REDUCING THROUGHPUT TIME FOR THE FRAME PRODUCTION LINE AT NIJHUIS TOELEVERING B.V.

A SIMULATION STUDY ON THE LAYOUT AND ORGANISATIONAL DECISIONS

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PREFACE

Dear reader,
You are about to read my bachelor's thesis “Reducing throughput time for the frame production line at Nijhuis Toelevering B.V.: A simulation study on the layout and organisational decisions”, which is the final assignment of my bachelor's degree.

First, I would like to thank my supervisor at Nijhuis Toelevering B.V., Mark Spaans, for allowing me to work on an interesting and challenging graduation assignment in a very complex production environment. During my time at Nijhuis Toelevering, I experienced a lot of interactions with the colleagues who helped me in every possible way and provided me with helpful details on the complex production environment. Therefore, I would also like to thank the organisation in its entirety for making me feel welcome and being able to answer all my questions quickly.

I would also like to express my gratitude toward my supervisor at the University of Twente, Martijn Koot. Especially for always being available with quick responses to my questions and being available for discussion meetings, so I could tackle all the problems that occurred. I would also like to thank my second supervisor, Martijn Mes, for his help, feedback and insights in the final stages of this research. His neutral and fresh perspective on my research gave me useful hints toward finalizing my thesis.

Finally, I want to thank my family and friends for their support during the research and the writing of this bachelor thesis. Especially, by distracting me from the thesis sometimes and providing other perspectives to encountered problems.

I hope you enjoy reading this bachelor’s thesis.

Jesse hoge Bavel

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Management Summary

This research is about the wooden frame carpentry factory of Nijhuis Toelevering B.V., where wooden frames with windows and doors are produced for the construction of houses or shelters. In the past year, the company has been going through a transition within the frame production line towards more automation and creating opportunities to grow its production capacity. Therefore, the management of Nijhuis Toelevering B.V. was also looking for answers on how to organize their production line towards their situation after the transition with new machinery towards more automation to make sure not only their production capacity will increase, but also how their current throughput time of on average 5,6 working days could be reduced towards 3 working days given the opportunities created by the transition. Therefore, we formulated the following main research question:

"What will be the layout and organisation of the frame production line at Nijhuis Toelevering B.V. to reduce the throughput time to 3 working days for all batch types?"

For this research, we used a simulation study according to the methodology initiated by Robinson (2004). Therefore, we started this research by analysing the current production line. This analysis was done as exploratory research to get more knowledge about the way of working at Nijhuis Toelevering without already judging its performance. This made clear that the production line consists of sequential production processes which can be defined in 4 different departments: machinery, pre-assembly, painting, and finishing assembly. On this production line are three different kinds of production batches of frames produced. These three production batches can classified as: construction projects, online orders, and shelters. These different types of batches have each a different throughput time which differs significantly for online orders as follows from the 4 working days compared to the 5 to 6 working days for the others.

Once the current production line processes were clear, we performed a systematic literature research on theories that could help in identifying the wastes and bottlenecks at the production line of Nijhuis Toelevering, so we could reduce the throughput time. From this literature research, we decided to use the lean framework, with tools such as a Value Stream Map, and Theory of Constraints to guide us in this process of reducing the throughput time.

The next step was to apply these theories in the context of the production line at Nijhuis Toelevering. This was done by analysing the current performance using a Value Stream Map that displays the cycle times, time available, uptime, and an analysis on the percentage of value-adding time within the cycle time. The information for this analysis is collected with observations on the production and interviewing the supervisors/managers. All this information is also used for identifying bottlenecks and wastes. The bottlenecks are identified using the Theory of Constraints by looking for the system's constraints. After that, we started to analyse the information looking for the three different types of wastes defined by the lean framework: *muda (non-value-adding activities), mura (lack of consistency), and muri (unreasonable requirements).*

From this analysis, we found that there are a lot of non-value-adding activities on the production line such as waiting times and repair work. Furthermore, the were also bottlenecks found at the production capacity of the pre-assembly department and the batch sizes that caused higher waiting times within the production line.

After identifying the existing bottlenecks, wastes, and other problems at the production line, we used the methodology of Robinson to perform the actual simulation study. This started with defining a conceptual model, followed by data analysis on the included production processes. After that, we were able to construct a simulation model of the current situation using Siemens Tecnomatix Plant Simulation, so we could experiment with several potential

solutions within the simulation model on how to tackle the bottlenecks and wastes that are present in the production line.

Following the results of the simulation research study on the production line of Nijhuis Toelevering B.V., we want to make the following recommendations to be able to reduce the throughput time for all batch types to the desired norm of 3 working days.

- First of all, in a short-term time period it is important to make three interventions within the production line. The first intervention that has to be made is the reduction of the project batch size by reducing the average batch size for project batches to 20 frames per batch.
- Secondly, a second pre-assembly line should be added to the pre-assembly line department. This means there will be the first pre-assembly line with a takt time of 4 minutes and 48 seconds and a second pre-assembly line with a takt time of 6 minutes.
- Thirdly, the working hours of the manual painting station should be extended from 7.00 – 16.00 hours to 5.00 – 22.00 hours, so that all the products will be manually top-coated.
- Last of all, finishing assembly line 4 should be extended, so it can have a similar takt time as finishing assembly line 1 or 2 and finishing assembly line will be able to process shelter batches and project batches.

Our simulation study showed that when these recommendations are successfully implemented the norm of three working days for all batch types can be achieved in the long term. This while the recommendation on finishing assembly line 4 is only possible in a longer time period, rather than the three first recommendations. This means that in a short-term period with implementing a smaller project batch size, a second pre-assembly line, and extending the working hours of the manual painting station. Nijhuis Toelevering will be able to reduce the average throughput time for project batches from 5 days and 3 hours to 3 days and 9 hours, for online batches from 3 days and 13 hours to 3 days and 4 hours, and for shelter batches from 5 days to 3 days and 19 hours.

Furthermore, when looking at the long term when the uptime of the new machinery will be higher after more training of the employees and the implementation of an expanded finishing assembly line 4. The average throughput time per batch for project batches can be reduced to 2 days and 15 hours, for online batches to 2 days and 15 hours, and for shelter batches to 3 days and 2 hours. This means that the desired norm by Nijhuis Toelevering B.V. of 3 working days for all batch types has been achieved.

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1. Research Introduction

In this chapter, we give a brief introduction to the company. Furthermore, we will also discuss the problem definition, methodological approach, research design, theoretical framework, research scope, and deliverables.

1.1. Company Introduction

Nijhuis Toelevering B.V., located in Rijssen, is one of the largest carpentry factories in the Netherlands. They produce wooden window- and doorframes, timber frame construction facade elements, and prefab parts in their carpentry factory. They believe in cross-project collaboration with their colleagues, customers, partners, and suppliers because together they want to arrive at optimal solutions: products of the highest quality, for the lowest price (Nijhuis Toelevering B.V., 2024). Nijhuis Toelevering B.V. has currently almost 100 employees of which most are working at the production lines in the factory. Nijhuis Bouw was founded in the year of 1906 with a small shed at the Molendijk in Rijssen. Following the main company, in 1973 the sister company Nijhuis Toelevering B.V. was founded and located at the business park “De Mors” in Rijssen. This is still the location of the carpentry factory of Nijhuis Toelevering B.V. At his production factory, Nijhuis Toelevering is currently in an ongoing transition of the production line towards more automation and innovation. This transition also provides opportunities to reduce the throughput time of the production line, but also dilemmas and uncertainties in the organisation and layout of the production line after this transition.

1.2. Problem Context

The wooden window- and doorframe production line at Nijhuis Toelevering B.V. consists of the following steps and working stations. The production process starts with the machinery department where the wooden beams are processed to a frame element. After that, the frame elements are put together into a frame at the pre-assembly department. When the frames are pre-assembled, they go through the painting department to be painted. After that, the frames first have to dry before going to the finishing assembly department where all the last adjustments and attachments are made to the frames, such as hinges, glass, doors and windows.

At the production facility of Nijhuis Toelevering B.V., there is currently a transition happening in the production line of the wooden window- and doorframes. Prior to this transition, internal research was performed in 2022 on the performance of the old production line and the production facility was expanded with 800 m^2 in 2023 which made the total production facility surface 8800 m^2. To make sure the production of the wooden window- and doorframes is not interrupted during the transition process, it will go only step-by-step to make sure there will always be a running production line. The transition was necessary for a couple of reasons: the current machines were outdated, the current process required a lot of heavy physical work for the employees and they wanted to increase their production capacity. By increasing the production capacity, Nijhuis Toelevering is making efforts to improve its throughput time (Nijhuis Toelevering B.V., 2024). The transition consists of 9 steps toward the end goal of using a new production line with more automation and higher production capacity. These are the steps of the transition:

1. Transfer of the office units on the right side of the factory to the front side and the removal of some of the toilets inside the production facility near the entrance.
2. Expansion construction for the new “kortlijn” with a total of 800 m^2 and also extra electricity power. Also, the capacity of the central extraction system has to be increased.
3. The installation of the new “kortlijn” machine.

4. Use the new “kortlijn” machine instead of the old machine for the production line, but still use the two Conturex machines.
5. Remove the old “kortlijn” machine and build/install the two new Computer Numerical Control (CNC) machines.
6. Partly use the new CNC machine production line, but still keep operating on the old production line through the Conturex machines. In this step, it is mainly about testing the new CNC machines.
7. Remove Conturex machine number 1.
8. Placement of an extra pre-assembly line where the old toilets were located.
9. Use the CNC machines as the main production line with also two pre-assembly lines. (Spaans, 2024)

The transition, which at this moment is in step 6, has to make sure that the current production revenue of the factory, which is 27 million euros, will increase with 29,6 % to 35 million euros. However, this will not be the only positive change in the transition. With the transition, the employees are not required to do a lot of heavy work anymore, such as carrying the wooden frame elements on and off the machines. Furthermore, making the transition to more automation gives the opportunities for more production capacity and control in the production in terms of priority scheduling.
Nevertheless, the transition also creates a lot of uncertainties between the theoretical expected performance of the new production line and the actual transition/performance of the new production line. Therefore, we will look into how the new production line can be organised when fully operational to provide a fluent production flow and reduce the total throughput time of the production line. This, while by reducing the throughput time of the production the company will be able to produce more frames within a year to achieve the desired revenue. In this process, Nijhuis Toelevering is looking for an improved throughput time for the new production line. The company desires the new throughput time to be 3 working days for all product types, which means that Nijhuis Toelevering wants to be able to have a frame ready for transport at the end of the production line within 3 workings days from the moment the production process starts with the wooden beams.

1.3. Problem Identification

The problem identification phase consists of identifying the action problem, which is defined by Heerkens & van Winden as the discrepancy between norm and reality as perceived by the problem owner (Heerkens & van Winden, 2017), and researching what all the related problems/causes are to make a problem cluster. The result of this problem cluster will be a causal relationship diagram which results in core problems that can be researched for solutions. The action problem, which serves as the research goal, is defined as the following from the problem context:

“The wooden window- and doorframe production facility of Nijhuis Toelevering B.V. wants to reduce their current throughput time to 3 working days for all product types.”

Given the action problem, we conducted interviews with stakeholders, observed the production, and read available intern research results from the transition process, that provided us with several causes to the action problem. As can be seen in the problem cluster (*Appendix B.1*), the old production line had to deal with a lot of problems. This led to a situation of two different throughput times for two product types, online orders from Toelevering Online and construction orders, where online orders are produced within 4 working days and construction orders within 6 working days. The found problems can be divided into three main concepts that had an impact on the main action problem: technical, people, and managerial-related problems. The problem list with the categorisation and origin of where these problems have been found in the company can be found in *Appendix B.2*.

1.3.1. Core Problem

In this section, we will discuss the potential core problems and choose the core problem for this research thesis. The problem cluster shows the relationship between the problems and the action problem. From the problem cluster, which can be found in *Appendix B.1*, the following problems are identified as core problems:

1. Usage of manually moving carts
2. Multiple different machine suppliers that are difficult to align
3. Outdated machines
4. Ineffective communication with suppliers and between working stations
5. Important parameters for the improvements of the bottlenecks in the production line are not certain
6. Uncertainty on the know-how perspective used to approach an optimum design of the production line.

Out of those six potential core problems only one core problem has to be chosen for the research. When analysing the possible core problems there are a few guidelines for selecting a core problem: it has to be possible to influence the problem, leave out what you do not know and the most relevant problem of the remaining candidates needs to be chosen (Heerkens & van Winden, 2017). Nijhuis Toelevering already researched the old production line, which resulted in a transition to a new production line with new machinery and more automation in 2023. Therefore, the first three problems cannot be selected as core problems. At this moment, Nijhuis Toelevering already replaced the old 'kortlijn' machine and is currently building two new CNC machines to replace the old Conturex machines. These new machines are from the same supplier Bos Machines Holland (BMH) and are more automated which means that Nijhuis Toelevering is already implementing solutions for the problems 'Usage of manually moving carts', 'Multiple different machine suppliers which are difficult to align' and 'Outdated machines'.

The third potential core problem 'Ineffective communication' is mainly related to the supply chain management department of Nijhuis Toelevering. These problems often occur in the ordering processes and therefore fall outside the scope of this research which is primarily focused on the layout and organisation of the production line itself, because Nijhuis Toelevering is already conducting internal research on the implementation of an Enterprise Resource Planning (ERP) system on supply chain management level. Furthermore, this problem is rather occasional than substantial. This means it is a less bigger problem with the high throughput time.

The last two potential core problems are 'important parameters for the improvements on the bottlenecks in the production line are not certain' and 'Uncertainty on the know-how perspective used to approach an optimum design of the production line'. Since both potential core problems can be chosen, the most relevant and important one will be chosen as the core problem. In close consideration with multiple managers of Nijhuis Toelevering 'Uncertainty on the know-how perspective used to approach an optimum design of the production line' will be chosen as the core problem. This problem is chosen as the core problem due to two reasons. First of all, according to the management of Nijhuis Toelevering B.V. focusing on the entire organisation and layout of the production line will have the most impact on working towards a lower throughput time. Secondly, the problem of the important parameters will be partly taken into consideration for this research project, because it will be useful for the organisation of the production line. In the problem cluster in *Appendix B.1*, the core problem is marked orange.

1.3.2. Norm and Reality

As discussed in Section 1.2. and Section 1.3., the wooden frame production line wants to reduce its throughput time with the ongoing transition. With the transition and results of this research project, Nijhuis Toelevering B.V. wants to achieve a throughput time of 3 working days for all product types. Therefore, the norm of this research project will be 3 working days for all product types. The problem statement, that was presented by the company, already had a measurable variable for the norm and reality. The action problem is about improving the throughput time and therefore the variable that will be used will also be throughput time in working days. Currently at the production facility of Nijhuis Toelevering the wooden window- and doorframes are produced with two different throughput times: 80% of the frames, which are mainly bigger projects from construction sites, are produced with a throughput time of 6 working days and 20% of the frames, that are mainly from the online website of Toelevering Online, are produced with a throughput time of 4 working days. The throughput time includes the mandatory 24 hours of drying time after the frames are painted. The norm that Nijhuis Toelevering wants to achieve is that 100 % of the frames produced will have a throughput time of 3 working days. Therefore, the action problem will focus on a reduction of 46,4 % of the current throughput time.

This reduction percentage is calculated with the following formula:

$$reduction\ througput\ time = \frac{3-(0{,}8*6+0{,}2*4)}{(0{,}8*6+0{,}2*4)} = -46{,}42 = 46{,}4\ \%$$

1.4. Research Design

This thesis will aim to find a solution to the given action problem from the problem identification in Section 1.3. To be able to come up with a solution to this problem, the following main research question will be answered during this research:

“What will be the layout and organisation of the frame production line at Nijhuis Toelevering B.V. to reduce the throughput time by to 3 working days for all batch types?”

For the layout, we will be looking at the layout of the machines and production stations and for the organisation, we will be looking at the organisational decisions and configurations, such as batch size, priorities, and production decisions. To answer the main research question there are several sub-research questions and a methodology needed. Furthermore, for this research question, we will use a simulation model in Siemens Tecnomatix Plant Simulation 16.1 to be able to solve the given main research question. The choice for a simulation model study is made for three key reasons. First of all, the transition of the production line is not finished yet, and the research will already focus on the production line after this transition. Therefore, in a simulation model, this new production line can be modelled to experiment with. Secondly, the research project will focus on both the layout and organisation decisions of the new production line. This makes researching solutions, implementing solutions, and

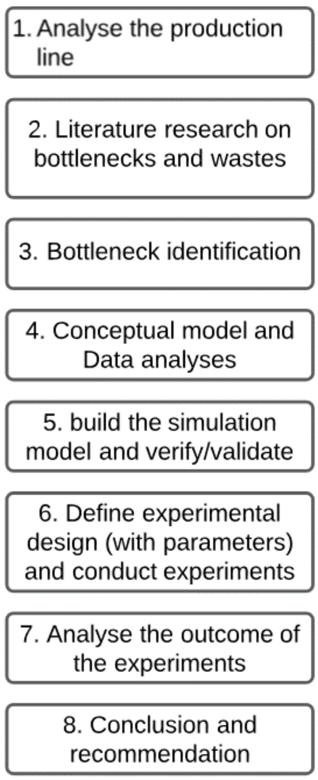

Figure 1 - research methodology

evaluating these implementations too expensive. Last of all, a simulation model will provide opportunities to experiment on multiple different factors at once in a short time period.
This results in a more accurate reduction of throughput time, given that a lot more scenarios and experiments can be conducted in the allowed time constraint.

This research will use an adjusted format applicable to this research of the Simulation Study methodology of Robinson (Robinson, 2004). The adjustments of the Robinson simulation study methodology are: an extra analysis of the production before building the conceptual model, literature research on bottleneck/waste identification, and the recommendation on the organisation of the production line instead of an implementation. These adjustments were made since Nijhuis Toelevering not only just wanted a layout of the new production line. For them, it was important to know which theory to use for this layout and how to organise this. Therefore, for this research project, it is important to understand what the problems are with the current organisation, what theories on these problems are available and which they should implement with the recommended organisation. The different phases of the methodology used can be found in *Figure 1*. Each phase consists of a research question with possible sub-questions that will support answering the research question of the given phase.

1.4.1. Research Questions

To be able to answer the main research question there are several sub-research questions needed. The following sub-research questions are composed to answer the main research question, with extra sub-questions that will support in answering the sub-research questions:

1. How does the frame production line at Nijhuis Toelevering B.V. currently operate during transition phase 6?
    - 1.1. What are the production steps of the frame production line?
    - 1.2. What changes are going to be made to the frame production line following the transition?

2. Which literature theories are available for identifying bottlenecks and improving the throughput time given the context at Nijhuis Toelevering B.V.?

3. How is the current performance of the frame production line at Nijhuis Toelevering B.V.?
    - 3.1. What are the throughput and waiting times for each working station?
    - 3.2. Where do bottlenecks/problems occur regarding the layout and organisation of the production line?

