44	00:00:47	00:00:49	00:00:51	00:00:53	00:00:55	00:01:08
Lane 21	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:29	00:00:32	00:00:34	00:01:21	00:01:23	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:00:51	00:01:10
Lane 22	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:32	00:01:19	00:01:21	00:00:38	00:00:40	00:00:42	00:00:44	00:00:47	00:00:49	00:01:15
Lane 23	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:01:14	00:01:17	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:00:44	00:01:17
Lane 24	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:00:34	00:01:17	00:01:14	00:00:32	00:00:34	00:00:36	00:00:38	00:00:40	00:00:42	00:01:21
Lane 25	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:00:38	00:00:36	00:01:19	00:01:17	00:00:29	00:00:29	00:00:32	00:00:34	00:00:36	00:00:38	00:01:23
Lane 26	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:00:42	00:00:40	00:01:23	00:01:21	00:00:34	00:00:32	00:00:29	00:00:29	00:00:32	00:00:34	00:01:28
Lane 27	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:00:44	00:01:27	00:01:25	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:00:32	00:01:32
Lane 28	00:01:15	00:01:13	00:01:10	00:01:08	00:01:06	00:01:04	00:01:02	00:01:00	00:00:57	00:00:55	00:00:53	00:00:51	00:00:49	00:00:47	00:01:29	00:01:27	00:00:40	00:00:38	00:00:36	00:00:34	00:00:32	00:00:29	00:01:34
Restack	00:00:49	00:00:51	00:00:53	00:00:55	00:00:57	00:01:00	00:01:02	00:01:04	00:01:06	00:01:08	00:01:10	00:01:13	00:01:15	00:01:17	00:02:04	00:02:06	00:01:23	00:01:26	00:01:28	00:01:30	00:01:32	00:01:34	00:00:29
Hold	00:00:44	00:00:46	00:00:48	00:00:50	00:00:52	00:00:55	00:00:57	00:00:59	00:01:01	00:01:03	00:01:05	00:01:08	00:01:10	00:01:12	00:01:59	00:02:01	00:01:18	00:01:20	00:01:23	00:01:25	00:01:27	00:01:29	00:00:00