4. What performance data and processes of the frame production line are needed for the conceptual model?
    - 4.1. Which processes should be taken into account for the conceptual model, due to found bottlenecks?
    - 4.2. What is the actual performance of the production line processes used for the simulation model?

5. How can we model the production line at Nijhuis Toelevering B.V. for experimenting with the layout and organisational decisions?
    - 5.1. What are the input and output parameters of the simulation model?
    - 5.2. Which assumptions and simplifications have to be made for the simulation model?

    5.3. How representative is the simulation model of the real production line?

6. What will be the experimental design of the frame production line at Nijhuis Toelevering B.V. for reducing the throughput time?
    6.1. How many replications are necessary to make sure the simulation model will be valid and reliable?
    6.2. What will be the warmup length for the simulation model?
    6.3. What are the production configurations for the experiments?

7. Which organisational configurations will optimize the throughput time of the frame production line at Nijhuis Toelevering B.V.?
    7.1. Which experiments with the layout and organisation have a significant influence on the throughput time?
    7.2. What recommendations on layout and organisational decisions can be made to Nijhuis Toelevering to accomplish the desired throughput time reduction?

In *Appendix C*, an overview is displayed of the organisation of the sub-research questions. This will provide information on the type of research, research population, subjects, research methodology phase, method of data gathering and processing, and an activity plan.

1.4.2. Problem-Solving Approach

In this paragraph, the research methodology is explained and what each methodological phase consists of.

Phase 1: Analyse the production line

The first phase consists of analysing the current production line and future production line. This means that we will look into how they currently operate on their operation line and what changes are still to be made to the production line. This will mainly be done by interviewing important stakeholders, such as workstation supervisors, and observing the current production line.

Phase 2: Literature research on identification of bottlenecks and waste

In this phase, literature research is conducted on the theories that can be used to identify bottlenecks and wastes in the production line. Furthermore, we will look into how these theories can help to tackle these bottlenecks and remove waste.

Phase 3: bottleneck identification

In this phase, the bottlenecks and wastes will be identified using the theories found in phase 2. These bottlenecks and wastes will be taken into account for the conceptual model and experimental design for the research.

Phase 4: Conceptual model and Data analyses

In this phase, the conceptual model and all the necessary data, which mainly consists of secondary quantitative data that is semi-structured, of the production line will be collected for the simulation model. The conceptual model will be built using the Bizagi Modeler to get a visual model of how the production line is organised and where the bottlenecks/problems occur. Bizagi Modeler is used, because it is a platform enabling organizations to create and document their business processes to gain a better understanding of each step and identify the opportunities for process improvement (Bizagi, 2024). To make sure this model is valid, it will be discussed with the production manager. The data can be collected from the company's database which consists of several Excel files containing several data variables, such as production rates, hours planned, guidelines on batch sizes, and buffer capacities. This data is observed by employees on the production line and then administrated in the Excel files. Therefore, the Excel files contain a lot of raw data that has to be cleaned and organised to the needs of this research. Since this data gathering with raw data can take a lot of time, this research will focus on the specific data necessary to be able to run the simulation model. To make sure that the data from the company database is also reliable we will also conduct observations on the collected data at the production line.

Phase 5: Build the simulation model and verify/validate
In this phase, the simulation model will be built and coded in Siemens Tecnomatix Plant Simulations 16.1 using the conceptual model and collected data. After the simulation model is built of the current production line, we have to validate and verify that the simulation model represents the current real-world production line. To make sure the model is a reliable and valid representation of the current situation we will conduct several test runs and do statistical analysis (goodness-of-fit test). The statistical analysis will also decide if a warm-up period is needed.

Phase 6: Define experimental design (with parameters) and conduct experiments
In this phase, we will define the experimental design with the parameters that will be changed with those experiments and conduct the actual experiments within the simulation model. During this phase, several situations and solutions will be tested. To make sure that the outcome is reliable there will be several replications performed according to statistical analysis.

Phase 7: Analyse the outcome of the experiments
In this phase, the outcome of the experiments will be analysed. The outcomes are analysed using the output data and Excel. After the analysis of the experiments, the results will be presented to the production managers and stakeholders to see if the outcomes of the simulation are feasible and reliable.

Phase 8: Conclusion and Recommendation
In this last phase, we will conclude on the outcomes of the analysis in phase 7 and make a recommendation on the organisation and layout of the new production line. This outcome will result in certain production configurations for the organisation and layout of the production line. Given these settings and the knowledge about the current production line, we will make a recommendation on what the layout and organisation of the new production can be to reduce the throughput time to the desired 3 working days for all product types.

1.5. Theoretical Framework

As described in the problem-solving approach we will be using a simulation model for this research. Therefore, the main theory that will be used is Simulation as described in the research design the Simulation Study research methodology of Robinson (2004). Furthermore, for the research statistical analysis and probability distributions will be used for the data analysis, because for the simulation model, the parameters of the working stations need to be analysed and be given a certain probability distribution. At the end of the simulation, the output has to be analysed using statistical analysis to prove a significant improvement in the throughput time. Furthermore, there will be knowledge used during this research project on Business Process Management, Operation Strategy, and production flow. From Business process management, the modelling language Business Process Modelling and Notation (BPMN) is used, since BPMN "*… aims at supporting the complete range of abstraction levels,* *from a business level to a technical implementation level"* and its main goal is "*… to provide a notation that is easily readable and understandable for all business users, who design, implement or monitor business processes."* (Korherr, 2008). Therefore, BPMN will be useful for the documentation of the analysis on the production line, to provide a clear overview of the processes in the production process. Last of all, there will also be theories used to identify bottlenecks and improve throughput time, but this will be discussed in Chapter 3.

1.6. Research Scope

As mentioned earlier, this research will focus on the wooden window- and doorframe production facility of Nijhuis Toelevering B.V.. Within this facility, the research will focus only on the frame production line and therefore exclude the prefab production line. The research will focus on the frame production line in its entirety, so all the different working stations of the production line will be included. This means that the starting point for the throughput time will be the moment that the wooden beams are placed on one of the loading stations at the "Kortlijn" and the end of the throughput time will be the moment the frame is placed at the transport rack at the end of the finishing assembly line. During this research, Nijhuis Toelevering B.V. is researching the implementation of the Enterprise Resource Planning (ERP) system. Therefore, this research will not consider the usage of an ERP system as a solution into account.

1.6.1. Assumptions and Limitations

For this research, there is a limitation considering the time, because for this research the time constraint is ten weeks. This means that if the time does not allow it, some solutions might be taken out of the research analysis so that the research still can be finished with a proper scientific result. This exclusion might lead to the fact of not achieving the desired outcome. Further research should study the actual implementation, possible difficulties in changes and to what extent the proposed solution is an improvement.

At this moment Nijhuis Toelevering B.V. is also replacing some of the old machinery with new machines, but not all the new machines are already operational. Therefore, since the research will be focused on the production line with those new machines, there might have to be made an assumption on the throughput times and production rates of these machines in close consideration with the machine supplier and company supervisor. However, the company plans to have the new machinery operational at the beginning of May 2024, which means that there is no assumption necessary and we can perform observations and data analysis on the new machinery if there are no delays.

For this research, we will also assume that the current distribution of the different and amount of frame sizes will not be changed. This implies that we can use a statistical analysis on the historical data for a probability distribution.

1.7. Deliverables

As described in the problem-solving approach the final outcome of this research is a simulation model and a recommendation on the layout and organisation of the new production line. Therefore, this research has the following deliverables:

- Simulation model of the new production line with several experimental solution designs, which will be done with the experiment manager.
- Data analyses on the performance of the production line processes.
- Recommendation on the organisation and layout of the new production line with the best outcome of the simulation which provides the highest reduction in throughput time according to the research.

2. Production Analysis

In this chapter, sub-research question 1 "*How does the frame production line at Nijhuis Toelevering B.V. operate during and after the transition?"* will be answered, within Section 2.1 a description of the current production line and in Section 2.2 what changes will still be made. Furthermore, there are BPMN models created of the production process in *Appendix D* according to the description of the current production process in Section 2.1. and the floor plan in *Appendix A*.

2.1. Description of the current Production Process

At the frame production line of Nijhuis Toelevering B.V., there are 3 different kinds of production order origins which have an impact on the product mix of that order and therefore also on the throughput time. First of all, there are the main construction project orders, these originate from deals made with construction companies. The project orders consist of a variable amount of frames, doors, and windows. Therefore, the exact distribution for the frames, doors and windows will be discussed in *Section 5.2.1.*, but the construction project orders consist on average of 33 frames, 5 doors, and 19 windows. The second origin of the production orders are the online orders from Toelevering Online B.V. which is part of Nijhuis Holding. These production orders have a lot of variation in frames, doors, windows and difficulty of assembly, since customers can online order what they want and the production orders are started mostly the day after the production order is received. The online orders consist on average of 18 frames, 7 doors, and 10 windows. The third origin of the production orders are the shelter doorframes that are ordered by Trebbe, De Groot, or Toelevering Online. These production orders consist only of a simple doorframe with one door. Therefore, the shelter doorframe orders consist on average of 11 frames, 11 doors, and 0 windows. Although the differences in the production orders, they all have to follow the same production line in the factory. This production line at Nijhuis Toelevering B.V. consists of 4 different departments: machinery, pre-assembly, painting and finishing assembly. In this section, we will go through the entire production line per department and describe in detail what each consists of and what the steps are to get from the wooden beams to an actual frame (end product).
First of all, we will start with the machinery department where the production process starts with the wooden beams. The machinery department consists of two main production processes: the cutting and milling of the wooden beams, and the necessary operations such as drilling and milling that are different for each frame type. The machinery department is also the department where the changes from the transition are made. Therefore, we will discuss the steps and machines that are used during transition step 6, because that is the current situation. The current production line consists of the following steps (*Appendix D.2)*, which will be described in detail including machine types:

1) The wooden beams that are needed for production are loaded on one of the three loading stations at the BMH Loadmaster with a forklift truck. This can only be done when the loading station is pulled outside of the BMH Loadmaster, when the loading station is loaded with the wooden beams it has to be pushed inside the BMH Loadmaster again. After that, an operator has to scan a barcode with the information of the wooden beams that are loaded onto the loading station, so the system knows all the information about the wooden beams (type of wood, length, width, height, total amount of wooden beams, total amount of layers, and number of wooden beams per layer).
2) The BMH Loadmaster type 6300 PS-F triplex is a robotic machine that picks up the wooden beams one piece at a time from the loading station and then places them on a push platform towards the BMH Sawmaster.
3) The wooden beams then go through the BM Sawmaster Ultra, that cuts the wooden beams to the desired lengths. This machine uses optimization software to minimize the residual lengths that can be reused and the waste lengths. Residual lengths are pushed out of the conveyor belt to be reused and waste lengths are cut into small pieces to be

transported on a conveyor belt to a waste container. The actual product lengths proceed on the conveyor belt to the Kuper SWT XL.

4) At the Kuper SWT XL the wooden beams will be planed on the necessary sides, which is dependent on the product type. After the wooden beams are planed, they will be transported on a conveyor belt through a control system towards the BMH Sortingmaster.
5) At the end of the conveyor belt in the BMH Sortingmaster 8200, there is an extra BMH cutting blade placed since some of the lengths have to be cut into smaller lengths than the length cut at the BMH Sawmaster due to the minimal length necessary for the Kuper SWT XL. The lengths are then picked up by the BMH Sortingmaster and placed at another conveyor belt, where a decision has to be made if the wooden beams proceed to the buffers or bypass. If the decision has been made to proceed to the buffers, the production process continues with step 6. Otherwise, it continues in the next paragraph.
6) When the wooden beams are placed on the conveyor belt towards the 4 buffer platforms, which each have their own BMH Sortingmaster 5000, the wooden beams will be picked up by the BMH Sortingmaster that organises the wooden beams per length. Each buffer platform contains a different production batch, but the wooden beams will be combined at the start of the BMH Sawmaster for more optimization of the cut length. When 2 buffer platforms are full, one of the BMH Sortingmaster of full buffer platforms will start unloading the platform beam per beam onto a conveyor belt towards another BMH SortingMaster. This BMH Sortingmaster will transfer the wooden beams towards a conveyor belt that transfers the wooden beams to the BMH Windowmaster type 50 topline of which there 2 machines.
7) At the BMH Windowmaster the wooden beams are clammed into one of the movable holders and go through the machine where several adjustments for the specific frame and wooden beam are made, such as milling and drilling with several pieces of equipment. When the wooden beams are finished a pickup arm will pick the wooden beam from the holder and place it on a conveyor belt towards the output belt.
8) At the end of the conveyor belt there is a push-out mechanism followed by a vertical output conveyor belt, that moves the wooden beams towards the employee that picks the wooden beams from the belt onto a manual movable cart for the pre-assembly line. This employee also conducts a quality control and foresees the wooden beams from the information necessary for the pre-assembly line and paint station.

There also is the situation with the bypass followed by the Conturex machine. This path consists of the following steps, that start after step 5 of the previously explained process.

1) The wooden beams are transferred on the conveyor belt towards the bypass where at the end a pushout platform is placed. Where a pushout platform pushes the wooden beams out of the conveyor belt onto a platform.
2) At this platform, the wooden beams are labelled with a sticker with the following information: batch code, cutting length, width, cart number, layer number of the cart, location number of the cart and barcode with information for the Conturex machine.
3) When the wooden beams are labelled the employee places the wooden beams manually onto the cart and when fully loaded the cart will moved to the Conturex machine.
4) At the Conturex machine the fully loaded cart is placed in the machine that unloads the cart automatically and scans all the bar codes so the machine knows which adjustments are have to be made to the wooden beams (same as what is done at the BMH Windowmaster).
5) After those adjustments, the wooden beams are placed on a vertical output transport belt towards the employee operating the Conturex machine. This employee conducts a quality control and makes repairments where necessary, after which the employee also here provides the wooden beam of the necessary information needed for the pre-assembly line and painting station.

This is the end of the machinery department, because the carts with the adjusted wooden beams are now placed in the buffer for the pre-assembly line. This is also the start of the pre-assembly department, that consist of the pre-assembly line for frames and pre-assembly line for doors and windows. The pre-assembly line for frames consist of the following production steps (*Appendix D.3)*:

1) The pre-assembly starts with the main operator that gets a cart from a certain production batch out of the buffer. The main operator has a tablet with a blueprint of all the frames of that production batch, which helps in getting the right wooden elements together from the cart.
2) The process starts with unloading the wooden beams, where the main operator also conducts a quality control, and places the necessary wooden beams for each frame after each other on a roller track towards the hydraulic confinement bench.
3) On this roller track, the sides of the wooden beams that will be connected to each other are foreseen of sealant to glue the beams together. After the sealant is placed onto the wooden beams, they will be picked up and placed by another employee onto the hydraulic confinement bench.
4) At the confinement bench, the wooden frames are pushed together and superfluous sealant is removed on one side of the frame within the confinement bench. After that, the wooden frame is removed from the confinement bench, by hand, and placed onto the longer roller track of the pre-assembly line. This roller track consist of 4 stations.
5) When the frame is placed on the roller track from the confinement bench, the process starts at station 1 where the superfluous sealant on the other side of the frame is removed by one or two employees with putty knives and wipes. After that is finished the construction laths for the frame are collected from a cart and placed on the roller track near the frame. Then the frame with the laths are pushed towards workstation 2.
6) At workstation 2, the construction laths are attached to the wooden frames using nail guns and glue. After these construction laths are attached, the superfluous sealant is removed and the difficult cornered parts are foreseen of a layer of paint by hand. This process is executed by two employees. When finished they push the frame further towards workstation 3.
7) At workstation 3, the frames are foreseen of an information sticker about the frame and the colour for the painting station and the lifting loops are attached to the frame. At this workstation, it is also possible to paint certain spots on the frame by hand which are difficult to paint for the paint robot. After this is finished, the frame(s) will be pushed to workstation 4.
8) At workstation 4, the frames roll onto a rotatable roller track where the frames undergo a quality control and are lifted with hooks that are attached onto the lifting loops up to the painting rails. When the frames are lifted, they are pushed towards the painting buffer and the QR code of the information sticker is scanned for the automated painting trail system.

The pre-assembly line for doors and windows consist of the following production steps:

1) The employee at the starts gets a cart from the pre-assembly buffer and unloads the wooden elements per door or window. After unloading the elements, the employee foresees the attachment sides of glue.
2) When the elements are foreseen of glue, another employee will place the elements in the confinement bench and push the elements together into a door or window.
3) Then door or window is cleaned from the superfluous glue and placed on a rotatable working table where it is getting fine-tuned and a quality check is performed.
4) The last step is lifting the doors and windows on one of the traverse onto the paint the painting department rails towards the buffer.

This is the end of the pre-assembly line department, because the buffer at which the frames are pushed into is the start of the painting department. The painting department consist of the following production process steps (*Appendix D.4)*:

1) When the frames, doors, and windows are placed within the buffers of the painting department, the painting operator will also conduct a quality control of the frames before proceeding the frames into the automated paint line. The windows and doors that are pre-assembled on a different working station than the regular pre-assembly line will be prioritized over the frames, because they need to be painted first due to order of the finishing assembly.
2) The system knows exactly the information of each frame with the layout and paint colour due to scan made by the pre-assembly line, but first the frames go through a scanner to scan the actual position of how the frames is hanging on the hooks so the paint robots exactly know where to paint.
3) Then the frames go past two paint robots for each side for the first paint coating. After that, the frames go to a small drying room with a cold temperature and high humidity.
4) After the small drying room, the frames go to big drying room with a warm temperature and high humidity where the frames stay for a significant time to dry. The drying rooms are completely automated and regulated, which means they cannot be executed faster or can be intervened.
5) When the frames come out of the second drying room, there has to be a decision made whether the frames go again through the paint robots line or that the second layer of paint will be manually painted at the manual paint station through which the frames have to go anyway. When the decision is made to go to paint robots again they go through step 2, 3 and 4 again before going to step 7. If the decision is made to manually paint the frames for the second layer of paint, the frames go to a buffer before proceeding to step 6.
6) Before the frames a manually painted with a second layer of paint by the employee, there is a quality control performed by the painter. If the frames are of good quality the second layer of paint will applied on both sides, but if the quality is not good enough the frames will be extracted out of the paint spray line to a buffer station inside the manual painting station where the frame can be fixed before painting.
7) After the second layer of paint is applied, the frames go to drying room again where the frames need to dry. This process of drying can also not be fastened.
8) When the frames are through the drying rooms, a paint department employee will lift off the frames onto movable carts. This employee conducts a quality control of the frames and provides the frame of a sticker when they are lifted of the paint line (day) and when the frames can be released from the drying buffer in the paint department. The frames has to stay at least 24 hours in the paint department buffer to fully dry, according to the paint supplier. This means if the frames are lifted off on Monday, this means that the frames cannot leave the buffer room before Wednesday.
9) When the necessary drying time is over, the frames are placed from the painting department buffer to the finishing assembly buffer.