Table H.6: Restack Time from Lane x to Bin y

Appendix I - Simulation Warehouse Design

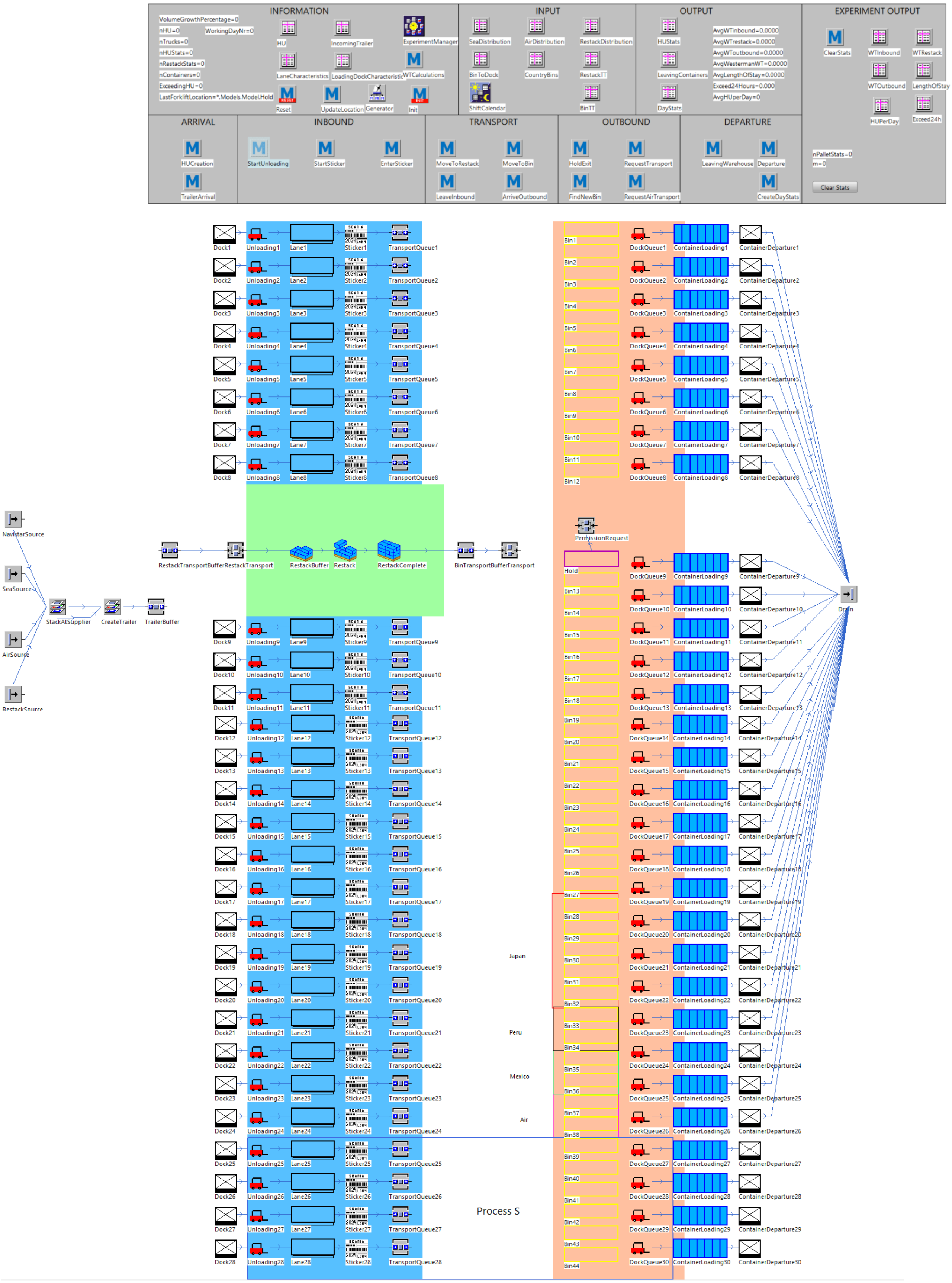

Figure I.1: Simulation Model of LBX

Appendix J – Logic Flow Charts of Methods

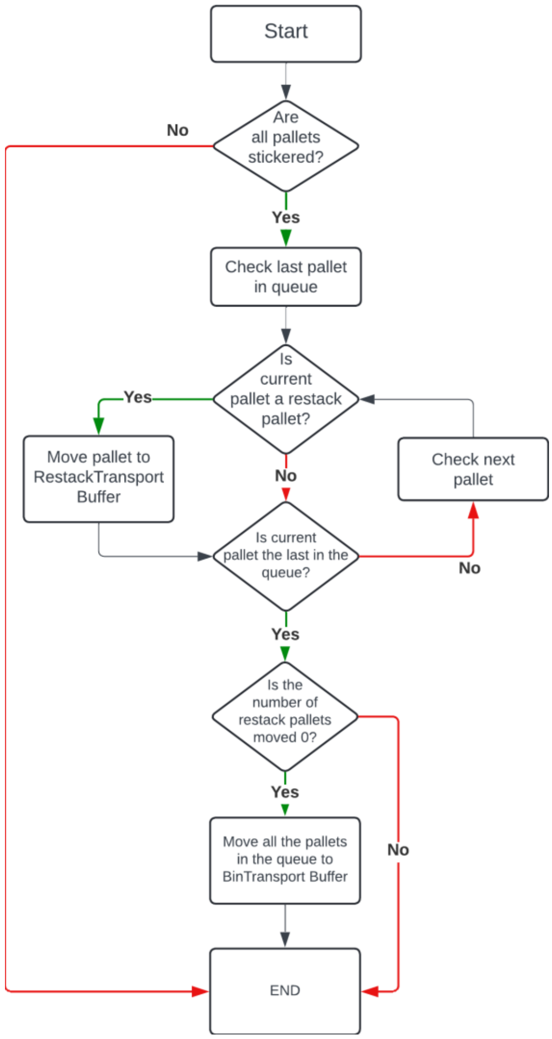

Figure J.1: Flowchart of MoveToRestack method

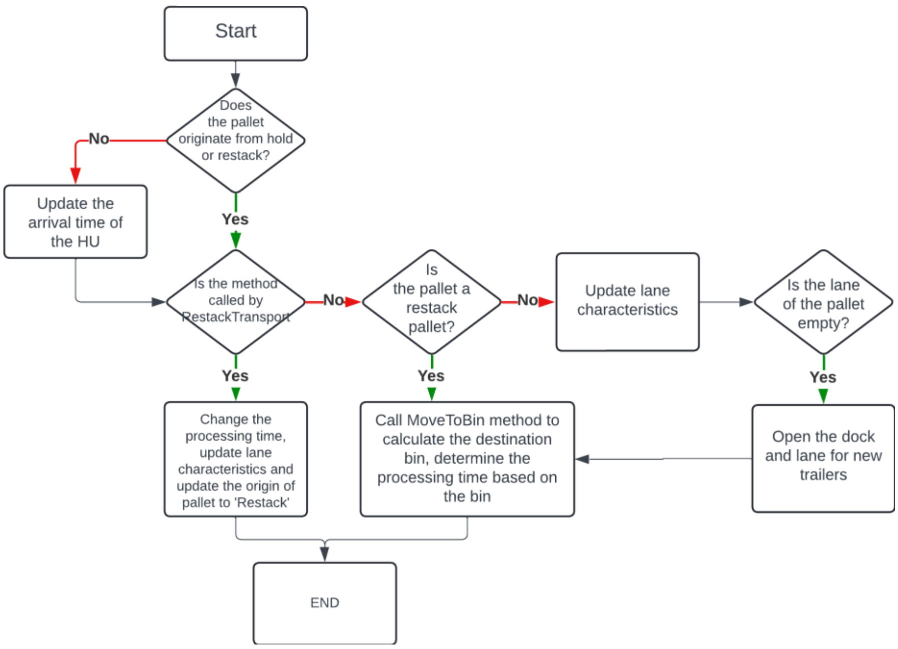

Figure J.2: Flowchart of LeaveInbound method

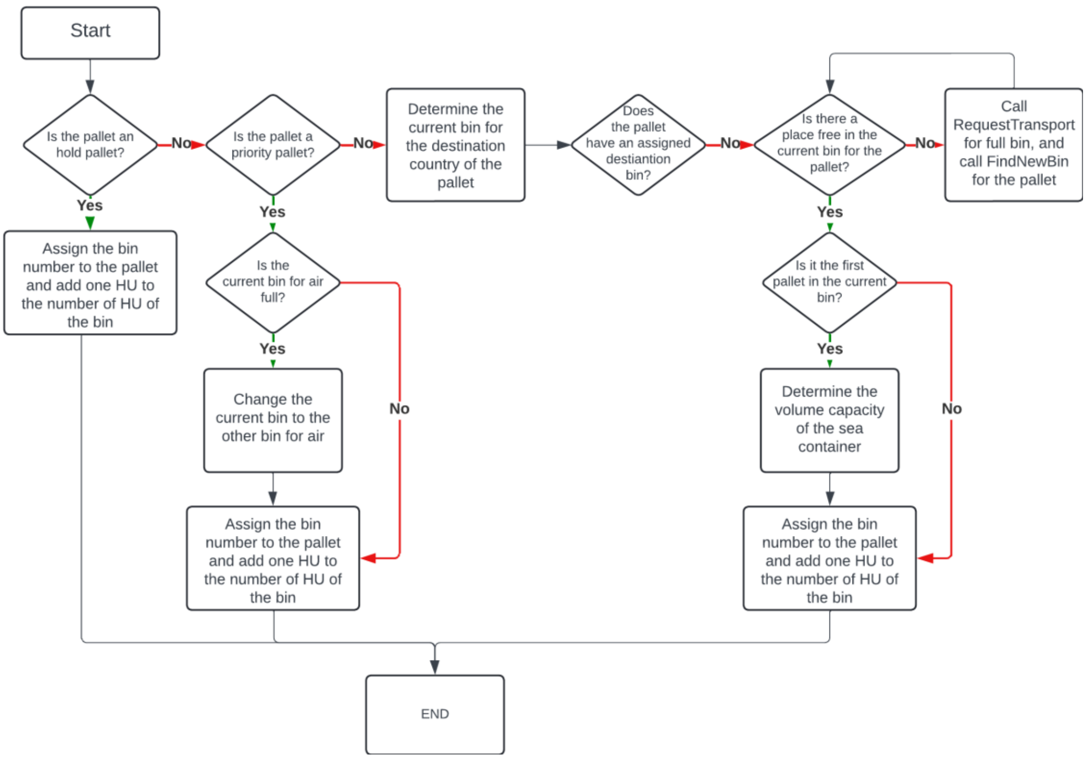

Figure J.3: Flowchart of MoveToBin method

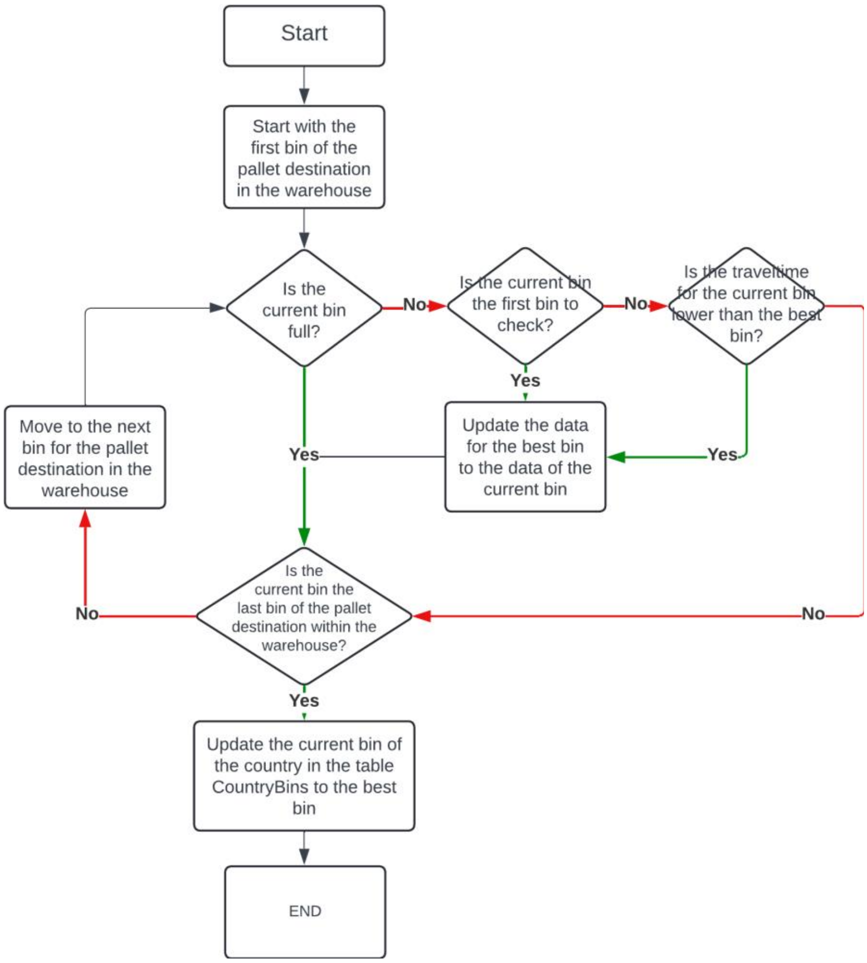

Figure J.4: Flowchart of FindNewBin method

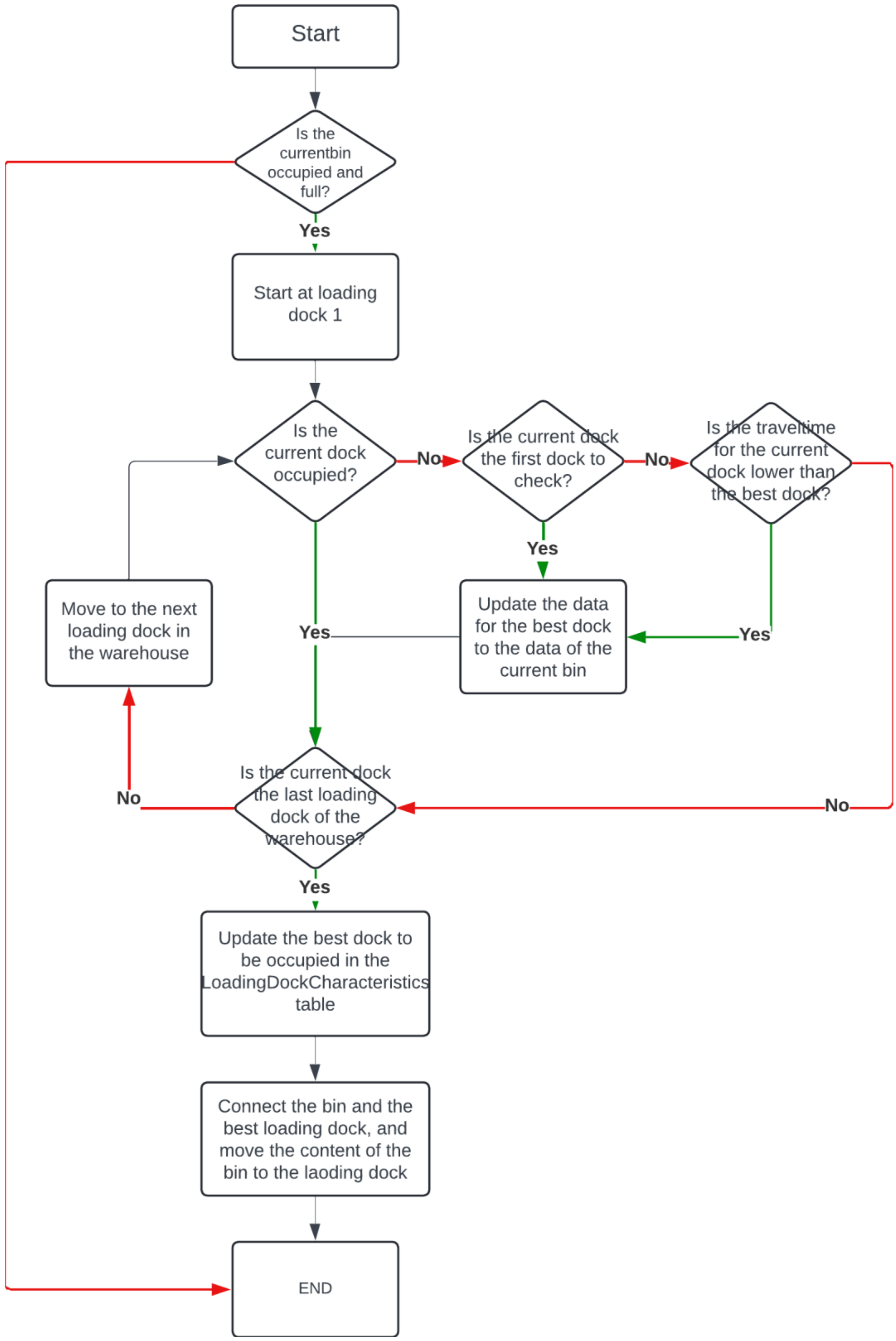

Figure J.5: Flowchart of Request(air)Transport method

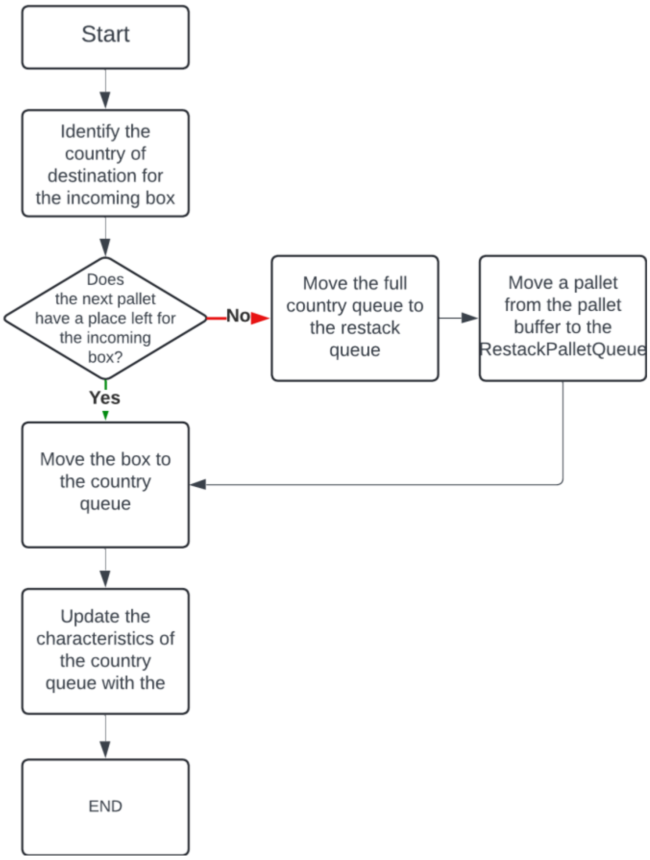

Figure J.6: Flowchart of CountrySorter method

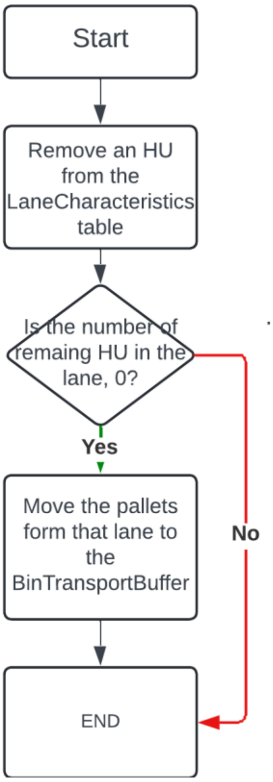

Figure J.7: Flowchart of CargoRelease method

Appendix K - Experimental Design

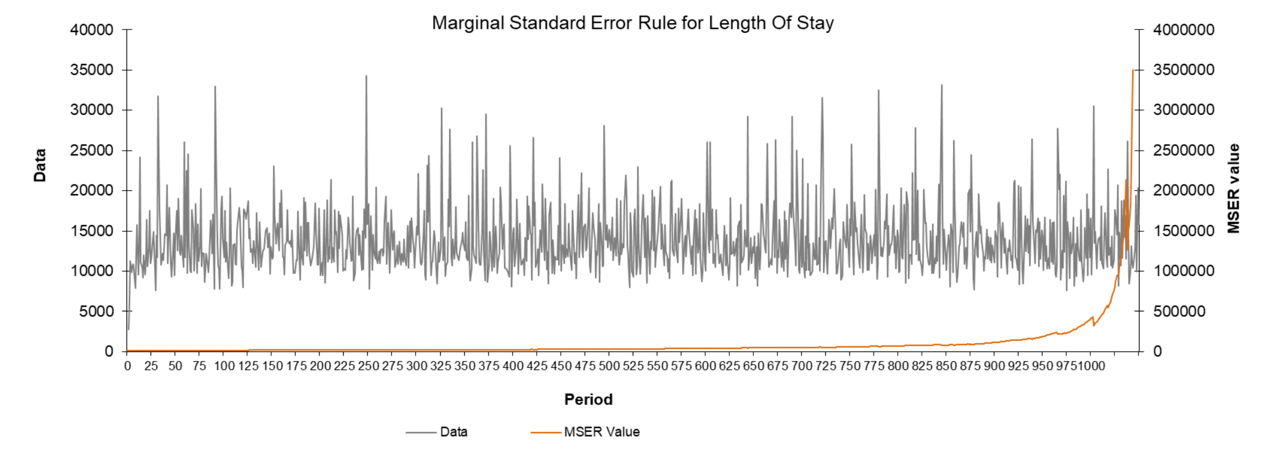

Figure K.1: MSER Graph for Warm-Up Period