This is the end of the painting department, because the frames are now at the buffer before the finishing assembly. The finishing assembly department consist of the finishing assembly of doors and 4 finishing assembly lines. Before the finishing assembly at one of the lines can start, it is necessary that the doors and windows of that production batch have been through the finishing assembly station for doors and windows. At that station, the doors and windows are foreseen of all the hinges, locks, and closing rubbers. From the 4 finishing assembly lines are line 1 and 2 identical and line 3 almost but it is just a bit shorter and designed for bigger frames. However, finishing assembly line 4 is completely different, because this line only focuses on doorframes for garden shelters. For the sake of simplicity, finishing assembly line 2 will be used to describe the production process steps of the finishing assembly lines (*Appendix D.5)*:

1) The carts with the frames are organised per production batch series and will be allocated to the finishing assembly lines by the supervisor of the department. The finishing assembly line (line 2) consist of 7 working stations that roller track platforms of which some of them can be laid down.
2) The finishing assembly starts at workstation 1, this is where the frames are titled onto the production line and all the adjustments on the outside of the frame are made. This differs per frame in detail, but most adjustments made are roughly the same.
3) At the second workstation are all the adjustments on the inside of the frame made and are windows with the hinges and locks placed.
4) The third workstation of the finishing assembly line is a buffer towards workstation 4.
5) The fourth workstation is where the door and window frames are being glazed with a dry glazing method. With this method they are using glazing beads to keep the glass in place. After the frames are glazed they proceed to workstation 5.
6) At workstation 5, the inner side of the glazed frames are made waterproof by using a sealant to make sure the space between the glass and the glazing beads is closed. Then superfluous sealant is removed and the glass is being cleaned.
7) At workstation 6, the outer side of the glazed frames is foreseen of the joint sealant. This is the process that takes place at workstation 5. After that is finished, the frame is finished and can move on to workstation 7.
8) At workstation 7, there is a last quality control performed by an employee and then the frames are titled of the production line using an overhead crane to place them on a stillage and prepare the frame to be ready for transport.

This is the end of the frame production process and therefore, also the end of the measured throughput time for this research.

2.2. Adjustments to be Made According to the Transition

Although the BMPN model suggest that only Conturex Machine 2 is in usage besides the BMH Windowmaster, it is still common that Conturex Machine 1 is used. This will however change in the near future for the production line at Nijhuis Toelevering, besides some other changes that are still planned according to the transition phases. As mentioned, Conturex machine 1 is still used, but this machine has already been sold and will be removed during the summer holiday break of 2024. For this reason, during the research we will consider that the production line does not include Conturex Machine number 1. Furthermore, the production currently only has one pre-assembly line, but according to transition phase 8 there will be an extra pre-assembly line exactly like the current one placed during the summer holiday break of 2024. However, some of the managers are still discussing whether or not this will be the best decision for the improvement of throughput time of the production line. Therefore, the second pre-assembly line will not be taken into account for the current production line model, but rather be taken into consideration for the experimental design of the simulation which will be discussed in *Chapter 7.*

3. Reducing Throughput Time: Literature Review

In this chapter, sub-research question 2: "*Which literature theories are available for identifying bottlenecks and improving the throughput time given the context at Nijhuis Toelevering B.V.?"* will be answered. For this research question a systematic literature review is performed on the available theories, that is summarized in Section 3.1. Next, Section 3.2 describes how to reduce throughput time by waste identification. At last, Section 3.3. describes how to identify and tackle bottlenecks in a production system.

3.1. Systematic Literature Review

To answer sub-research question 2, we performed a Systematic Literature Review on available literature theories for identifying bottlenecks and improving throughput time. In this section, we will summarize the findings of this literature review, which is described in detail in *Appendix E.* For the SLR, we used the databases of Scopus, Web of Science and Arxiv to make sure that a wide variety of sources are considered for the review. Following from sub-research question 2, the key concepts had to be defined. These key concepts are: "Theory", "Throughput time" and "Production line" and to prevent any bias in synonyms or related terms used a small research using the Power Thesaurus resulted in related, broader, and narrower terms for the key concepts. After that, the SLR is performed and documented as prescribed by (McGregor, 2018) which can be seen in detail in *Appendix E.* During this literature review several articles about Discrete Event Simulation were found, such as "*A continuous flow model for production networks with finite buffers, unreliable machines and multiple products"* (Kouikoglou & Phillis, 1997) and "*A continuum model for re-entrant factory"* (Armbruster, Marthaler, Ringhofer, Kempf, & Jo, 2006). Therefore, we will make use of a discrete event simulation for experimenting with potential solutions that will reduce the throughput time. However, first the production line has to be analysed on where potential solutions should be implemented. As a result of the SLR, there were several methodologies and theories applicable to the context of the production line at Nijhuis Toelevering, but the decision is made to use the lean framework consisting of several tools, and the theory of constraints. This, while the SLR showed us that multiple research papers used a form of the lean framework methodology or the theory of constraints for finding the wastes and bottlenecks of the production process researched in combination with a simulation study. The paper from Abdumalek et al. "Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector study" showed us that the lean framework and the lean framework provide opportunities to reduce throughput time that can be analyzed using a simulation model. Therefore, for this research, we will use the lean framework, value stream mapping, and the theory of constraints for analyzing the production line to search for improvement opportunities that will be tested using a Discrete Event Simulation model of the production line.

3.2. The Lean Framework

For the identification of wastes and the reducement of unnecessary throughput time, we will be using the lean framework. The lean framework consists of multiple tools and methodologies to improve production processes. To start with, according to Tébar-Rubio et al. "Lean Manufacturing is a methodology that seeks the systematically elimination of waste in order improve process performance" (Tébar-Rubio, Ramírez, & Ruiz-Ortega, 2022). Therefore, identifying waste is important to provide a lean manufacturing process. Waste is defined as all the activities in the production process that do not add value to the end product for the customer (Slack & Brandon-Jones, 2019). To identify wastes it is important to understand what non-value-adding activities are and the causes of waste are.

To understand what the non-value-adding activities are, it is more common to understand what the value-adding activities are since all other activities then can be classified as non-value-adding activities. We can classify activities to value value-adding if they satisfy the following criteria:

1. *The customer perceives value from the activity and is willing to pay for the activity performed*. The customer is for example not willing to pay for activities that are performed that are not in line with the requested product.
2. *The activity physically transforms the product.* The product will only get closer to the end product if the product undergoes physical transformation. For example, at Nijhuis Toelevering it is a physical transformation to begin with the wooden beams and get to a wooden element for a frame.
3. *The activity is performed correctly the first time.* A product should not have to undergo repairment work, neither the company nor the customer wants to spend extra resources, time or money on repairment work.

All the activities that cannot satisfy these three criteria are identified as a form of waste. According to Slack et al., there exist three different causes of waste in the lean framework (Slack & Brandon-Jones, 2019):

1. *Muda:* the activities in a process that do not add value to the operation or the customer, mainly caused by the poor communication or ineffective use of resources.
2. *Mura:* the lack of consistency that results in periodic overloading of staff or equipment.
3. *Muri:* unnecessary or unreasonable requirements that are put on the process will result in poor outcomes. This means that the organization is failing to understand the priority of tasks, the required time of them and the resources that are needed which will cause more non value adding activities.

Although this are three different causes of waste, according to Slack et al. they are still related. "When a process is inconsistent (mura), it can lead to overburdening of equipment and people (muri), which, in turn, will cause all kinds of non-value-adding activities (muda)." (Slack & Brandon-Jones, 2019).
To identify these wastes and their causes, a so-called Value Stream Map will be made. Value Stream Mapping (VSM) uses a graphical representation to visualize, analyse and improve production flow including material and information flow (Tébar-Rubio, Ramírez, & Ruiz-Ortega, 2022).

3.3. Theory of Constraints

The second theory we will be using with this research project is the Theory of Constraints (TOC). TOC is the philosophy of operations management that focuses on capacity constraints or bottlenecks of an operation system (Slack & Brandon-Jones, 2019). The theory focuses therefore on the weakest links within the production process which hinders the organisation in achieving its goals. This theory was chosen, since it provides opportunities in reducing throughput time by providing a better production flow in combination with the lean framework. The theory of constraints will focus more on the bottlenecks in the production system instead of the wastes that will be analysed with the lean framework.

The Theory of Constraints originates from the book "The Goal", by Goldratt and Cox (1984) and uses a 5-step guideline on the Process Of Ongoing Improvement (POOGI) (Goldratt & Cox, 2004). This guideline uses the following 5 steps to improve the throughput time of a production process:

1. *Identify the system's constraint(s).* The constraint is seen as the bottleneck of the production system, that can either be the capacity of a production step or certain production decisions.
2. *Decide on how to exploit the system's constraint(s).* In this step, we attempt to use the constraint as much as possible with minimum investment, by considering several alternatives.

3. *Subordinate everything else to the above decision.* This step is about adjusting all the other activities of the production process to the capacity of the constraint so the constraint can operate at maximum effectiveness. If this step moves the bottleneck to another place in the production process, go back to step 1.
4. *Elevate the system's constraint(s).* If steps 2 and 3 are not successful, the constraint has to be eliminated by applying major changes to the system's constraint.
5. *If in the previous steps a constraint has been broken, go back to Step 1, but do not allow inertia to cause a system's constraint.*

According to Goldratt TOC should use the bottlenecks as the control point, by making the constraints in the production process the major input to the planning and control. Therefore, TOC uses the terminology of 'drum, buffer, rope' to explain its planning control approach (Slack & Brandon-Jones, 2019). Where the bottleneck is seen as the drum, determining the pace for the rest of the production process. The drum determines the schedules in non-bottleneck areas and the rope pulling through the work in line with the bottleneck capacity. Last of all, there is the buffer that represents the inventory before the bottleneck.

4. Performance of the Production Line

In this chapter, sub-research question 3: "*How is the current performance of the frame production line at Nijhuis Toelevering B.V.?"* will be answered. We will start with an analysis on the performance of the production line by making a Value Stream Map in Section 4.1. After that, we will continue with an analysis on the wastes and bottlenecks of the production line using the lean framework and theory of constraints in Section 4.2. Last of all, are the found bottlenecks discussed in Section 4.3.

4.1. Value Stream Map

As discussed in Chapter 3 we will make use of Value Stream Mapping following the lean framework to analyse the performance of the production line and possible wastes. A Value Stream Map (VSM) provides a general overview of the duration of the production processes on the production line and the total throughput time of the production line. For the VSM, we decided to use the following data as performance indicators: Cycle Time (C/T), Waiting time, Available time, Percentage of value-adding time (%VAT), and Uptime.

Since there are three different kinds of product types there will be made three different VSMs, because the product types have different cycle times for some of the production processes in the production line due to processing difficulty and batch size.

For the performance data are observations and indications of production supervisors used to provide estimates. These estimates are not completely accurate, since the time constraint of this thesis made it only possible to observe every production step a few times. Therefore, to make sure the performance data is more reliable, the supervisors of the four different production departments were asked to provide estimates on the performance data of their department.

To make sure the performance data is understood correctly, it is important to define what is meant by the data types. This also prevents that the collected data is not valid for this research. First of all, there is the Cycle Time (CT) which is the average time between units of output emerging from a production process (Slack & Brandon-Jones, 2019). There is also the waiting time that is defined as the time spent in between production processes or in buffers. For each production department, there is also the available time for the production processes given the shift times they are using. Last of all, there are the two important time measurements on the efficiency of the production processes, namely the Percentage of value-adding time (%VAT) and the uptime. The uptime is defined as the time the production process is working, so it means that all the time that the machine or people cannot work on their tasks has to be subtracted from the total available time. This uptime can be lower than 100 percent due to for example not enough supplies or machine breakdowns. The percentage of value-adding time follows from the non-value-adding activities discussed in Section 3.2 about the lean framework philosophy. Therefore, this percentage of value-adding time can be calculated with the following formula for each production process:

$$\%VAT = \frac{time\ spent\ on\ value\ adding\ activies}{cycle\ time} * 100\ \%$$

It should be noted that even though the formula provides an accurate percentage of the time spent on value-adding activities it is still an estimate, since the time spent on value-adding activities and cycle times used are already estimates following from the observations and production supervisors due to the time constraint. Since the production line has to produce three different kinds of product origin types in terms of construction projects, online orders and shelter frames, of which the one for construction projects is showcased in *Figure 2.* Furthermore, the three different VSMs are showcased in detail in *Appendix F.*

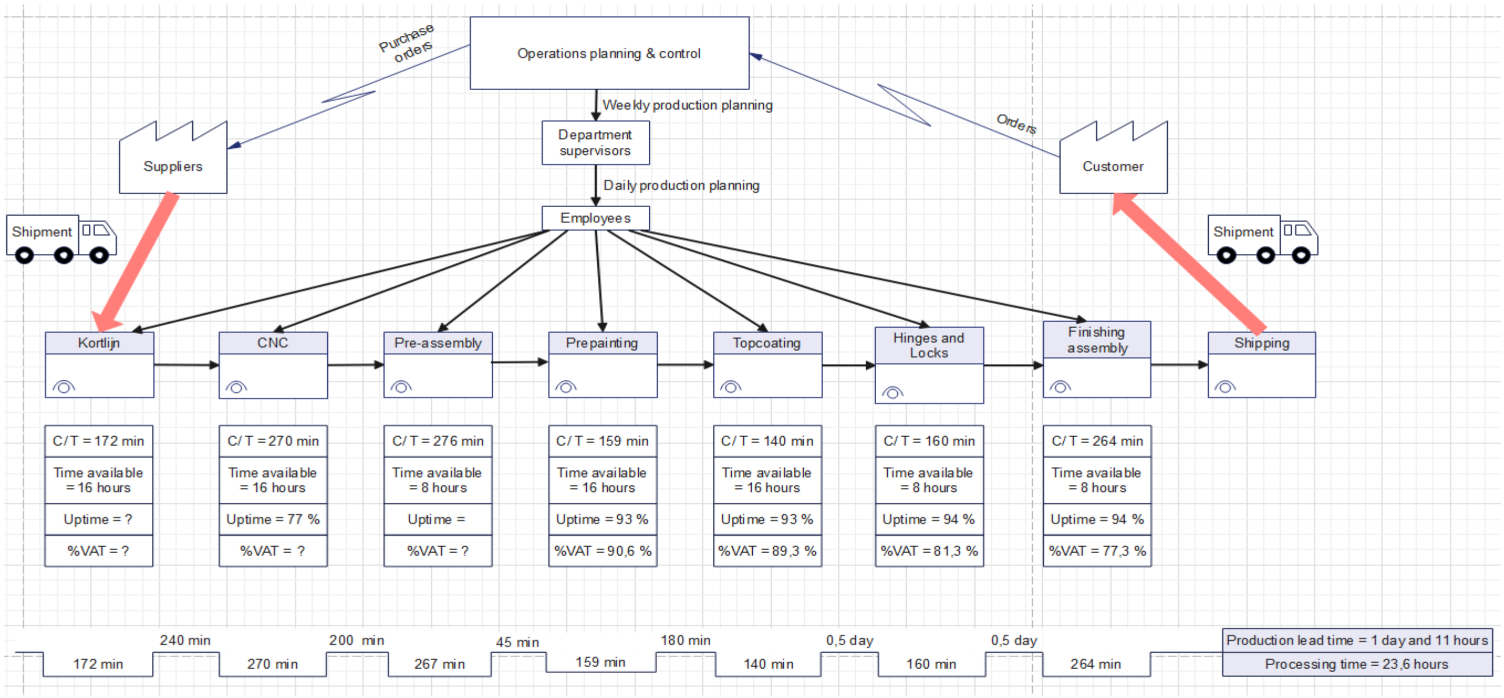

Figure 2 - Value Stream Map of the production line with project batches

The VSM also shows us the minimal waiting time in between the production processes as calculated by the available data, observations and interviews with the production supervisors. However, it has to be noted that currently on the production line, the batches observe a higher waiting time than the minimal waiting time used in the VSM. This while the company with the ongoing transition decided to build in bigger buffers in case of any failures or breakdowns. *Figure 2* displays the format used for the VSM models of the three different production batches, all can be found in detail in *Appendix F*. However, the most important results are summarized in *Table 1*. This includes the time available, uptime as a percentage, cycle time of the three different production batches, and the average percentage VAT for the defined production processes in *Figure 2.*

	Time available	Uptime	C/T project	C/T online	C/T shelter	Average %VAT
Kortlijn	16 hours	60 %	172 min	131 min	61 min	40 %
CNC	16 hours	77 %	270 min	206 min	96 min	40 %
Pre-assembly	8 hours	86%	276 min	196 min	83 min	76 %
Pre-painting	16 hours	93 %	159 min	112 min	36 min	78,5 %
Top coating	16 hours	93 %	140 min	95 min	30 min	74,5 %
Hinges and locks	8 hours	94 %	160 min	128 min	N/A	94 %
Finishing assembly	8 hours	94 %	264 min	150 min	168 min	64,4 %

Table 1 - Summarized data from the Value Stream Maps in Appendix F

From the results in *Table 1* and the VSMs, we can conclude that there is a big difference in cycle times between the different production batches and the overall production lead time is relatively high compared to the production time. The big difference in cycle times between the production is mainly caused by the difference in batch sizes and the production difficulty for some of the production processes. Furthermore, the high production lead time that is defined as the waiting times in between the production processes is mainly due to the necessary drying time for the paint and certain decisions made for buffers in between production processes.

4.2. Identified Wastes

As described in Section 3.2. there are three different causes of waste according to the lean framework theory: Muda (Non-value adding activity), Mura (unevenness), and Muri (overburden). In this section, we analysed the production line looking at all these three different causes of waste.

4.2.1. Muda (non-value adding)

One of the most important classifications of waste is that if the activity does not add value to the end product for the customer, it can be defined as a waste (Slack & Brandon-Jones, 2019). Therefore, we will start in this section with the muda waste, which was defined as "all the activities in a process that do not value to the operation or the customer, mainly caused by poor communication or ineffective use of resources". In other words, we will analyse the production line on where in the production process non-value-adding activities are performed that are time-intensive and therefore have a negative influence on the throughput time. As previously discussed in Section 3.2, activities are value-adding if: the customer perceives value from the activity and is willing to pay for the activity performed, the activity physically transforms the product, and the activity is performed correctly the first time.

Table 2 provides a summarised list of all the non-value-adding activities found with the criteria of value-adding activities that are not fulfilled, an explanation of why the activity is classified as non-value adding and if the activity is necessary for the production process. As discussed in *Section 3.2.,* the value-adding criteria are defined as: 1. The customer perceives value from the activity and is willing to pay for the activity performed, 2. The activity physically transforms the product, and 3. The activity is performed correctly the first time.

Non-value adding activity	**Value Adding criteria that are not fulfilled**	**Explanation**	**Necessary?**
Quality control after planing the wooden beams	Criteria 2	To check for the planing quality and the measurements	Yes, to prevent value reduction
Filling of the buffers/carts for Conturex or BMH Windowmaster	Criteria 1 and 2	Before the BMH Windowmaster or Conturex can process the wooden beams a Conturex cart or BMH buffer platform has to be filled	Necessary for the production flow, but could be reduced
Quality control and repairment work after the CNC process	Criteria 2	Quality should be good enough, but currently there are still a lot of repairments that need to be made with fillers	Yes, to prevent value reduction
Waiting time spent in the buffer between machinery and the pre-assembly department	Criteria 1 and 2	Every minute spent waiting before the frames can be pre-assembled is a minute lost, since no value is added to the product	Not completely, should be reduced closer to the minimum needed
Quality control at the start of the pre-assembly line	Criteria 2	This is a double quality control performed since the same wooden elements are being checked after the CNC process	No, because there is already a quality control at the end of the machinery department

Removal of superfluous glue	Criteria 3	All the superfluous glue that is put on the frame elements has to be removed, but this could be prevented by applying the right amount of glue	No, because there are methods available to prevent it
Placement of a temporary wooden bar at the places of a sill	Criteria 1 and 3	Currently, the sills cannot be placed directly on the frame, due to the painting of the frames	Yes, within the current production flow
Quality control at the end of the pre-assembly line	Criteria 2	Quality control if all the attached elements are of good quality put together	Yes, to prevent value reduction
Waiting for the paint robot to be ready	Criteria 1 and 2	The frames have to wait in a buffer before the paint robot to be ready for painting	Not completely, it could be reduced to the minimum.
Drying time at the painting department	Criteria 2	The frames have to dry in between the first and second layer of paint, and after the second layer to fully dry	Yes, for the quality of the paint
Repainting of some of the frames	Criteria 1 and 3	Some frames are not painted good enough and have to undergo repair painting at the manual painting station.	No, because the frames should be painted correctly the first time
Repairment work detected after painting	Criteria 1 and 3	Some of the rotating parts or frames have significant damages that still passed the quality check at the pre-assembly even though they should not	No, because the frames should not have passed the quality controls earlier in the system
Waiting time in the buffer before pre-assembly line	Criteria 2	Time spent waiting before the frames can be finished on the finishing assembly line, which adds no value	Not completely, it could be reduced to the minimum.
Collecting and checking all the frames and materials of a production batch	Criteria 2	All the necessary materials and frames have to be collected for each production batch	Yes, since the batches should be complete
Repairment works on the finishing assembly due to mistakes earlier in the production process	Criteria 3	These mistakes should not have arrived at the finishing assembly, but detected earlier in the production line process	No, because the frames should not have passed the quality controls earlier in the system
Movement of employees when supplies are not present at the finishing assembly	Criteria 1, 2 and 3	There should not be made any mistakes in the supply of materials to the finishing assembly	No, because all the supplies should be present according to the used kanban system

Table 2 - Non-value adding activities

4.2.2. Mura (unevenness)

The second cause of waste is mura that is about the lack of consistency in the production processes that results in periodic overloading of staff or equipment (Slack & Brandon-Jones, 2019). As previously defined and as can be seen in *Table 2*, waiting is seen as a non-value-adding activity. That is why the lack of consistency in the production processes should be reduced, since this leads to high variability in processing time and therefore increases the waiting times for other products. Therefore, reducing high variability in the production process has several benefits, including the reduction of throughput time of the production process. In this section, we will discuss the mura wastes that were observed on the production line.

When observing the production line of Nijhuis Toelevering B.V., it immediately became clear that there was a lot of variation in the different types of frames produced. However, due to the fact the company is producing on a customer-order basis, it will not be possible to standardize the entire production of the frames. This waste is something that is already recognized by the management board itself, but is something that they have to deal with in the production planning since they cannot change the wishes of their customers. However, at Nijhuis Toelevering there are already agreements written down on what the maximum of certain product types are for a production batch to make sure the variability in production batches is controlled. Although there is already a control factor on this variability in production batches, there is still a lot of periodical overloading observed on multiple working stations. Therefore, this variability is still seen as a waste and has to be taken into account whether or not the current production mixes for production batches are the best ones to use.

In the production line of Nijhuis Toelevering, they also often have to make repairments to wooden beams or processed wooden elements at the machinery department or, even worse, later in the production line. This repairment works or reworks often are related to the quality of the wood or the quality of the adjustments made by the machinery department. However, although there are quality checks in place, there are still often scenarios where some of the frames pass through the quality check even though they should not. This causes even more delays when those problems on the quality are found later in the production line, since when the problem is found at the finishing assembly it sometimes is the case that an entire door or frame has to be reproduced or reworked at the pre-assembly line. This creates delivery delays, since the production batches are scheduled with only a few days in spare time for delivery.

4.2.3. Muri (overburden)

The last cause of waste is muri, which is defined as “unnecessary or unreasonable requirements that are put on a process will result in poor outcomes” (Slack & Brandon-Jones, 2019). That means that the organization is failing to understand the importance of scheduling and tracking its production process which eventually will cause more non-value-adding activities such as waiting time. With the analyses on the production line of Nijhuis Toelevering, there were two muri types of waste found.

First of all, it was found that on the current production line, the throughput time is only approximately measured from the start of the production till the end when the frames are ready for transport. Therefore, the current data on the throughput time of the production line in its entirety is not completely reliable. Furthermore, since the throughput time is not measured per working station is the production planning currently based on outdated data on the performance of the production line a few years ago or some re-estimates were made although they are not completely accurate. On days when the new machines from BMH are fully operational without any errors, it now seems that the machinery department can perform their tasks faster than the time scheduled in the production planning. However, it has to be noted that the supervisors of the production department including the general production manager and the planning employee meet every day to make sure the schedule can be updated where necessary and track where current production series are within the production line.

The second muri cause of waste is related to unforeseen scheduling changes and necessary changes that are made frequently in the delivery agreements with clients. At the production line of Nijhuis Toelevering it often occurs that there are so-called “spoedjes”, which are production series with the highest priority, on production planning or renovation works. These are often on short-term notice to the production supervisors which can cause unnecessary pressure on the production, that eventually can lead to mistakes with other production series. It also happens from time to time that for certain production series mistakes are made in the management of the supplies, technical drawings or machinery control that leads to delays in the production process, unnecessary costs and reworks. Due to these mistakes and poor outcomes, it often is the case that the supervisor of the delivery department has to call the clients and try to re-arrange the agreed delivery date with the client. This is unnecessary if these mistakes can be prevented and also not ideal for the client relationships.

4.3. Identified Bottlenecks

When looking at the performance of a production line it is important to not only understand where the wastes are located in the production line, as we discussed in Section 4.2., but also where the bottlenecks in the production line are located that prevent the improvement of the throughput time. For the identification of these bottlenecks, we will be using the Theory of Constraints as discussed in Section 3.3. However, according to the Theory of Constraints, there have to be 5 steps executed to improve the throughput time of a production process, but in this section we will only be looking at step 1 of the theory since this step focuses on the identification of the system’s constraint. According to Goldratt et al., “the constraint is seen as the bottleneck of the production system, that can either be the capacity of a production step or certain production decisions” (Goldratt & Cox, 2004).
For the identification of these constraints, there are several tools available. However, for this research project, we decided to make use of the Value Stream Maps (VSM) in *Appendix F* and the capacity constraint method which implies comparing the maximum production capacity of each department to look for the constraint. When analysing the three different VSMs it became clear that there are a few constraints within the production line that cause the relatively high throughput time. To start with, the production lead time within each different type of production batch is the biggest of the total throughput time. Therefore, we can consider the production lead time spent in buffers and queues of the production line as the first constraint of the production line, but not all the production lead time can reduced. This, while some of the production lead times are mandatory or preferable for the production flow. These are the lead time spent within the painting department where the paint has to dry, the lead time between the “kortlijn” and the CNC machines to provide continues production and a minimum sorting lead time spend at the buffer before the pre-assembly line and finishing assembly line. To continue on the constraints, it became clear after analysing the uptime of the new CNC machines that during the test phases and after the official delivery date when the machines are up and running is relatively low with a percentage of 77 %[1]. This, while the machines are still new for the employees and they have to get used to the new software used to be able to quickly handle any errors. Therefore, we will consider this percentage as a work in progress that will increase over time. Furthermore, the initially calculated throughput rate per BMH Windowmaster was theoretically 40 wooden elements per hour per Windowmaster, but in practice the machines can on average only 20-30 elements per hour with some exceptional peaks to 35 elements per hour. Although this is a constraint when looking at future developments for the company for the current situation, we will not consider this as the main constraint of the production line given the work in progress on the knowledge of the employees about the new machines and there is another constraint in the production line which has a more significant impact on the throughput time looking at the cycle time, time available and production capacity per hour. This constraint is the pre-assembly department, in particular the

[1] Based on estimates from observations and interviews with the machinery department supervisors.

pre-assembly line for frames, which causes a constraint when the machinery would be producing at its maximum production capacity for an entire production day. At the pre-assembly line, there is currently a maximum production capacity of 136 frames per day, with an average production rate of 105 frames per day. When looking at the production capacity of the machinery department in terms of frames we can conclude that on a production day without any failures or errors, the machinery department is able to produce 190 frames when only producing through the BMH Windowmaster if they are running at a production rate of 30 elements per hour. This will lead to a pre-assembly buffer that keeps adding up in numbers and eventually, this will lead to a throughout time that keeps rising.

5. Conceptual Model and Data Analysis

In this chapter, sub-research question 4: "*What performance data and processes of the frame production line are needed for the simulation model?"* will be answered. We will answer this question by defining the conceptual model in Section 5.1., providing the collected data in Section 5.2., and performing statistical analysis on the data where possible for the distributions in Section 5.3.

5.1. Conceptual Model

After analysing where the bottlenecks and wastes are located in the production line, we can decide on where the real-world production line model as showcased in *Appendix D* and described in Chapter 2 can be simplified for the simulation model. These decisions have to be made since according to Robinson: "The conceptual model is a non-software specific description of the simulation model that is to be developed, describing the inputs, outputs, content and simplification of the model" (Robinson, 2004). Therefore, we will describe the conceptual model with the input and output variables in Section 5.1.1., the scope of the model with a flowchart and inclusion table of the included production processes in Section 5.1.2., and conclude with simplifications and assumptions that had to be made for the simulation model in Section 5.1.3.

5.1.1. Input and Output Variables

As mentioned before there are several input variables needed for the simulation model to represent the production line at Nijhuis Toelevering. Therefore, we will provide a list of the necessary input variables for the model with an explanation before turning to the output variables of the model. These input variables should be investigated for their data, organizational configurations and processes:

1. **The arrival rates of production batches**: this includes the total number of arrivals for each of the different origins: construction projects, online and shelter frames per day.
2. **The distribution of frames, doors and windows**: this includes the number of frames, doors and windows within a production batch for all the different origins.
3. **The production process activities taken into consideration:** this includes all the production processes that follow from Chapter 2. However, these processes might have to be simplified for the sake of simplicity in a simulation model, but this will be described in Section 5.1.2. and 5.1.3.
4. **The cycle times of the production processes:** this includes the cycle times following the production processes taken into consideration from input variable 3.
5. **The capacity of the buffers:** this includes the buffer or queue capacities in between the different production processes
6. **The shift hours:** this includes the different shifts at the production line for the different production departments

Now we can turn to the output variables of the simulation model that are the statistical data used for analysis to check whether or not the objectives are being met. Therefore, since for this research project, we want to reduce the throughput time by looking at the organisation and layout of the production line, the following output variables are used:

1. **Throughput time in working days:** the throughput time is the most important output variable, since we want to reduce this. The variable will be given as throughput time measured in working days, but also measured in hours to give a more accurate measurement.

2. **Perceived waiting time per buffer/queue:** within the production line the products perceive several waiting times in the buffers and before processing on the working stations. These times will be calculated and given as output. However, the drying time will be excluded from this variable, since this is a fixed waiting that cannot be changed.
3. **Throughput time per production department:** within the production line each production department has a different contribution to the total throughput time and we are interested in where the reduction in the total throughput time originates from. This will also provide insights into the effects of experiments on certain departments of the production line
4. **Utilization of production processes:** this includes the utilization of the different workstations of the production processes to see if working stations are completely operational or if there is a bottleneck early in the process which causes inconsistent production flow.

5.1.2. The Scope of The Model

In this section, we will discuss the content and scope of the model according to the definitions from Robinson. Robinson defines the content of the model as "The components that are represented in the model and their interconnections." (Robinson, 2004) and the scope of the model as "the model boundary or the breadth of the real system that is to be included in the model." (Robinson, 2004). Table 3 provides the contents of the model including all the used entities, activities, and queues with a decision on whether or not they are included and a justification.

Component	Include/Exclude	Justification
Entities		
Construction project batches	Include	Main products
Online batches	Include	Big uncertainty factor and growing part in the factory
Shelter frame batches	Include	Important weekly production amount from regular client agreements and online orders
Specials	Exclude	Are not significantly present
Activities		
Loading wooden beams on Loadmaster	Exclude	This activity does not have a significant impact on the throughput time, since 3 load stations can be loaded separately while maintaining production
Cutting of wooden beams	Include	Important value-adding activity
Planing of wooden beams	Include	Important value-adding activity
Sorting of the wooden beams	Exclude	Not the main focus, but included as the dwell time for the BMH buffer
CNC adjustments on Windowmaster or Conturex 2	Include	Important value-adding activity
Filling the pre-assembly carts	Include	Activity that determines the production speed of the CNC machines
Preparing cavity battens for the pre-assembly department	Exclude	Not the main focus
Preparing glazing beads for the placement of glass	Exclude	Not the main focus
Pre-assembly line in its entirety	Include	The pre-assembly in its entirety is important in the production line
Quality control and unloading at the pre-assembly line	Exclude	The specific activities within the pre-assembly are not the main focus

Applying glue at the pre-assembly line	Exclude	The specific activities within the pre-assembly are not the main focus
Confinement bench at the pre-assembly line	Exclude	The specific activities within the pre-assembly are not the main focus
Workstation 1 pre-assembly line	Exclude	The specific activities within the pre-assembly are not the main focus
Workstation 2 pre-assembly line	Exclude	The specific activities within the pre-assembly are not the main focus
Workstation 3 pre-assembly line	Exclude	The specific activities within the pre-assembly are not the main focus
Workstation 4 pre-assembly line	Exclude	The specific activities within the pre-assembly are not the main focus
Pre-assembly station for doors and windows	Include	Important value-adding activity for the production of the doors and windows
Painting at paint robots	Include	Important value-adding activity
Manual painting	Include	Important value-adding activity and used for decisions made on the organisation of the production line
Offloading of the frames after painting	Include	Necessary activity performed at the painting department
Sorting centre department for the necessary supplies	Exclude	Not the main focus of this research
Finishing assembly station for rotating parts	Include	Important value-adding activity that is necessary in the production process
Finishing assembly line 1	Include	Important for the organizational decisions made at the finishing assembly department
Finishing assembly line 2	Include	Important for the organizational decisions made at the finishing assembly department
Finishing assembly line 3	Include	Important for the organizational decisions made at the finishing assembly department
Finishing assembly line 4	Include	Important for the organizational decisions made at the finishing assembly department
Independent workstations on the finishing assembly lines	Exclude	The specific activities within the pre-assembly are not the main focus
Transportation	Exclude	Not the main focus and excluded within the measured throughput time
Queues		
Production batch/order queue at the “Kortlijn”	Include	Each day several production batches/orders arrive at the factory according to the production planning, but these cannot be produced all at the same time
BMH buffer platforms	Include	The buffer is used for the sorting of four different production batches that are combined at the “Kortlijn”, but also used as a buffer for the difference in production capacity between the “Kortlijn” and BMH Windowmaster
Conturex buffer	Include	The buffer used for the difference in production capacity between the “Kortlijn” and Conturex 2
Pre-assembly buffer	Include	Buffer used between the machinery department and pre-assembly department due to the difference in shifts
Buffer after pre-assembly	Include	Buffer space for the paint robot
Drying buffer after paint robots	Include	Important for the mandatory drying time after applying the first layer of paint
Drying buffer after manual painting station	Include	Important for the mandatory drying time before offloading
Drying buffer after offloading	Include	Important buffer used for the mandatory drying time of the paint from the paint supplier
Queue for finishing assembly of rotating parts	Exclude	The entities will remain in the drying buffer
Finishing assembly buffer	Include	Important buffer used for the finishing assembly and to sort the different production entities to the different lines

Table 3 - Scope of the conceptual and simulation model

Given the included components for the conceptual model in *Table 3*, we made general overview of the conceptual model including all the production processes and queues. For this overview, we used a flowchart model that describes the logic flow of the conceptual model. This logic flow diagram can be seen in *Figure 3* and in more detail in *Appendix G*.

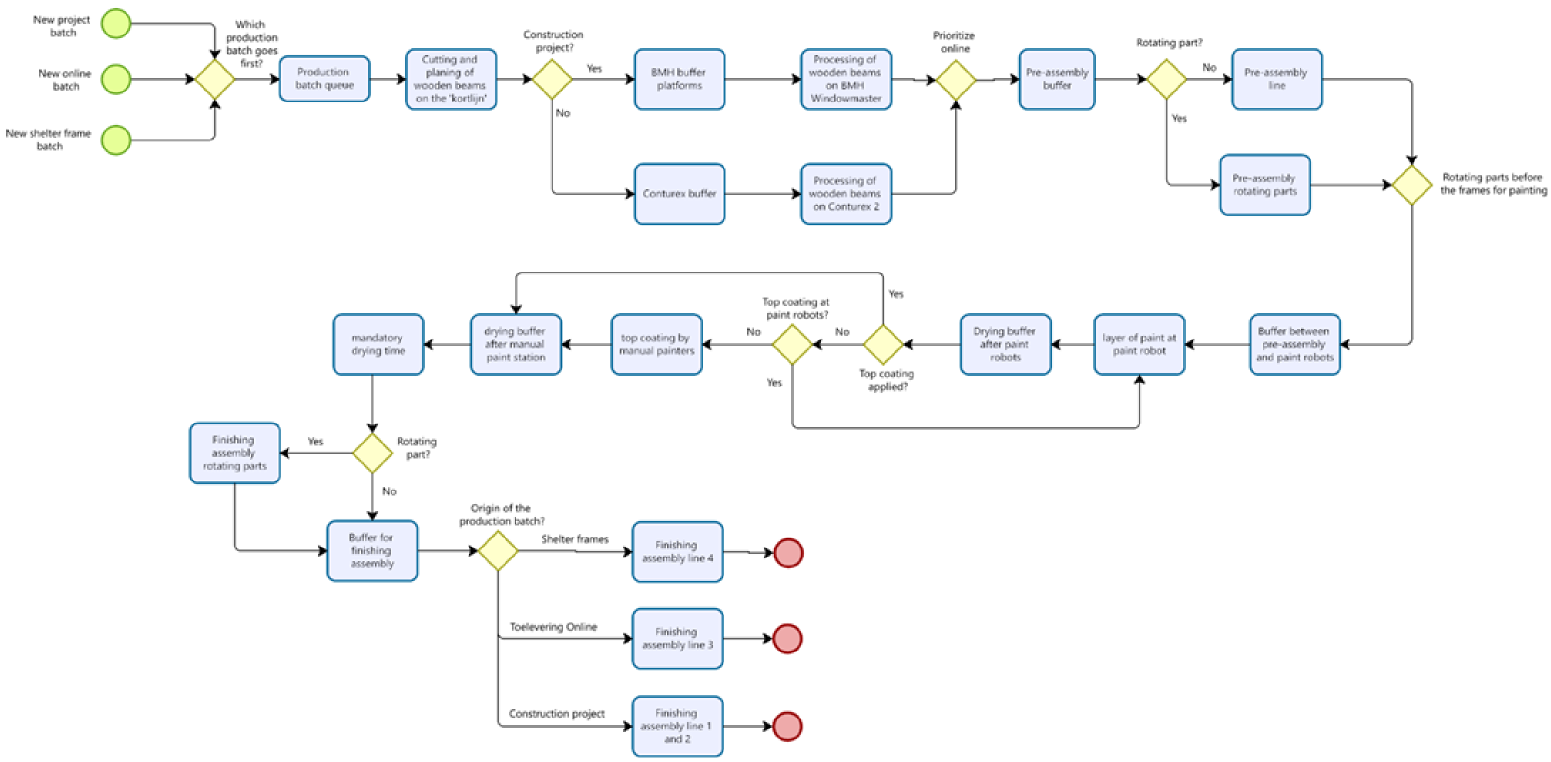

Figure 3 - Conceptual model of the production line at Nijhuis Toelevering B.V.