NUMBER OF REPLICATIONS	WAITING TIME AT INBOUND	MEAN WAITING TIME	ERROR	TEST
1	7638,9	7638,9		
2	7854,4	7746,6	0,1250	Not Enough
3	7955,3	7797,1	0,0504	Not Enough
4	7862,7	7750,8	0,0230	Enough
5	7797,9	7718,4	0,0128	Enough
6	7502,5	7570,7	0,0095	Enough
7	7592,7	7615,8	0,0028	Enough
8	7810,7	7724,8	0,0093	Enough
9	7812,4	7725,7	0,0086	Enough
10	7545,4	7592,1	0,0044	Enough
11	7582,0	7610,4	0,0025	Enough
12	8016,0	7827,4	0,0153	Enough
13	7901,7	7770,3	0,0102	Enough
14	7724,0	7681,4	0,0032	Enough
15	7765,8	7702,3	0,0046	Enough
16	7626,9	7632,9	0,0004	Enough
17	7950,1	7794,5	0,0103	Enough
18	7564,4	7601,7	0,0024	Enough
19	7569,8	7604,4	0,0022	Enough
20	7709,8	7674,4	0,0022	Enough
21	7820,1	7729,5	0,0053	Enough
22	7644,6	7641,8	0,0002	Enough
23	7630,5	7634,7	0,0002	Enough
24	7663,0	7650,9	0,0007	Enough
25	8054,8	7846,8	0,0109	Enough
26	7516,3	7577,6	0,0033	Enough
27	7819,1	7729,0	0,0046	Enough
28	7978,6	7808,7	0,0084	Enough
29	7719,5	7679,2	0,0020	Enough
30	7741,4	7690,1	0,0025	Enough

Table K.1: Number of Replications Calculation

Appendix L - Paired T-Test for Validation

SIMULATION DATA (AVERAGE WAITING TIME IN DAYS)	REAL DATA (AVERAGE WAITING TIME IN DAYS)	DIFFERENCE (AVERAGE WAITING TIME IN DAYS)
0,082	0,063	-0,019
0,085	0,022	-0,063
0,083	0,024	-0,059
0,085	0,077	-0,008
0,084	0,112	0,028
0,082	0,051	-0,031
0,088	0,084	-0,004
0,087	0,114	0,027
0,087	0,131	0,044
0,096	0,072	-0,023
0,092	0,085	-0,007
0,091	0,079	-0,012
0,100	0,118	0,018
0,099	0,062	-0,037
0,084	0,092	0,008
0,091	0,055	-0,036
0,087	0,057	-0,030
0,083	0,073	-0,010
0,083	0,128	0,045
0,089	0,074	-0,015
0,089	0,007	-0,083
0,083	0,065	-0,018
0,094	0,102	0,008
0,089	0,118	0,029
0,093	0,084	-0,009
0,097	0,095	-0,002
0,090	0,105	0,015
0,086	0,138	0,052
0,087	0,138	0,051
0,088	0,162	0,074
0,093	0,049	-0,043
0,097	0,098	0,001
0,094	0,142	0,048
0,091	0,047	-0,043
0,084	0,087	0,003
0,082	0,101	0,019
0,092	0,113	0,021
0,092	0,101	0,009
0,089	0,106	0,016
0,082	0,106	0,024
0,083	0,059	-0,024
0,083	0,073	-0,010
0,082	0,057	-0,026
0,087	0,023	-0,064
0,094	0,100	0,006
0,094	0,120	0,026
0,097	0,047	-0,050
0,091	0,087	-0,003
0,089	0,140	0,051
0,096	0,096	-0,001

0,084	0,089	0,005
0,088	0,120	0,032
0,084	0,086	0,002
0,085	0,100	0,016
0,082	0,118	0,036
0,084	0,127	0,043
0,084	0,037	-0,047
0,085	0,125	0,040
0,084	0,112	0,028
0,085	0,097	0,012
0,091	0,099	0,009
0,090	0,082	-0,007
0,087	0,084	-0,003
0,090	0,063	-0,027
0,086	0,072	-0,015
0,089	0,108	0,018
0,092	0,103	0,011
0,092	0,107	0,015
0,088	0,126	0,038
0,084	0,135	0,050
0,090	0,133	0,043
0,084	0,118	0,033
0,085	0,080	-0,005
0,086	0,084	-0,002
0,085	0,088	0,003
0,087	0,084	-0,004
0,088	0,049	-0,040
0,090	0,013	-0,078
0,084	0,093	0,009
0,086	0,109	0,023
0,091	0,106	0,015
0,086	0,117	0,031
0,086	0,081	-0,005
0,086	0,079	-0,007
0,097	0,110	0,013
0,098	0,056	-0,041
0,082	0,090	0,008
0,086	0,125	0,039
0,090	0,131	0,041
0,095	0,083	-0,012
0,091	0,103	0,013
0,097	0,096	-0,001
0,091	0,095	0,004