5.1.3. Simplifications and Assumptions

As already can be recognized when comparing the scope of the model in Section 5.1.2. and the description of the current production process in Section 2.1., there are several assumptions and simplifications necessary to the real-world scenario to build a representative simulation model in accordance with the conceptual model. According to Robinson are “assumptions made either where there are uncertainties or beliefs about the real world being modelled and therefore the assumptions are used to fill the knowledge gaps in the real world system.” (Robinson, 2004). There are also the simplifications which, according to Robinson, are choices that are made to reduce the complexity of the model and enable a more rapid model development and use of the simulation model (Robinson, 2004).

For the simulation model the following assumptions had to be made:

Assumption 1: The products of each production batch, such as frames, doors and windows, are produced consecutively before the next production batch is started.

Assumption 2: The first production batch that enters the BMH or Conturex buffer is also the first to start on the CNC process.

Assumption 3: The BMH Windowmasters are expected to each process 30 wooden elements per hour, so the total production capacity of the BMH Windowmasters is 60 elements per hour.

Assumption 4: There are no mistakes made at the work preparation department in terms of technical drawings and ordering the right supplies

Next to the assumptions, the following simplifications had to be made:

Simplification 1: All the activities starting from the loading platforms at the BMH Loadmaster until the BMH Sortingmaster 8200 are merged into one activity called "Kortlijn".

Simplification 2: All the working activities, including working stations, of the pre-assembly line are combined into one activity called "pre-assembly line"

Simplification 3: All the working activities at the pre-assembly of rotating parts are combined into one activity called "pre-assembly rotating parts"

Simplification 4: All the working activities on each finishing assembly line are combined into their representative activity that represents the four finishing assembly lines.

5.2. Data analysis

Now that we defined the conceptual model, we can search for the specific data needed for the simulation model to be able to run. This means that there are several data inputs needed from the production line about the performance of individual working stations, but also the arrivals of production batches and batch sizes. In Section 5.2.1., we will discuss the arrival rates of the different production batches and their size using statistical analysis. After which, we will continue with the processing times of the individual working stations in Section 5.2.2. To make sure the collected data is reliable and valid, we will use three different data collection methods: interviews with production supervisors/managers, observations on the production line, and data from the company's database. The main input for the data will be the database, but the interviews and observations are also used as validation and to support the database were necessary if there is a lack of data. A detailed table with all the collected data and the source it originates from can be found in *Appendix H*.

5.2.1. Arrival Rates

At the production line, the arrival of production batches is managed through production planning and is also dependent on the sales made by the sales department. However, for the sake of simplicity for the simulation model, there are a few parameters that will be used for the input data of the batch arrivals and batch sizes according to historical data of the production batches that were produced in 2023 and 2024. The data from 2023 is used since some of the data in 2024 has a bias due to the ongoing transition in the production process and the managerial challenges.
First, we will look into the amount of production batches that arrive at the production line each day. During interviews held with the production manager and with other stakeholders it became clear that there is a lot of variation in the exact amount of production batches per day, because it is dependent on the batch size, delivery dates, and also the amount of online orders received each day. However, it became clear in the interviews that 60 % of the frames produced originate from construction projects, 30% from online orders and 10 % from shelters. This is also in line with the data analysis performed on the production data from 2023 that showed a distribution of 55 % construction projects, 31 % online orders, and 14 % shelters based on the total frames produced of 23 768 in 225 working days. When looking at what this means for the number of project batches for each day, we first need to analyse the average batch size for each product type. However, it has to be noted that according to the interviews, there are on average 2-3 project batches, 0-4 online orders, and 1 shelter batch per day.

For the batch size of the three different origins and their distribution of frames, doors and windows we looked at the production planning of 2023 and 2024 in the company's database that contains an Excel sheet with all the information of each production batch such as the number of frames, doors, and windows. From the collected data are the following parameters for the frames, doors, and windows in a production batch calculated using statistical formulas in Excel: mean, standard deviation, minimum and maximum. The outcomes of these statistical analyses can be found in *Table 4.*

Distributions of production batches		**Average**	**Standard deviation**	**Min**	**Max**
Number of frames in construction projects		33	13	1	57
Number of doors in construction projects		5	5	1	21
Number of windows in construction projects		19	12	1	58
Number of frames in online		18	6	2	33
Number of doors in online		7	4	1	18
Number of windows in online		10	6	1	42
Number of frames in shelter batches		11	5	1	25
Number of doors in shelter batches		11	5	1	25
Number of windows in shelter batches		0	0	0	0

Table 4 - Distribution of production batches

After that, the data is analysed using histograms to check whether or not we can assume a normal distribution for the input parameters. These histograms can be found in *Appendix I* and as can been seen we can assume the normal distribution for all the input parameters displayed in *Table 4* , except for the number of doors in online and construction projects, and the number of shelter frames per batch. For these input parameters we will assume a negative exponential distribution. For the arrival rates the decision was made not to apply a Chi-square normality test, since the data sets consisted of to many outliers that resulted in a rejection of the normal distribution even though the histogram showed us a normal distribution. Therefore, the assumption on normality is based only on the histograms for the arrival rates.
To conclude on the arrival rates of production batches per day, we can calculate that on average there will arrive 2-3 construction project batches, 1-2 online order batches and 1 shelter frame batch per day.

5.2.2. Processing Times

In this section, we will analyse the processing times of the included production processes of the production line. However, as already mentioned in Section 4.2.3. are the throughput times of the independent production processes not measured throughout the production line. Nevertheless, the company keeps track of its performance using a Key Performance Indicator (KPI) document for each year with the production numbers per day. For the analysis, we will use the production data in the KPI document to calculate the distribution and input parameters to be able to calculate the estimates of the processing times for each production process.

When looking at the conceptual model that is defined in Section 5.1., it can be concluded that for the following production processes we need to analyse the processing times: the "Kortlijn", BMH Windowmaster, Conturex 2, loading the wooden elements in the carts, the pre-assembly

line, pre-assembly station for rotating parts, the paint robots, the manual painting station, loading the frames off the paint rails, finishing assembly of rotating parts, and the four finishing assembly lines.
For all these production processes a statistical analysis is performed using descriptive statistics on the mean, standard error, median, mode, standard deviation, sample variance, skewness, range, minimum, maximum, and count. To simplify these descriptive statistics we will only be looking at the Mean, Standard deviation, skewness, minimum, maximum, and count, because these are important for the input parameters of the working stations and needed to perform a goodness of fit test. The descriptive statistical analysis and normality test will be showcased using the example of finishing assembly line 1 to showcase the method used.

For the statistical analysis, the production data 2024 is used from the Excel file “KPI 2024”. This data set consisted of 99 production days that are used for the data set. It has to be noted that the data set represents the number of frames produced per day and not the cycle time. Therefore, we will analyse and test the distribution using the number of frames produced per day and after determining the distribution make use of a formula to calculate the cycle time distribution. First, the descriptive statistics of the data set are calculated of which especially the mean, standard deviation, and skewness are important to check whether or not the data set can be assumed to follow a normal distribution. These results can be found in *Table 5.* Furthermore, that is also where the histogram analysis is made for the histogram showcased in *Figure 4.* After that we made use of the Cumulative Distribution Function (CDF) and the Chi-Square test for testing the data sets on the normal distribution. The chi-square test value is based on 0,05 degrees of freedom. If the total error value is smaller than the chi-square test value, we can assume that the data set follows a normal distribution. For the example of finishing assembly line, it is also proven that the data set follows a normal distribution and therefore we will use a normal distribution for the processing time on finishing assembly line 1.

	Lijn 1		**Normal distribution**			
	Mean	32,05051				
	Standard Error	0,640065				
	Median	33				
	Mode	34				
	Standard Deviation	6,368567				
	Sample Variance	40,55865				
	Kurtosis	1,055658				
	Skewness	-0,01198				
	Range	39				
	Minimum	15				
	Maximum	54				
	Sum	3173				
	Count	99				
	Confidence Level(95,(	1,270188				
	BinWidth	3,919647				
	#NumBins	9,949874				
		Bin	*Frequency*	CDF	ExpFre	Error
1	19	19	3	0,020220995	2,001879	0,497656
2	23	23	7	0,077640781	5,684559	0,304401
3	27	27	10	0,213878332	13,48752	0,90178
4	31	31	21	0,434491057	21,84066	0,032357
5	35	35	32	0,678365556	24,14358	2,556515
6	39	39	17	0,862411509	18,22055	0,081762
7	43	43	6	0,957220369	9,386077	1,221545
8	47	47	2	0,990547209	3,299357	0,511715
9	51	51	0	0,998537311	0,79102	0,79102
10	55	55	1	0,999843054	0,129269	5,865101
					Error	12,76385
					Test	16,91898

Table 5 - Statistical analysis on finishing assembly line 1

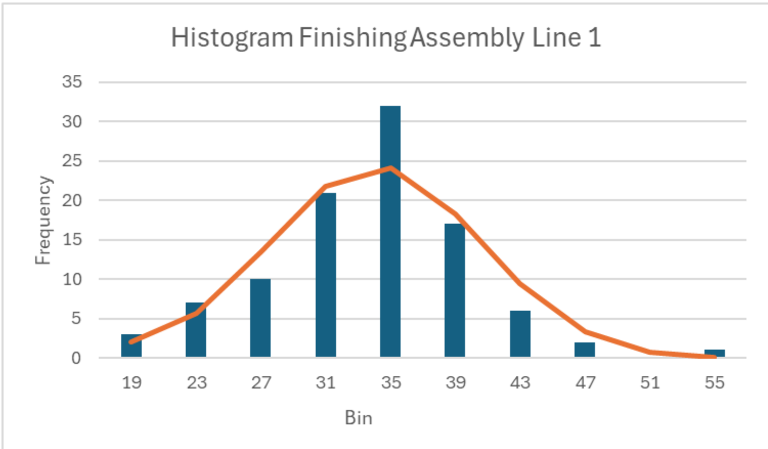

Figure 4 - Histogram finishing assembly line 1

According to the performed statistical analysis, we can conclude this section with a summary of the processing times for each production process. This summary is displayed in *Table 6.*

Production process	Mean	Standard deviation	Minimum	Maximum	Distributio n
Kortlijn	Frame: 3,2 min Door: 5,75 min Window: 2,5 min	N/A	N/A	N/A	Constant
BMH Windowmaster	Frame: 13 min Door: 18 min Window: 8 min	N/A	N/A	N/A	Constant
Conturex 2	Frame: 10 min Door: 18 min Window: 8 min	N/A	N/A	N/A	Constant
Pre-assembly line	4,6 min	3,9 min	3,3 min	8,9 min	Normal
Pre-assembly rotating parts	5,5 min	4,2 min	2,9 min	19,2 min	Normal
Paint robots	Frame: 7 min Door: 5 min Window: 4 min	N/A	N/A	N/A	Constant
Manual painting station	Frame: 6 min Door: 4 min Window: 3 min	N/A	N/A	N/A	Constant
Offloading from painting rails	2 min	N/A	N/A	N/A	Constant
Finishing assembly rotating parts	6,2 min	4,9 min	3,4 min	19,2 min	Normal
Finishing assembly line 1	15 min	2,5 min	8,9 min	32 min	Normal
Finishing assembly line 2	13,7 min	2,7 min	8,7 min	32 min	Normal
Finishing assembly line 3	15,5 min	3 min	11,7 min	120 min	Normal
Finishing assembly line 4	31,4 min	7,9 min	13,7 min	120 min	Gamma or Poisson

Table 6 - Processing times

From *Table 6* it also can be noted that not for all production processes there is a distribution used with a standard deviation, minimum, and maximum. For example, at the machinery department the decision is made to use a constant cycle time, since the margins in the processing time are too small to have a real impact on the throughput time. Furthermore, the machines are processing wooden beams and wooden elements, while the simulation makes use of frames, doors and windows as a whole. This simplification made it more convenient to work with formulas to calculate the cycle time for a frame using the average processing capacity of the machine and the average number of wooden elements per frame. For these calculations, the average number of wooden elements per frame, door and window is: 5 elements per frame, 9 elements per door, and 4 elements per window. After analysing the machines from BMH we also concluded that the BMH Windowmaster (WM) can on average 20-30 elements per hour per machine which is also dependent on the difficulty of the adjustments that have to be made. For example, for a frame we used the following formula to get to 15 minutes of Cycle time:

$$Cycle\ time = \frac{elements\ per\ product}{production\ capacity\ per\ WM\ per\ hour} * 60\ \mathrm{min} = \frac{5}{20} * 60\ min = 15\ min.$$

6. Simulation Model

In this chapter, sub-research question 5: "*How does the simulation model has to look like for the research at Nijhuis Toelevering B.V.?"* will be answered. We will start with an explanation of the simulation model in Section 6.1. after which we will continue to the verification of the simulation model in Section 6.2.

6.1. Simulation Model Explanation

In this section, it will be explained how we implemented the conceptual model into a working simulation model in Siemens Tecnomatix Plant Simulation. For the simulation model, we used the software of Siemens Tecnomatix Plant Simulation 16.1 with a license from the University of Twente. With Plant Simulation we are able to model, simulate, visualize and analyse the production line to optimize material flow and resource utilization (Siemens, 2024). Following from the conceptual model in *Appendix G*, we created the following simulation which is showcased in *Figure 5.*

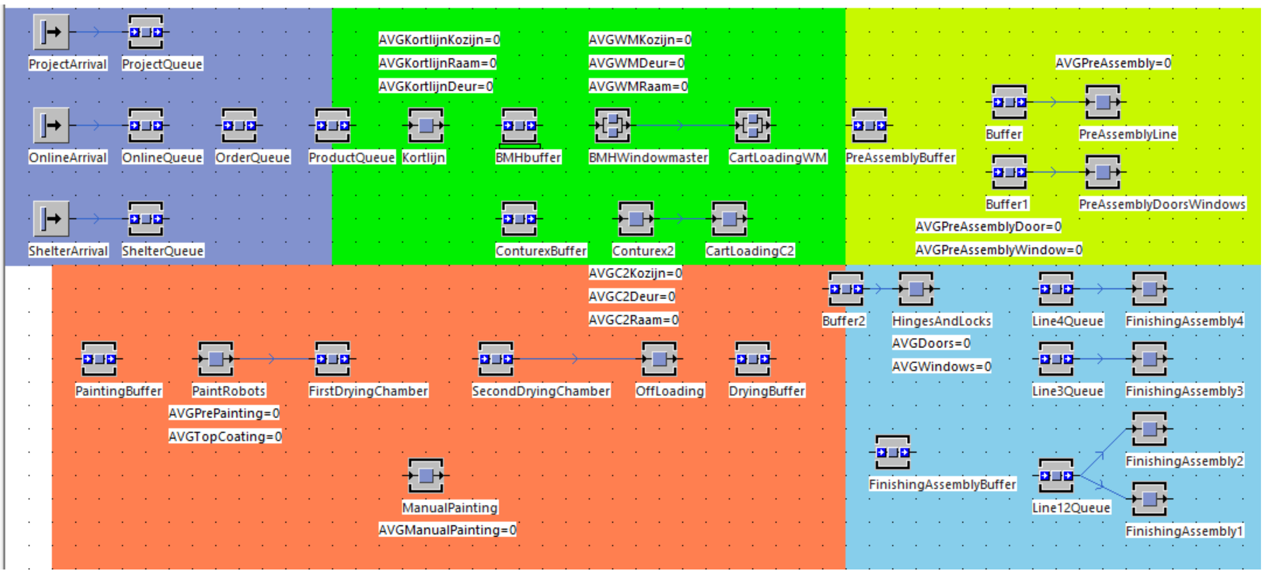

Figure 5 - Production flow of the simulation model

As can be seen in *Figure 5*, we made each department of the production line a different colour to keep the simulation model well organised. In the simulation model we defined the planning and order arrival as dark blue, the machinery department as green, the pre-assembly department as yellow, the painting department as red and the finishing assembly as light blue. For the simulation model, there are 5 different kinds of material flow objects used which represent the production processes, buffers and queues in the real-world scenario. Those different kinds of material flow objects are (Siemens, 2024):

- Source: the arrival of moving units (MUs), in this case production batches, are created here.
- Station: a processing station that can represent a production process in the production line such as the CNC adjustments made or painting.
- ParallelStation: a processing station that can process multiple MUs at once, that is used for the representation of the two Windowmasters
- Buffer: the buffer object has the purpose of holding MUs before they can enter a station or the next buffer object. In the production line of Nijhuis Toelevering are the buffer objects for example used for the BMH Buffer platforms, the buffer carts, and the drying rooms.

- **Drain**: the drains removes MUs when they are finished with the production system which happens in this simulation model when the MUs are finished on the finishing assembly line and then ready for transport.

Besides the material flow objects, there are also multiple methods used with SimTalk coding to make sure there is continuous production flow within the simulation model that represents the production flow of the production line at Nijhuis Toelevering. In *Figure 6* are all the used methods displayed from the simulation model and in *Appendix J* are for the most important methods a logic flow chart created to showcase the implemented logic.