Table L.1: Data Points for Paired T-test

DIFFERENCE SIMULATION AND REALITY	
MEAN	0,00245
VAR	0,00098
SE	0,00324
T-VALUE	0,755
P-VALUE	0,452

Table L.2: Parameters for Paired T-test

Appendix M - Experiment Results

VOLUME INCREASE	REMOVE STICKER	REMOVE CARGO RELEASE	ASSIGN DOCK ALLOCATION MODEL	AvgWT Inbound	AvgWT Restack	AvgWT Outbound	AvgWT Company Z	Avg Lengthofstay	Exceed24hours	Avg HUperDay
0%	FALSE	FALSE	FALSE	01:42:43	00:28:49	03:08:19	02:12:54	03:14:30	0,43%	4072,5
0%	TRUE	FALSE	FALSE	00:39:49	00:28:11	03:11:42	02:14:50	03:02:31	0,45%	4083
0%	TRUE	TRUE	FALSE	00:27:03	00:28:38	03:13:40	02:13:21	02:49:04	0,40%	4082
0%	TRUE	TRUE	TRUE	00:23:51	00:28:24	03:15:49	02:15:28	02:46:20	0,44%	4074
0%	FALSE	TRUE	TRUE	01:27:10	00:28:59	03:12:23	02:12:25	03:00:45	0,40%	4078
0%	FALSE	FALSE	TRUE	01:38:25	00:28:23	03:08:15	02:11:08	03:09:15	0,45%	4079,5
0%	FALSE	TRUE	FALSE	01:29:41	00:28:38	03:13:18	02:13:24	03:05:16	0,42%	4077
0%	TRUE	FALSE	TRUE	00:36:26	00:28:08	03:07:58	02:10:59	02:53:35	0,43%	4089
15.3%	FALSE	FALSE	FALSE	01:47:21	00:32:44	03:19:43	02:14:09	03:32:58	0,41%	4671,5
15.3%	TRUE	FALSE	FALSE	00:43:02	00:32:28	03:18:36	02:13:27	03:16:31	0,38%	4692,5
15.3%	TRUE	TRUE	FALSE	00:30:01	00:32:44	03:21:01	02:14:34	03:03:56	0,34%	4702
15.3%	TRUE	TRUE	TRUE	00:24:55	00:32:41	03:19:13	02:11:02	02:53:48	0,36%	4696
15.3%	FALSE	TRUE	TRUE	01:25:01	00:33:07	03:16:51	02:09:09	03:06:33	0,38%	4686
15.3%	FALSE	FALSE	TRUE	01:39:57	00:32:46	03:17:42	02:11:39	03:22:53	0,39%	4683,5
15.3%	FALSE	TRUE	FALSE	01:33:07	00:32:58	03:23:02	02:15:41	03:19:35	0,38%	4676
15.3%	TRUE	FALSE	TRUE	00:38:01	00:32:26	03:15:43	02:10:08	03:05:59	0,36%	4695,5
30%	FALSE	FALSE	FALSE	01:50:34	00:31:09	03:11:03	02:12:54	03:29:02	0,34%	5279
30%	TRUE	FALSE	FALSE	00:45:28	00:30:55	03:11:56	02:14:34	03:12:00	0,34%	5299
30%	TRUE	TRUE	FALSE	00:31:54	00:31:08	03:11:31	02:12:43	02:58:15	0,29%	5285
30%	TRUE	TRUE	TRUE	00:25:20	00:31:09	03:11:44	02:12:06	02:47:17	0,32%	5292
30%	FALSE	TRUE	TRUE	01:27:40	00:31:19	03:11:16	02:10:42	03:03:30	0,34%	5290
30%	FALSE	FALSE	TRUE	01:42:34	00:30:57	03:10:03	02:11:03	03:17:06	0,35%	5287
30%	FALSE	TRUE	FALSE	01:37:32	00:31:21	03:13:55	02:12:58	03:18:35	0,35%	5285
30%	TRUE	FALSE	TRUE	00:38:55	00:30:52	03:09:32	02:10:33	02:59:53	0,33%	5286,5