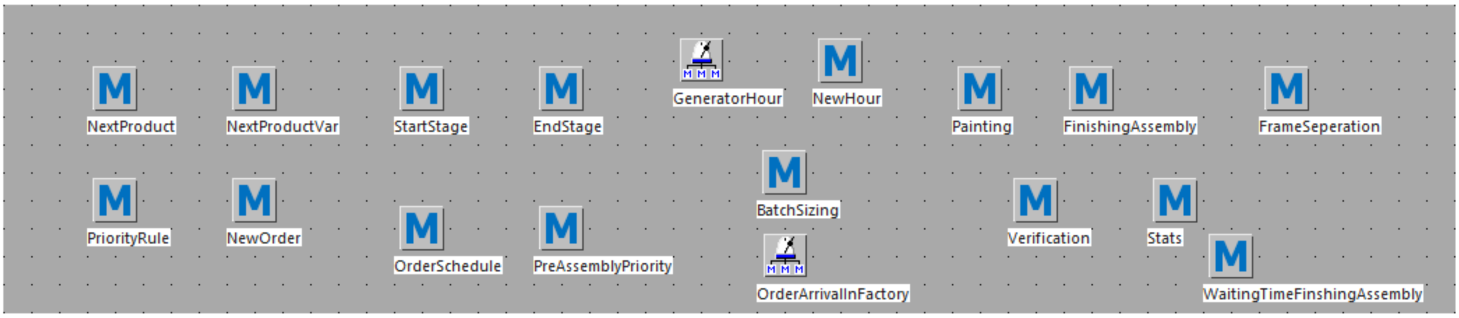

Figure 6 - methods and generators used in the simulation model

As previously described in Section 5.1.1. there are multiple input and output variables used within the simulation model. For the input variables we use DataTables for an organized overview and to make it more convenient to experiment with the simulation model. The most important input variables that can be found in the tables shown in *Figure 7* are: the cycle Times of the production processes, the number of production batches per day for the different types of production orders, and the distributions for the batch sizes in terms of number of frames, doors and windows per production batch.

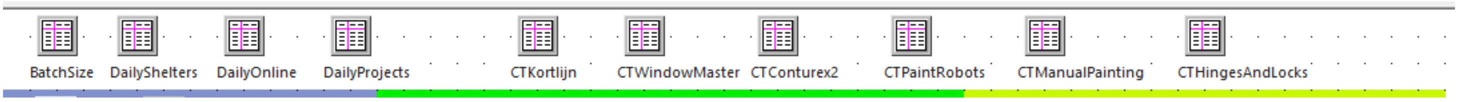

Figure 7 - DataTables with input variables

Furthermore, we also made use of the so-called "Shift Callendar" in Plant Simulation to make sure that the production processes in the production line are only operative according to the available time that aligns with the shifts that are used for the different departments. These shift calendars can also be seen in *Figure 8.* The other input data tables, are filled with the data that is found during the statistical analysis in Chapter 5.

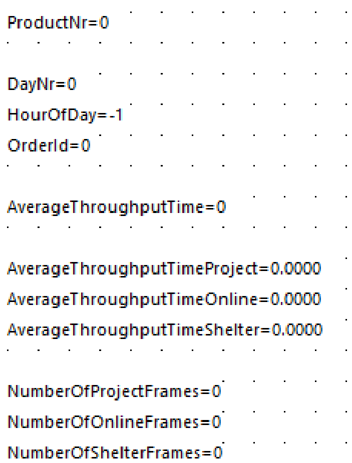

Figure 9 - Output data variables

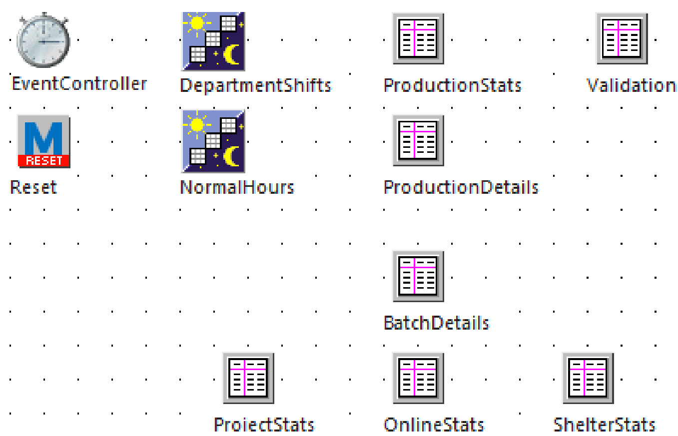

Figure 8 - Shift Calendars and DataTables for output data

Besides the input data, there are also output variables, Data Tables and final output indicators used within the simulation model. As discussed in Section 5.1.1. and following from the main research question, the most important output data for this research project is the throughput time of the production batches on the production line. Therefore, the three main output variables used in the simulation model are: AverageThroughputTimeProject, AverageThroughputTimeOnline, and AverageThroughputTimeShelter that represent the average throughput times for one frame of the different types of frames. Furthermore, the amount of frames produced is also important to keep track of the total production each year and to prevent a reduction in throughput time that also results in the production of fewer frames per year. Within the simulation model, there is also output data of each independent production batch and product within the simulation model of the production line that are displayed in *Figure 9*. These tables also keep track of the perceived waiting times for each production batch throughout the production line. From all these collected output data are also the averages calculated per production batch type and stored in the table “Validation”.

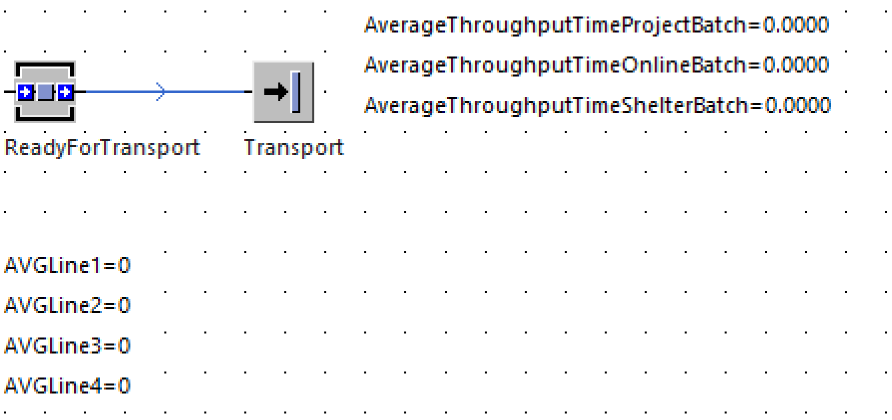

Figure 10 - throughput time output data

As a final calculation for the throughput time per production batch on average there are three output variables shown in the simulation as showcased in *Figure 10* and as can been seen in *Figure 5* the average production rates for each production process are also calculated.

6.2. Simulation Model Verification and Validation

After implementing the conceptual model into the simulation model with all the corresponding data and necessary coding, we could start testing the simulation model whether or not the simulation model also represents the current situation of the production line at Nijhuis Toelevering. The book of Robinson prescribes several methods to be able to verify and validate the simulation model, but for this research project we choose to use: verification, and black box validation. According to Robinson: “verification ensures that the content of the model is true to the real to the conceptual model, which implies that verification can be performed by the modeler alone” (Robinson, 2004). Therefore, for the verification of the simulation model we will only consider the production flow of the simulation model and if all the activities that are defined in the conceptual model are present and working properly in the simulation model. *Figure 5* in Section 6.1. shows the implementation of the conceptual model into the simulation model in terms of the production processes, it can be concluded after testing the simulation model several times, discussing the simulation flow with the production supervisors and comparing it with the initiated logic from the conceptual model in *Appendix G* the simulation can be considered as verified. In the simulation model are all the necessary production processes, which are defined in the conceptual model, present and working according to the pre-defined production flow. Although there are some differences within the production flows of the real-world production, the simulation model can still be considered as a well enough representation of the real-world production line for the research aim.

Since the simulation now is verified we can continue with the black-box validation to make sure the simulation model is also a valid representation of the real-world production line within the pre-defined assumptions and limitations of the simulation model. According to Robinson is Black-Box Validation used for determining that the overall simulation model represents the real world with sufficient accuracy for the purpose at hand and therefore can be considered as a macro validation check of the simulation model (Robinson, 2004).
For the validation part, we will start with the black-box validation check, since this is the most important for the proposed research project which mainly focuses on the general performance of the production line. For the Black-Box validation, we will be looking at the average throughput time of a production batch for the three different types of production batches and at the total number of frames produced for each different type of production batch which will add up to the total number of frames produced on the production line. For this validation test, we will use an effective run time of 112 working days which will make it more compatible with the comparable data of the real-world production line.
For the black-box validation, we let the simulation model run for 5 replications, that are set for each replication at a runtime of 112 working days, to make sure the output data is reliable. Furthermore, a warmup period of 5 days will be used to make sure the production line is filled. Given the research aim, the following Key Performance Indicators (KPIs) will be used for the output of the simulation model:

1. Average throughput time of a construction project batch
2. Average throughput time of an online batch
3. Average throughput time of a shelter frame batch
4. Number of construction project frames produced in a year
5. Number of online frames produced in a year
6. Number of shelter frames produced in a year
7. Total number of frames produced in a year

The results of the KPI's from the replications are showcased in *Table 7,* where the output data for the throughput time is displayed in the following format "Days: Hours: Minutes: Seconds".

Output variable	Mean	Standard deviation	Minimum	Maximum
Throughput time project batch	5:03:11:08	00:16:15:36	4:04:11:26	5:23:48:44
Throughput time Online batch	3:13:07:30	00:06:02:00	3:07:08:50	3:19:36:53
Throughput time Shelter batch	5:00:18:47	00:10:11:06	4:08:43:30	5:10:56:33
Number of project frames	14409	276,69	13967	14650
Number of online frames	6436,2	180,87	6266	6694
Number of Shelter frames	2407,8	41,73	2356	2459
Total number of frames	23253	332,16	22680	23546

Table 7 - Black-Box Validation output data

Now that the simulation output is known, there has to be made a comparison with the actual data on the throughput time measured on the production line of Nijhuis Toelevering. Although the measured throughput time on the production has a bias due to the measurement method chosen where the throughput time is measured on a weekly basis on Wednesdays, it can be considered after multiple interviews, observations and available data from one week of more accurately measured throughput times on the production line that the simulation model provides a valid output of the real world production at Nijhuis Toelevering given the taken assumption and simplification. The production line currently produces a project batch in 5 to 6 working days and are planned according to a throughput time of 5 working days. Therefore, we can conclude that the throughput time in the simulation is an accurate enough representation of the current situation with a mean of 5 working days and an interval of 4 to 5,5 working days. To continue with the online batches that are currently planned according to a throughput time of 3 working days, but it has to be noted that in the current situation it often occurs that the throughput time for the online batches takes one or even two more days which means that the throughput time for the online batches will become 4 or even 5 days. Therefore, we will consider the actual throughput time for an online batch at the production batch on average 4 working days with an interval of 3 to 5 working days. Then looking at the throughput time of an online batch in the simulation model where the average throughput time of an online batch is 3,5 working days and the interval is 3 to 4 working days, we can also consider this output as valid. At last, there are the shelter frame batches, that are currently being planned on a throughput time of 5 working days. However, there is a lot of variation in the throughput times of the shelter frame batches due to high variation in batch size and the shelter frames are given less priority within the production line. However, when analysing the actual throughput time of the shelter frame batches we came to the conclusion that it is reasonable to say that they are produced within 5 working days in normal conditions with an interval of 4 to 7 working days. Therefore, we compare the actual throughput time of the shelter batches with the given output data of the simulation model we can also consider the shelter batch throughput time as valid, since the simulation model gives a mean throughput time of 5 working days with an interval of 4 to 5,5 working days.

The last factor we want to validate from the simulation model is the amount of frames produced on the production and the given distribution of the different types of frames, since for the purpose of this research project it is important that the simulation model produces roughly the same amount of frames per year to validate the actual production conditions the production line currently deals with. Therefore we compared the production data on the number of frames produced in the year 2023 with the given output of the simulation model. According to the production data from 2023, there were 23768 frames produced on the production line of which 13018 project frames, 7423 online frames, and 3327 shelter frames. This provides us with a distribution of the number of frames that is calculated at 55 % project frames, 31 % online frames and 14 % shelter frames. From the output data of the simulation model in *Table 7*, we can notice that on average the simulation model produces in an entire year 23253 frames consisting of: 14409 project frames, 6436 online frames and 2408 frames. This means that the simulation model has a distribution of the different types of frames that is calculated at: 62 % project frames, 27,7 % online frames, and 10,3 % shelter frames. Although there is a small difference in the distribution of the frames between the production line and the simulation model, we can consider the simulation model as a valid distribution of the frames. This, since the company also wants to approach the following distribution of frames produced on the production line: 60 % project frames, 30 % online frames, and 10 % shelter frames.

7. Experimentation

In this chapter, sub-research question 6: "*What will be the experimental design of the frame production line at Nijhuis Toelevering B.V. for reducing the throughput time?" and* sub-research question 7: "*Which organizational configurations will optimize the throughput time of the frame production line at Nijhuis Toelevering B.V.?"* will be answered. In Section 7.1. the objectives of the experiment will be explained with the experimental design. After that, the experiments will be explained in Section 7.2. and we will continue with an analysis on the output results of the experiments in Section 7.3. Last of all, in Section 7.4. we will combine the best interventions of Section 7.3. to be able to provide insights into the total reduction of throughput time.

7.1. Experiments

As discussed in Chapter 4, there are several wastes and bottlenecks present in the current production line of Nijhuis Toelevering that prevent them from achieving their desired throughput time of 3 working days for all batch types. However, for this research thesis, we decided to experiment with the four bottlenecks/wastes that have the biggest impact right now according to the performance analysis. From the performance analysis of the production in Chapter 4, it became clear that the following factors have the most impact on the throughput time at the production line:

1. Batch size of the construction project batches
2. Capacity of the pre-assembly line for the frames
3. Organisational decision on where to apply the top coating
4. The takt time and capacity of finishing assembly line 4

Given these 4 factors, we will use 5 scenarios in which we will make interventions based on a sensitivity analysis method. Sensitivity analysis is a technique to study how various interventions in a mathematical model contribute to the outcome of the scenario. The decision for these 4 scenarios is chosen based on the waste and bottleneck identification of Chapter 3, where it became clear that batch size of construction is one of the main disruptions in the production line that causes high waiting times. Furthermore, are scenarios 2 and 4 based on the bottleneck analyses of the production capacities and cycle times using the Value Stream Maps. Last of all, scenario 3 follows from the intern questions raised on the decision-making in the painting department.

7.2. Experimental design

In this section, we will discuss the experimental design of the four scenarios explained in Section 7.1. The experimental design consists of the runtime, warm-up period, number of replications, and the interventions made for each scenario. We will start with the general settings that are the same for each scenario. The runtime is set for half a production year, to be able to analyse the output results over a longer period. Half a production year at the production of Nijhuis Toelevering is 112 working days, that means with the given warm-up period from Section 6.2 the total runtime is set to 117 working days. Now we can turn to the number of replications used for each experimental observation, that is set at 5 replications. This means that for each intervention within a scenario, the simulation model will simulate 5 times the runtime of 117 working days to have reliable output data. With the given general settings for the experiments, we can turn to the experimental design of the interventions with each scenario.

For the first scenario with the batch size, we will experiment with 2 input parameters of the batch size for the construction project batches. These input parameters are the maximum number of the batch and the mean of the batch size. For the experimental runs in the simulations, we make use of a percental decrease on the maximum for the batch size and continue with a percental decrease on the mean of the batch size. The input parameters for the interventions in the first scenario can be found in *Table 8* The input parameters for the number of batches are determined by testing the simulation model with several settings and adjusting these variables to maintain an equal production workload.

Scenario 1 – batch size of construction project batches	Mean # Frames Project batch	Maximum # frames project batch	Mean number of project batches	Minimum number of project batches	Maximum number of project batches
Experiment 1.1	33	57	2,4	1	4
Experiment 1.2	33	51	2,4	1	4
Experiment 1.3	33	46	2,4	1	4
Experiment 1.4	33	40	2,4	2	4
Experiment 1.5	33	34	3,4	1	4
Experiment 1.6	30	34	3,4	1	4
Experiment 1.7	26	34	3,4	2	4
Experiment 1.8	23	34	3,4	2	5
Experiment 1.9	20	34	3,4	3	5
Experiment 1.10	17	34	4,4	3	5
Experiment 1.11	13	34	4,4	3	6
Experiment 1.12	10	34	5,4	4	7

Table 8 - Experimental design scenario 1 of decreasing batch size for construction project batches

For the second scenario with the pre-assembly line, we will experiment with 2 input parameters of the pre-assembly department. These input parameters are the number of pre-assembly lines and the takt time of the pre-assembly line(s). The takt time refers to the rate of output from the last workstation of the pre-assembly line or in other words the time in between a single unit is completed (Tiwari & Jana, 2023). The input parameters for the interventions made in the second scenario can be found in *Table 9*.

Scenario 2 – pre-assembly line	Number of pre-assembly lines	Takt time pre-assembly line 1 (mm:ss)	Takt time pre-assembly line 2 (mm:ss)
Experiment 2.1	1	04:22	N/A
Experiment 2.2	1	04:10	N/A
Experiment 2.3	1	03:50	N/A
Experiment 2.4	1	03:41	N/A
Experiment 2.5	1	03:34	N/A
Experiment 2.6	1	03:26	N/A
Experiment 2.7	1	03:20	N/A
Experiment 2.8	2	06:00	08:00
Experiment 2.9	2	06:00	08:00
Experiment 2.10	2	04:48	06:00
Experiment 2.11	2	04:48	06:00

Table 9 - Experimental design scenario 2

For the third scenario with the organisational decision of the top coating, we will experiment with 1 input parameter of the painting. This input parameter is the working time of the manual painting station within the painting department. This includes the start and end times of when the frames will be painted with a top coating at the manual painting station. The input parameters for the interventions made in the third scenario can be found in *Table 10*.

Scenario 3 – working time manual painting station	Start time top coating by hand (hh:mm)	End time top coating by hand (hh:mm)
Experiment 3.1	06:00	16:00
Experiment 3.2	05:00	16:00
Experiment 3.3	05:00	17:00
Experiment 3.4	05:00	18:00
Experiment 3.5	05:00	19:00
Experiment 3.6	05:00	20:00
Experiment 3.7	05:00	21:00
Experiment 3.8	05:00	22:00

Table 10 - Experimental design scenario 3

For the fourth scenario with finishing assembly line 4, we will experiment with 2 input parameters of finishing assembly line 4. These input parameters are the takt time and the frame types that are processed on finishing assembly line 4. This means that we will take the takt times of lines 1, 2, and 3 as interventions and the decision made if only shelter frames or also project frames will be processed on finishing assembly line 4. The input parameters for the intervention made in the fourth scenario can be found in *Table 11*.

Scenario 4 – finishing assembly line 4	Takt time finishing assembly line 4 (mm:ss)	Type of frames processed on finishing assembly line 4
Experiment 4.1	14:29	Shelter frames
Experiment 4.2	13:43	Shelter frames
Experiment 4.3	14:59	Shelter frames
Experiment 4.4	14:29	Shelter & project frames
Experiment 4.5	13:43	Shelter & project frames
Experiment 4.6	14:59	Shelter & project frames

Table 11 - Experimental design scenario 4

7.3. Experiment Results

In this section, we will discuss the results of the interventions made with all the scenarios discussed in *Section 7.2.* These results follow from the experimental runs in the simulation model discussed in *Chapter 6.* To visualize the results we make use of 95 % confidence intervals that showcase the results of all the replications per intervention. By using a 95 % confidence interval, we can assume with a 95 % confidence level that the outcome of the intervention lies within that interval. However, we will be mainly looking at the mean of the intervention to compare the impact with the current situation.

After running the first scenario in the simulation model, we ended up with the results of mean throughput time for the different batch types as displayed in *Table 12* As discussed in Section 7.1., experiments 1 until 7 are focussed on the reduction of the maxima for project batches and experiment 8 until 12 are focussed on the reduction of the mean for these project batches.

Scenario 1 – batch size of construction project batches	Mean throughput time project batch (dd:hh:mm:ss)	Mean throughput time online batch (dd:hh:mm:ss)	Mean throughput time shelter batch (dd:hh:mm:ss)
Experiment 1.1	3:23:18:40	3:11:11:29	4:05:44:58
Experiment 1.2	3:18:49:01	3:12:42:29	4:02:43:54
Experiment 1.3	3:15:11:01	3:11:01:05	4:00:40:07
Experiment 1.4	3:12:58:10	3:08:39:15	3:22:45:48
Experiment 1.5	5:11:08:08	4:05:47:01	5:23:27:57
Experiment 1.6	4:01:10:12	3:10:10:13	4:13:55:12
Experiment 1.7	3:13:21:20	3:07:42:08	4:01:21:28
Experiment 1.8	3:14:11:38	3:10:48:23	4:02:44:59
Experiment 1.9	3:14:03:29	3:09:45:12	4:02:17:13
Experiment 1.10	6:16:16:31	5:06:48:50	7:06:19:04
Experiment 1.11	4:20:00:47	3:20:08:02	5:10:46:43
Experiment 1.12	11:12:11:32	9:21:08:18	12:04:27:59

Table 12 - Output data scenario 1

From the results in *Table 12*, we can conclude from scenario 1 that the interventions made in experiments 4 and 7 reduce the throughput time the most for project batches. However, when looking at the other two batch types, we can conclude that the interventions made in experiment 7 create the most reduction on all batch types. The interventions in experiment 7 are a batch maximum of 34 frames and a mean number of frames of 26.

For the second scenario with the pre-assembly line, we got the results as shown in *Table 13*. From the results, we can conclude that reducing the takt time of the currently used pre-assembly line to the lowest time possible with the current design will not provide a high reduction in throughput time for the different batch types. However, when a second pre-assembly line is added to the production system with both a relatively lower takt time, due to design and available employees, there is a significant reduction in throughput time for all batch types. After analysing the results of each experiment with its intervention, we concluded that experiments 10 and 11 are the best interventions to make for scenario 2 with the pre-assembly line. This means that the best outcome will be realized on the production line by using two pre-assembly lines with a takt time of 6 minutes for pre-assembly line 1 and 8 minutes for pre-assembly line 2.

Scenario 2 – pre-assembly line	Mean throughput time project batch (dd:hh:mm:ss)	Mean throughput time online batch (dd:hh:mm:ss)	Mean throughput time shelter batch (dd:hh:mm:ss)
Experiment 2.1	4:00:23:53	3:13:10:41	4:07:43:15
Experiment 2.2	3:23:22:29	3:11:37:25	4:05:43:50
Experiment 2.3	3:22:51:19	3:10:22:36	4:04:10:41
Experiment 2.4	3:22:41:11	3:10:08:44	4:03:50:01
Experiment 2.5	3:22:51:38	3:10:05:20	4:03:35:46
Experiment 2.6	3:22:47:33	3:10:05:43	4:03:29:29
Experiment 2.7	3:22:37:05	3:09:58:57	4:03:16:28
Experiment 2.8	3:20:09:32	3:06:50:52	4:01:04:22
Experiment 2.9	3:19:51:04	3:06:56:34	4:00:52:34
Experiment 2.10	3:19:54:51	3:06:40:55	4:00:36:51
Experiment 2.11	3:19:57:20	3:06:29:05	4:00:36:37

Table 13 - Output data scenario 2

In *Table 14* are the results of scenario 3 shown, with the 8 interventions made on the working time of the manual painting station that determines where the top coating will be applied during that time. This means that during the time the manual painting station is working, all the frames, doors, and windows will be top-coated at the manual painting station. From the results in *Table 14,* we can conclude that extending the working time of the manual painting station has almost no influence on the throughput time for the project and online batches. However, we can notice that extending the working time has a small influence on the shelter batches, but this is only a small reduction of the total throughput time for a shelter batch. This reduction for only the shelter batches mainly originates from the decision in the production system to give shelter batches the lowest priority which causes the effect that those will processed the latest on the production line.

Scenario 3 – working time manual painting station	Mean throughput time project batch (dd:hh:mm:ss)	Mean throughput time online batch (dd:hh:mm:ss)	Mean throughput time shelter batch (dd:hh:mm:ss)
Experiment 3.1	3:22:56:45	3:10:44:41	4:04:36:42
Experiment 3.2	3:22:57:35	3:10:49:20	4:04:38:00
Experiment 3.3	3:23:01:56	3:10:51:27	4:04:22:13
Experiment 3.4	3:23:06:41	3:10:48:31	4:04:17:25
Experiment 3.5	3:23:08:13	3:10:51:41	4:04:10:00
Experiment 3.6	3:23:08:21	3:10:50:44	4:04:06:40
Experiment 3.7	3:23:06:50	3:10:50:54	4:03:59:01
Experiment 3.8	3:23:06:50	3:10:50:54	4:03:59:00

Table 14 - Output data scenario 3

In *Table 15* are the results shown of the fourth scenario about the interventions made on finishing assembly line 4. With this scenario, we looked into the impact that expanding finishing assembly line 4 could have on the throughput time for shelter batches due to the relatively high cycle time on the finishing assembly department. Furthermore, we looked into the overall impact if finishing assembly line would be processing also construction project batches.

Scenario 4 – finishing assembly line 4	Mean throughput time project batch (dd:hh:mm:ss)	Mean throughput time online batch (dd:hh:mm:ss)	Mean throughput time shelter batch (dd:hh:mm:ss)
Experiment 4.1	3:01:24:59	2:23:17:34	3:07:14:42
Experiment 4.2	3:01:24:59	2:23:17:34	3:07:09:53
Experiment 4.3	3:01:24:59	2:23:17:34	3:07:22:14
Experiment 4.4	3:00:48:28	2:23:17:34	3:07:26:52
Experiment 4.5	3:00:48:16	2:23:17:34	3:07:19:21
Experiment 4.6	3:00:49:41	2:23:17:34	3:07:33:04

Table 15 - Output data scenario 4

From the results of scenario 4 in *Table 15*, we can conclude that the expanding finishing assembly 4 and making the organisational decision to also process project batches on finishing assembly line 4, when expanded, will create a significant decrease in throughput time for shelter batches. Furthermore, it will help decrease the throughput time for project batches even more to get closer to the throughput time of 3 days.

To conclude on this section, we analysed the output results of all the four scenarios with its interventions. From this analysis, we can conclude that for scenario 1 the best interventions to make are to reduce the project batches maxima to 34 frames per batch and reduce the mean number of frames per batch to 26 frames per batch. For the second scenario, the best interventions to make are to add an extra pre-assembly line to the production line and change those takt times to 6 and 8 minutes respectively. For the third scenario with the working time of the manual painting station, the best intervention to make are to extent the working time where possible although the impact is not that much. For the fourth scenario with finishing assembly line 4, the best intervention to make is to expand finishing assembly line 4 to make it possible to have an equal takt time to either line 1 or 2 and to make the organisational decision to also process project batches on finishing assembly line 4.

7.4. Combination of Experimental Scenarios

In this section, we will test the total impact on the throughput time of all batch types with all four scenarios and their best interventions combined. To do this we will make use of two experimental scenarios, one for the short term with the implementation of scenarios 1,2, and 3 about the project batch size, pre-assembly line, and working time of the manual painting station. After that, we will continue with the scenario on the long term, where it will also be possible to implement scenario 4 with expanding finishing assembly line 4.

For the short-term scenario, we decided to run experiments based on all possible combinations by combining scenario 1,2 and 3 from Section 7.3. This resulted in the experimental design shown in *Table 16.*

Scenario 5 – short term implementation of scenarios	Experiment 1.7	Experiment 2.11	Experiment 3.8
Experiment 5.1	Not active	Not active	Active
Experiment 5.2	Not active	Active	Active
Experiment 5.3	Active	Not active	Not active
Experiment 5.4	Active	Not active	Active
Experiment 5.5	Active	Active	Active

Table 16 - Experimental design scenario 5

To make sure to also have some insights into what could be achieved on the long term looking at the expansion of finishing assembly line 4, we designed the last scenario with two experiments. The design of these experiments are shown in *Table 17.*

Scenario 6 – long term implementation of scenarios	Experiment 1.7	Experiment 2.11	Experiment 3.8	Experiment 4.5
Experiment 6.1	Active	Active	Active	Not active
Experiment 6.2	Active	Active	Active	Active

Table 17 - Experimental design scenario 6

Although it might seem that the only adjustment made in scenario 6 is the activation of Experiment 4.5, we also increased the uptime of the machinery department to a more realistic number for the long term. This, while the machinery employees will be more trained with the new machinery and most small problems, will be fixed that currently occur. Therefore, the results of Experiment 6.1 will be a bit lower than Experiment 5.5.

Now given the experimental designs of Scenario 5 and 6 about the short and long-term implementation of the experimental results in Section 7.3. We can turn to the results of Scenario 5 first and continue with the results of Scenario 6. The results of scenario 5 about the short-term implementation of the best experimental outcomes of scenarios 1, 2, and 3 are shown in *Table 18.*

Scenario 5 – short term implementation of scenarios	Mean throughput time project batch (dd:hh:mm:ss)	Mean throughput time online batch (dd:hh:mm:ss)	Mean throughput time shelter batch (dd:hh:mm:ss)
Experiment 5.1	3:23:06:50	3:10:50:54	4:03:59:00
Experiment 5.2	3:19:51:16	3:06:26:24	3:23:37:49
Experiment 5.3	3:12:10:14	3:08:31:25	3:22:45:15
Experiment 5.4	3:12:11:28	3:07:50:46	3:21:48:07
Experiment 5.5	3:09:05:43	3:04:13:42	3:18:55:01

Table 18 - Output data scenario 5

Looking at the results in *Table 18,* we can see that the implementation of scenarios 1 and 2, that are about the project batch size and pre-assembly line have the most impact on the throughput time. However, the most reduction on throughput time can be achieved by combining all interventions made of scenarios 1,2 and 3 as in Experiment 5.5. This results in an approximated throughput time of 3 days and 9 hours for project batches, 3 days and 4 hours for online batches, and 3 days and 19 hours for shelter batches. This means that on a short-term time period the desired norm of 3 working days for all batch types can almost be achieved by making interventions on the project batch size, pre-assembly line, and working time of the manual painting station.

Given the results of the short-term implementation towards a throughput time of 3 working days for all batch types, we can continue with the results of the long-term implementation including the expansion of finishing assembly line 4 and higher uptime of the machinery department. The results from Scenario 6 with the long-term implementation of all the scenarios can be found in *Table 19.*

Scenario 6 – long term implementation of scenarios	Mean throughput time project batch (dd:hh:mm:ss)	Mean throughput time online batch (dd:hh:mm:ss)	Mean throughput time shelter batch (dd:hh:mm:ss)
Experiment 6.1	3:02:25:13	2:23:17:34	3:14:45:03
Experiment 6.2	2:15:24:25	2:15:04:27.	3:02:16:49

Table 19 - Output data scenario 6

Looking at the results from Scenario 6 in *Table 19,* we can notice that increasing the uptime of the machinery department already has a significant impact on the throughput time of the different batch types. Comparing Experiment 5.5 with Experiment 6.1, we can see that increasing the uptime of the machinery department has on each batch type an impact of 4 to 7 hours decreasing the average throughput time of a batch. Furthermore, in Experiment 6.2

we can see that the throughput time for project and online batches can even be reduced to less than 3 working days on average. Therefore, we can conclude that on the long term it is key to implement the proposed expansion of finishing assembly line 4 in combination with a higher uptime of the machinery department. This will result in an average throughput time for project batches of 2 days and 15 hours, for online batches of 2 days and 15 hours, and for shelter batches of 3 days and 2 hours according to the simulation study performed.

8. Conclusion and Recommendation

In this last chapter, we will provide an answer to the main research question: "*What will be the layout and organisation of the frame production line at Nijhuis Toelevering B.V. to reduce the throughput time by 46,4 %?".* This question will be answered by starting in Section 8.1. with a conclusion to the sub-research questions, followed by a recommendation on the layout and organisation of the production line in Section 8.2. Furthermore, we will provide recommendations on further research for Nijhuis Toelevering in Section 8.2.

8.1. Conclusion

To be able to answer the main research question, the sub-research questions that were developed in Section 1.4.1. has to be answered first. In this section the conclusions to these sub-research questions will be given, using the information provided in the related chapter.

Sub-research question 1: *How does the frame production line at Nijhuis Toelevering B.V. currently operate during transition phase 6?*

Following from the description of the production process in Section 2.1., the production line operates in a consecutive production line process that consists of four different production departments: machinery, pre-assembly, painting, and finishing assembly. Each production department consists of different kinds of production processes that are made to get closer to the end product which is a frame including a door, window, both, or none. At the production line are three different kinds of production batches, that consist of frames, windows, and doors, produced: construction projects, online orders, and shelter frames. These batches are produced on the production line starting at the machinery department where the production process starts with just wooden beams that are cut and planed, after which the wooden beams are being processed on the CNC machines to door, window, or frame elements. Those frame elements are then pre-assembled into a door, window, or frame at the pre-assembly department. After the pre-assembly, the doors, windows, and frames are being painted with a primer and top-coating at the painting department. When paint is dried, the finishing department is responsible for applying the finishing touches to the doors and windows, and assembling these doors and windows into the frames. There are also several finishing touches made to the frames at the four finishing assembly lines. After that, the frames are loaded onto transportation stillages and ready for transport.

Sub-research question 2: *Which literature are available for identifying bottlenecks and improving the throughput time given the context at Nijhuis Toelevering B.V.?*

For the available theories, we performed a Systematic Literature Review (SLR), that provided several candidate theories for reducing the throughput time and identifying bottlenecks given the context at Nijhuis Toelevering B.V.. From these candidates, there are theories chosen that would fit the most to the context of the production line at Nijhuis Toelevering that are explained in detail in Chapter 3. In short, the first theory that is used for reducing the throughput time is the lean framework. The lean framework consists of a combination of several lean theories that are used for identifying wastes and providing tools and methodologies to improve production processes. The main tools and methodologies used from the lean framework are: non-value adding activities, wastes (muda, mura, and muri), and the Value Stream Map. The second theory that is used for identifying bottlenecks is the Theory of Constraints. The Theory of Constraints focuses on identifying constraints in a production system and trying to exploit the system's constraint or even elevate the constraint.

Sub-research question 3*: How is the current performance of the frame production line at Nijhuis Toelevering B.V.?*

The current performance of the production line at Nijhuis Toelevering B.V. is analysed using the theories from sub-research question 2. For the analysis on the performance of the production line were several methods used such as observations and interviews. Following from these analyses and integration of the theories, it became clear that the production line is currently dealing with high waiting times, several non-value adding activities, multiple wastes and some system constraints that lead to the high throughout time of 5 to 6 working days for construction projects, 5 working days for shelter frames, and 3 to 4 working days for online orders. Within the production line there is currently a lot of time lost in non-value adding activities such as repetitive quality controls, waiting time spent in buffer, and repairment works. Furthermore, at the production line if often occurs that mistakes are made within the production system. These mistakes vary from: the wrong technical drawings to frames that got through a quality control even though they should have been dismissed or even worse that not all the right supplies are present at the production line. This often leads to a non-optimal usage of the production time available.

Sub-research question 4: *What performance data and processes of the frame production line are needed for the simulation model?*

This question is mainly focused on creating a conceptual model for the simulation model and these decisions are described in detail in Chapter 5. First, the decision on which production processes are taken into account for the conceptual model had to be made. The production line at Nijhuis Toelevering consists of a lot of small production process steps that for the sake of simplicity and given the research aim are mainly grouped into production processes that can be seen as one or when no decisions are made on the production flow within a part of the production line. Furthermore, the decision is made to focus on the 4 production departments discussed at sub-research question 1 and leave the additional smaller departments, such as glazing beads and the sorting department, outside the model, because these departments also fall outside the scope of this research which is focus the main production flow of the production line. After defining the processes for the conceptual model, that can be found in *Appendix F*, the data was collected for the included production processes. The data consisted of the batch sizes and processing times of the production processes. It became clear after statistical analysis and observations that the construction project batches consist on average of 33 frames, 5 doors, and 19 windows. For online orders, the batches consist on average of 18 frames, 7 doors, and 10 windows. Last of all, for the shelter frames the batches consist on average of 11 frames and 11 windows. For the processing times, a statistical analysis is performed to calculate the mean, standard deviation, minimum, and maximum. After that, there is a statistical test performed to check whether or not the normal distribution can be assumed. These results are described in detail in Section 5.2.2.

Sub-research question 5: *How does the simulation has to look like for the research at Nijhuis Toelevering B.V.?*

For the simulation model, the software of Siemens Tecnomatix Plant Simulation 16.1 is used. This software program provides the possibility to create a 2D simulation model of the production line in accordance with the conceptual model and the opportunity to experiment with the layout and organisation of the production line in a fast and cost-efficient manner. After implementing the simulation model, the warmup period and run-length had to be determined. For the warm-up length, we used a rough estimation due to the time constraint and we are dealing with a terminating simulation. Therefore, the warm-up period is set at 5 days to prevent any bias in the results due to startup issues, since the simulation starts with an empty production line. To continue with the run length which determines the number of days that the simulation model is simulating. The decision was made to set the run length to 225 working, because a production year at Nijhuis Toelevering consists of 225 working days which made it more compatible with the available production data.