Table M.1: Experiment Output of Improvement Combinations

Appendix N – Changed Flowchart of LBX

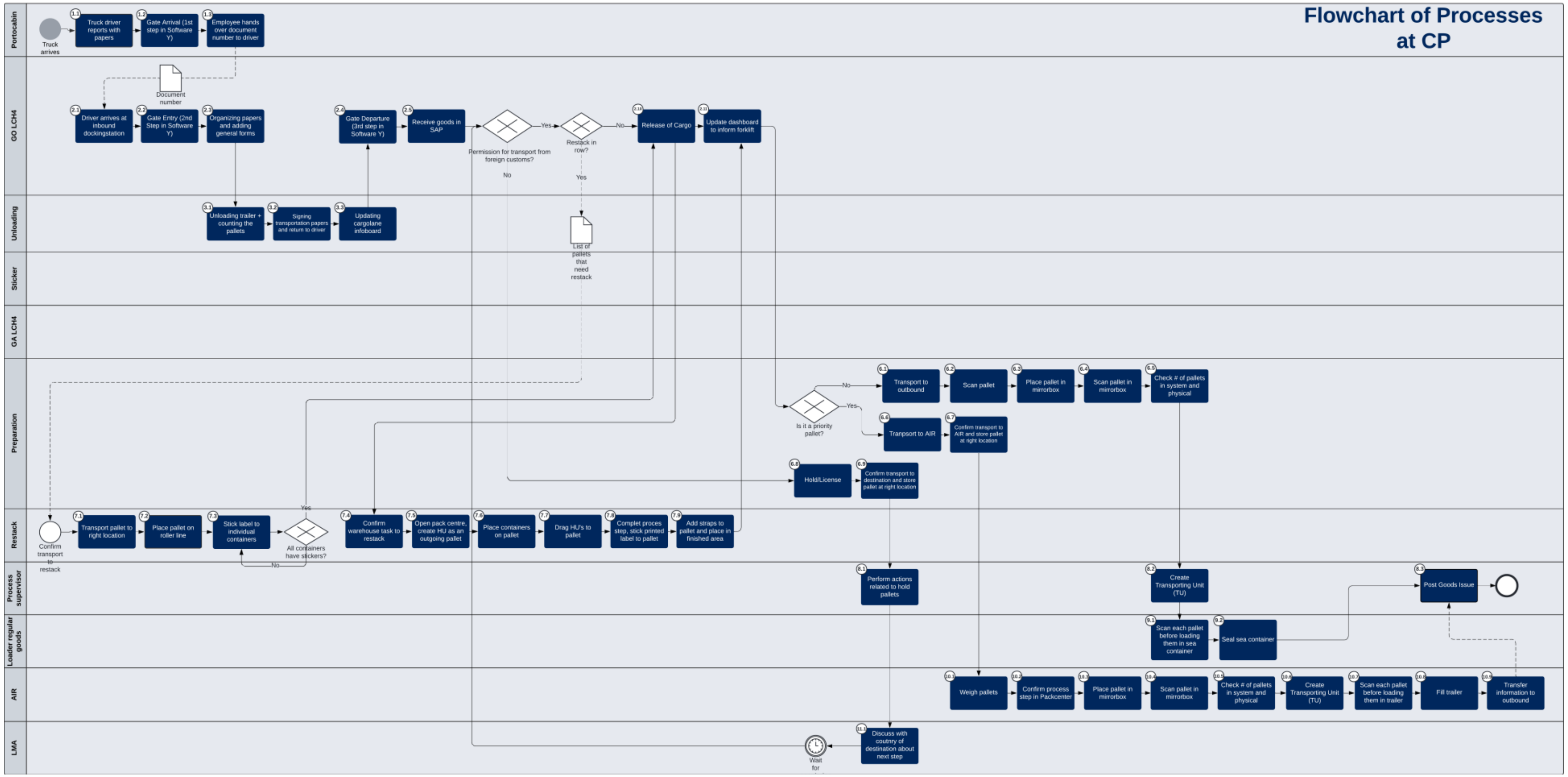

Figure N.1: Changed Flowchart - Removal of Stickering Process

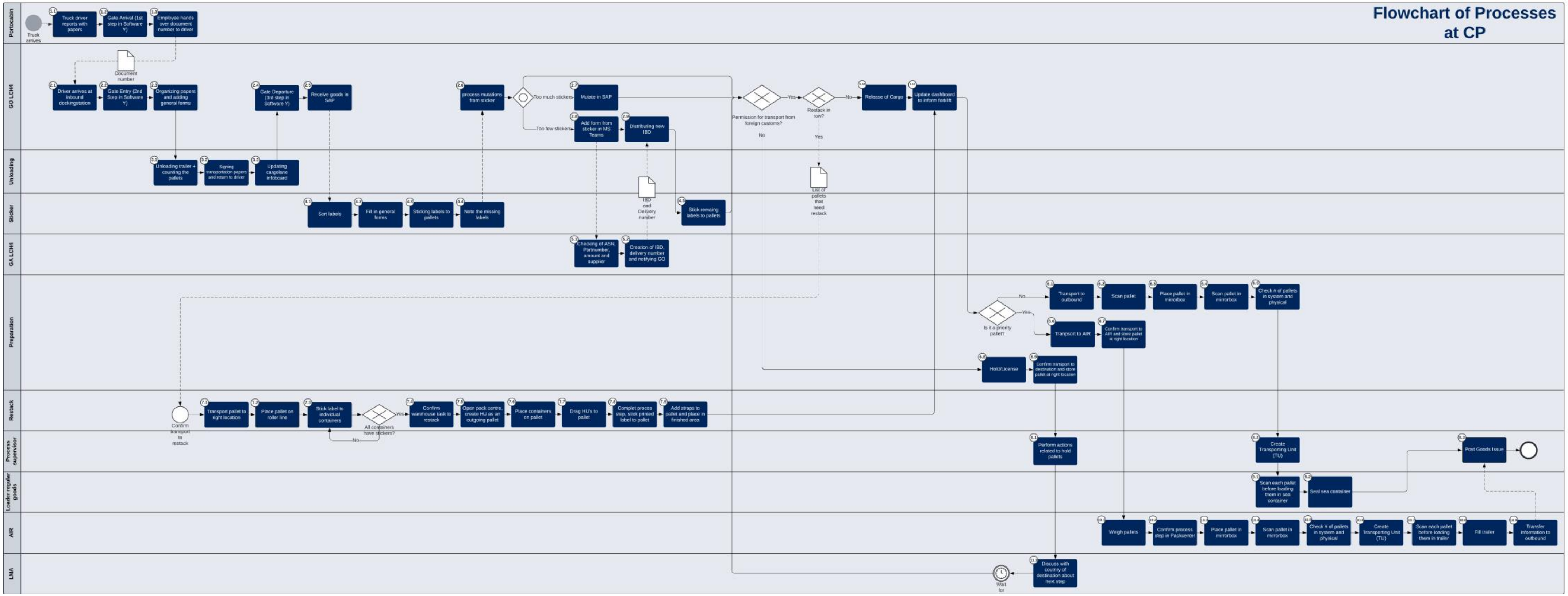

Figure N.2: Changed Flowchart - Removal of Cargo Release

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