Sub-research question 6: *What will be the experimental design of the frame production line at Nijhuis Toelevering B.V. for reducing the throughput time?*

The aim of this research is to reduce the throughput time of the production line at Nijhuis Toelevering by experimenting with the organizational decisions and layout of the production line. Therefore, the Key Performance Indicators for the output data of the experiments are the throughput time for the different production batches, the number of frames produced, and the distribution of the frame types. Following from the production line analysis performed for sub-research question 2 in Chapter 4. We came to the conclusion that there are 4 experimental factors where improvements can be made for the throughput time within the production line. We defined these 4 factors as the 4 experimental scenarios in which we perform interventions using sensitivity analysis on what the best intervention is to make on a certain experimental factor. The 4 experimental factors, and therefore the 4 scenarios for this research, are:

1. Batch size of the construction project batches
2. Capacity of the pre-assembly line for the frames
3. Organisational decision on where to apply the top-coating
4. The takt time and capacity of finishing assembly line 4

For scenario 1, we looked into the effects of decreasing the project batch maxima and mean using the sensitivity analysis method. For scenario 2, the interventions are focused on the takt time of the pre-assembly line and the decision on whether it is better to use 1 or 2 pre-assembly lines. For Scenario 3, we wanted to see what effects the extending the working time of the manual painting station had on the throughput time. For scenario 4, we looked into the effects of expanding finishing assembly line 4 that would results in a lower takt time and higher capacity for finishing assembly line 4. Given the 4 independent scenarios for the experimental factors, we also created a fifth and sixth scenario to test the short and long term implementation of the four experimental scenarios from the simulation study. This will make sure that we also have insights in the total decrease of throughput time per production batch on average for all batch types.

Sub-research question 7: *Which organisational configurations will optimize the throughput time of the frame production line at Nijhuis Toelevering B.V.?*

After simulating the experiments following from sub-research question 6, we analysed the results by looking at the descriptive statistics of the output parameters and the 95 % confidence intervals. When looking at these intervals and descriptive statistics, we can conclude that for each scenario a significant reduction in throughput time can be realised. For the first scenario about the project batch size, we concluded that reducing the project batch maxima to 34 frames per batch and the mean to 26 frames per batch is the best intervention to make. This results in an average batch size of 20 frames per project batch size. For the second scenario about the pre-assembly line, we can conclude that the best intervention to make is to add an extra per-assembly line where pre-assembly line 1 will have a takt time of 4 minutes and 48 seconds and pre-assembly line 2 a takt time of 6 minutes. For the third scenario about the working time of the manual painting station, we concluded that extending the working time of the manual painting station does not have much impact on the project and online batches. However, it has some impact on the shelter and therefore the best intervention to make in scenario 3 if possible is to extend the working time of the manual painting station from 7.00 – 16.00 hours to 5.00 – 22.00 hours. For the fourth scenario about finishing assembly line 4, we can conclude that expanding finishing assembly line 4 and processing project and shelter batches on finishing assembly line 4 is the best intervention to make. However, it has to be noted that will only be possible on a longer time period after implementing scenarios 1,2 and 3.

Given the results from these scenarios, we designed two final scenarios for the short and long-term implementation of the interventions. Following the scenario on the short-term implementation, it became clear that by implementing the interventions from scenarios 1,2 and 3, the desired norm of three working days for all batch types can almost be achieved. The results showed us that on the short term, the average throughput time for a project batch can be reduced to 3 days and 9 hours, for an online batch to 3 days and 4 hours, and for a shelter batch to 3 days and 19 hours.

After that, we looked at the implementation of scenario 4 and a higher uptime for the machinery department on the long term given a successful implementation of the short-term interventions. From the scenario on the long term, we can conclude that the norm for 3 working days for all batch types can be achieved and even more. The results showed us that on the long term, the average throughput time for a project batch can be reduced to 2 days and 15 hours, for an online batch to 2 days and 15 hours, and for a shelter batch to 3 days and 2 hours.

8.2. Recommendation

In this section, there will be a final answer given to the main research question using the conclusions from Section 8.1. and a recommendation will be made on further research plus other findings from this research project.
The main research question of this thesis is:

"*What will be the layout and organisation of the frame production line at Nijhuis Toelevering B.V. to reduce the throughput time to 3 working days for all batch types?".*

As a result of the simulation study performed on the production line at Nijhuis Toelevering B.V. with the conclusions summarized in Section 8.1., we can conclude that on a short-term period by implementing a smaller batch size for project batches, adding an extra pre-assembly line, and extending the working hours of the manual painting station, will result in a reduced average throughput time of 3 days and 9 hours for project batches, 3 days and 4 hours for online batches, and 3 days and 19 hours for shelter batches. Furthermore, we can conclude that on the long term period by implementing an expansion of finishing assembly line 4 and higher uptime of the machinery department, there will be a reduced average throughput time of 2 days and 15 hours for project batches, 2 days and 15 hours for online batches, and 3 days and 2 hours for shelter batches possible. This implies, that on the short-term, the desired norm of 3 working days for all batch types will not be achieved, but when looking at a long-term period the norm of this research project can definitely be achieved and even more.

Following the results of the simulation research study on the production line of Nijhuis Toelevering B.V., we want to make the following recommendations to be able to reduce the throughput time for all batch types to the desired norm of 3 working days.

- First of all, on a short-term time period it is important to make three interventions within the production line. The first intervention that has to be made is the reduction of the project batch size by reducing the average batch size for project batches to 20 frames per batch.
- Secondly, a second pre-assembly line should be added to the pre-assembly line department. This means there will be the first pre-assembly line with a takt time of 4 minutes and 48 seconds and a second pre-assembly line with a takt time of 6 minutes.

- Thirdly, the working hours of the manual painting station should be extended from 7.00 – 16.00 hours to 5.00 – 22.00 hours, so that all the products will be manually top-coated.
- Last of all, finishing assembly line 4 should be extended, so it can have a similar takt time as finishing assembly line 1 or 2 and the finishing assembly line will be able to process shelter batches and project batches.

For further research, there are also a few recommendations following from the overall research project and time spent at the company as a researcher. From these analyses, we want to make the following recommendation for Nijhuis Toevering B.V.:

- First of all, one of the problems that occurred during this research project is the lack of available production data for some of the production processes. Therefore, there are misunderstandings between what is theoretically possible and what is possible at the production line. Therefore, we would recommend to research the possibilities of implementing a more effective data management method.
- Secondly, since the simulation is based on the assumptions that have been made that no mistakes are made on the technical drawings, ordered supplies are in time present at the production line, and frames which would fail the quality test are immediately taken out of the production line. We would recommend doing further research on the failure rates of the working stations within the production line of Nijhuis Toelevering, because currently there are no insights into this topic although it happens frequently. This is important, since it has a significant influence on the throughput time and costs made at the production line.

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Appendices

Appendix A – Floor Map of the Production Facility

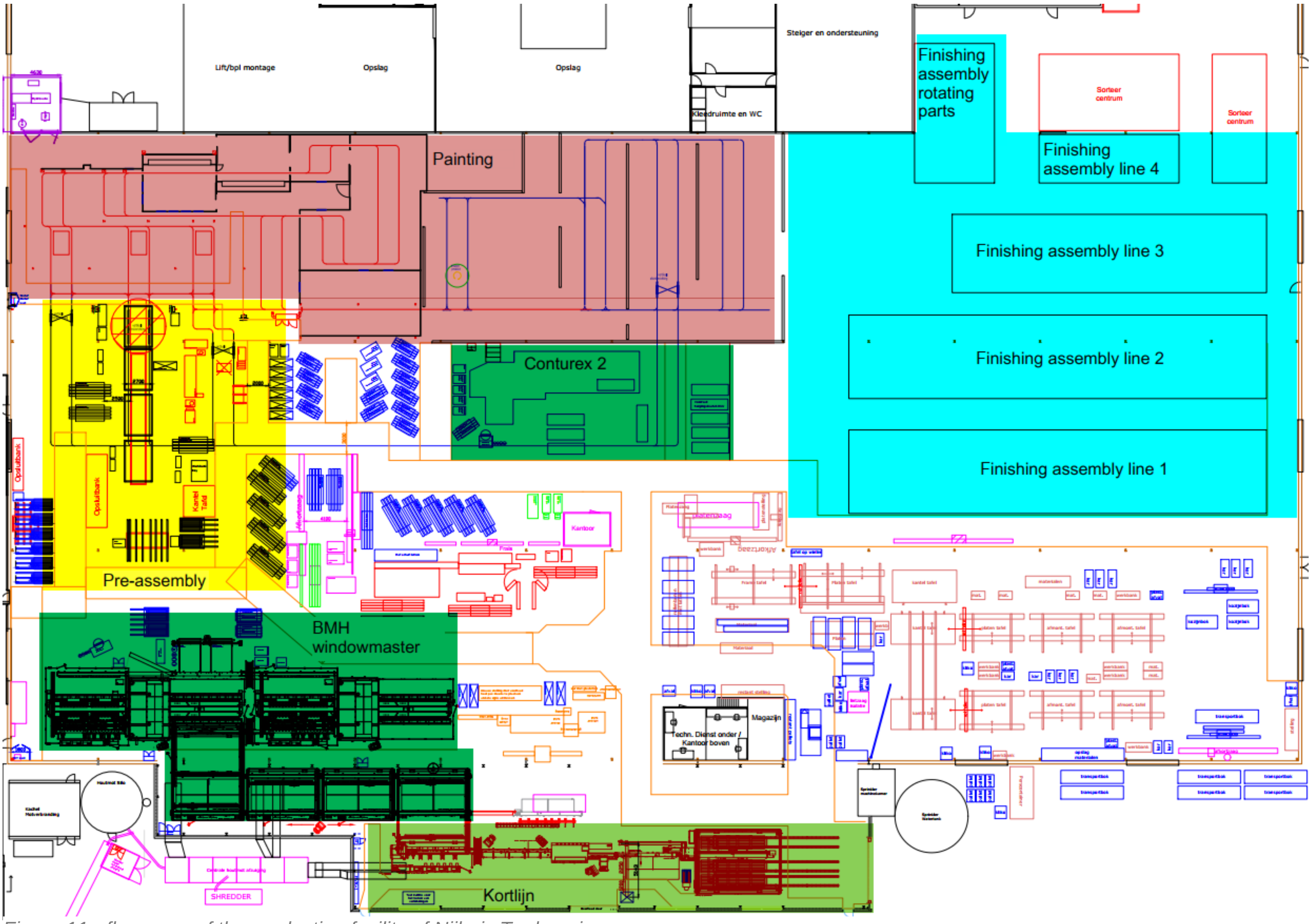


Figure 11 - floor map of the production facility of Nijhuis Toelevering

Appendix B – Problem Identification

Appendix B.1 – Problem Cluster

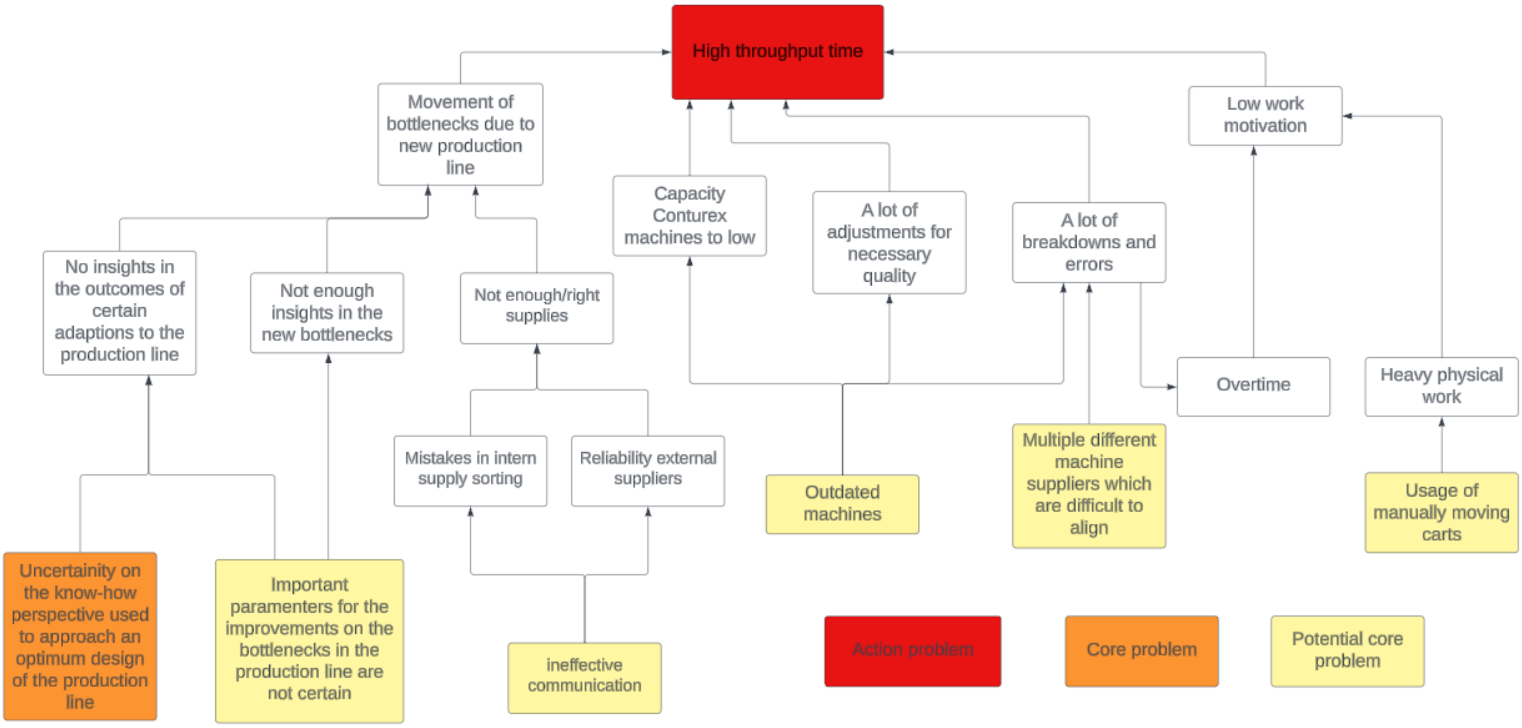


Figure 12 - Problem cluster

Appendix B.2 – Problem List

Description of problem	Problem type	Where found?
The low capacity of the two Conturex machines	Technical related	Interview with production manager (Spaans, 2024) and results of intern research on the old production line
A lot of adjustments had to be made to the settings of the Conturex machines to make sure the necessary quality was achieved	Technical related	Interview with the production manager (Spaans, 2024)
A lot of breakdowns and errors with the machines on the old production line	Technical related	Interview with the production manager (Spaans, 2024)
Multiple different machine suppliers which are difficult to align	Technical related	Interview with the production manager (Spaans, 2024) and observation of the production line
Outdated machines that also do not comply with safety regulations	Technical related	Interview with the production manager (Spaans, 2024) and results of intern research on the old production line
Low working motivation due to overtime	People related	Interview with the production manager (Spaans, 2024)
A lot of manual tilting with the heavy wooden beams on and off the machines	People related	Observation of the production line
Usage of manually moving carts for the wooden beams	People related	Observation of the production line

Due to all the technical problems, Nijhuis Toelevering had to ask a lot of times if the employees could stay longer for overtime work	People related	Interview with the production manager (Spaans, 2024)
The movement of bottlenecks in the production line	Managerial related	Interview with the production manager (Spaans, 2024)
There are no insights into certain adaptions to the production line and what the impacts are on the possible bottlenecks	Managerial related	Interview with the production manager (Spaans, 2024)
There are not enough insights into what the new bottlenecks will be	Managerial related	Interview with the production manager (Spaans, 2024)
The important parameters for the improvements on the bottlenecks in the production line are not certain	Managerial related	Interview with the production manager (Spaans, 2024) and found in data analysis
The optimal flow of the production line is based on know-how experience from managers, which raises questions by some of the production supervisors on how effective this is.	Managerial related	Interview with the production manager (Spaans, 2024) and observation combined with small interviews off the production line employees
Not enough or not the right supplies at the working stations on the production line	Managerial related	Observation of the production line
Mistakes in the intern supply sorting department for the different working stations in the production line	Managerial related	Interview with the production manager (Spaans, 2024)
The reliability of external suppliers is not always guaranteed	Managerial related	Interview with the production manager (Spaans, 2024)
Ineffective communication between working stations, and between working stations and management level	Managerial related	Observations in the production environment

Table 20 - Problem list with the origin of the found problems

Appendix C – Research Design

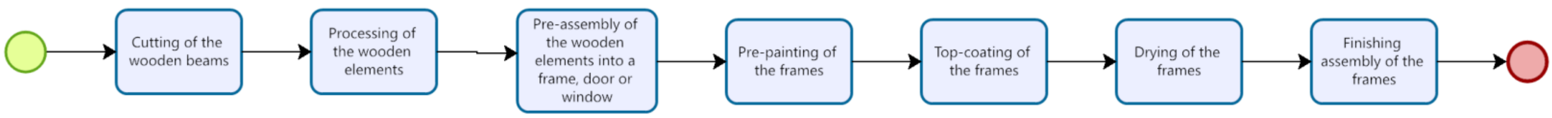
Knowledge problem	Type of Research	Research population	Subjects	Research methodology phase	Methods of data gathering	Method of data processing	Activity plan
How does the frame production line at Nijhuis Toelevering B.V. currently operate during transition phase 6?	Exploratory	Frame production line Nijhuis Toelevering B.V.	Employees, machinery at the production line	Phase 1	Interviews, observations	Visual representation of the production process and conceptual model in BMPN	Observe the production line → Interview employees → Create BPMN overviews
Which literature theories are available, to tackle the found bottlenecks in the frame production line, for improving the throughput time?	Exploratory	Literature	Academic and scientific theories	Phase 2	Literature research	Theoretical framework	SLR → Literature study → Describe important parameters → Describe theoretical framework
How is the current performance of the frame production line at Nijhuis Toelevering B.V.?	Descriptive	Frame production line Nijhuis Toelevering B.V.	Employees, machinery at the production line	Phase 3	Interviews, observations	Description of the bottlenecks and problems, conceptual model	Analyse the production line → Conduct interviews → Description of the bottlenecks
What performance data and processes of the frame production line are needed for the conceptual model?	Descriptive	Companies database, Frame production line	Frame production line, production data	Phase 4	Data from the company database, Results from questions 1 and 3	Data analysis, statistical distribution for parameters, conceptual model	Conceptual model → Data gathering → Verifying data → Statistical analyses
How can we model the production line at Nijhuis Toelevering B.V. for experimenting with the layout and organisational decisions?	Explanatory	Frame production line Nijhuis Toelevering B.V.	Simulation model	Phases 5	Results from phase 3 and 4, simulation model	simulation model	Building simulation model → Verifying simulation model
What will be the experimental design of the frame	Explanatory	Frame production line Nijhuis	Experimental design	Phase 6	Simulation model, results from	Experimental design	Description experiments → Define

production line at Nijhuis Toelevering B.V. for reducing the throughput time?		Toelevering B.V.			questions 2 and 5		experimental design → Perform experiments
Which organizational configurations will optimize the throughput time of the frame production line at Nijhuis Toelevering B.V.?	Evaluative	Frame production line Nijhuis Toelevering B.V.	Organizational configurations	Phases 7 and 8	The outcome of the experiments	Data analysis, graphs and tables, descriptive text, and visualisation of organisational configurations	Extract data from experiments → Analyse the data → Describe the organisational configurations → Make an implementation plan

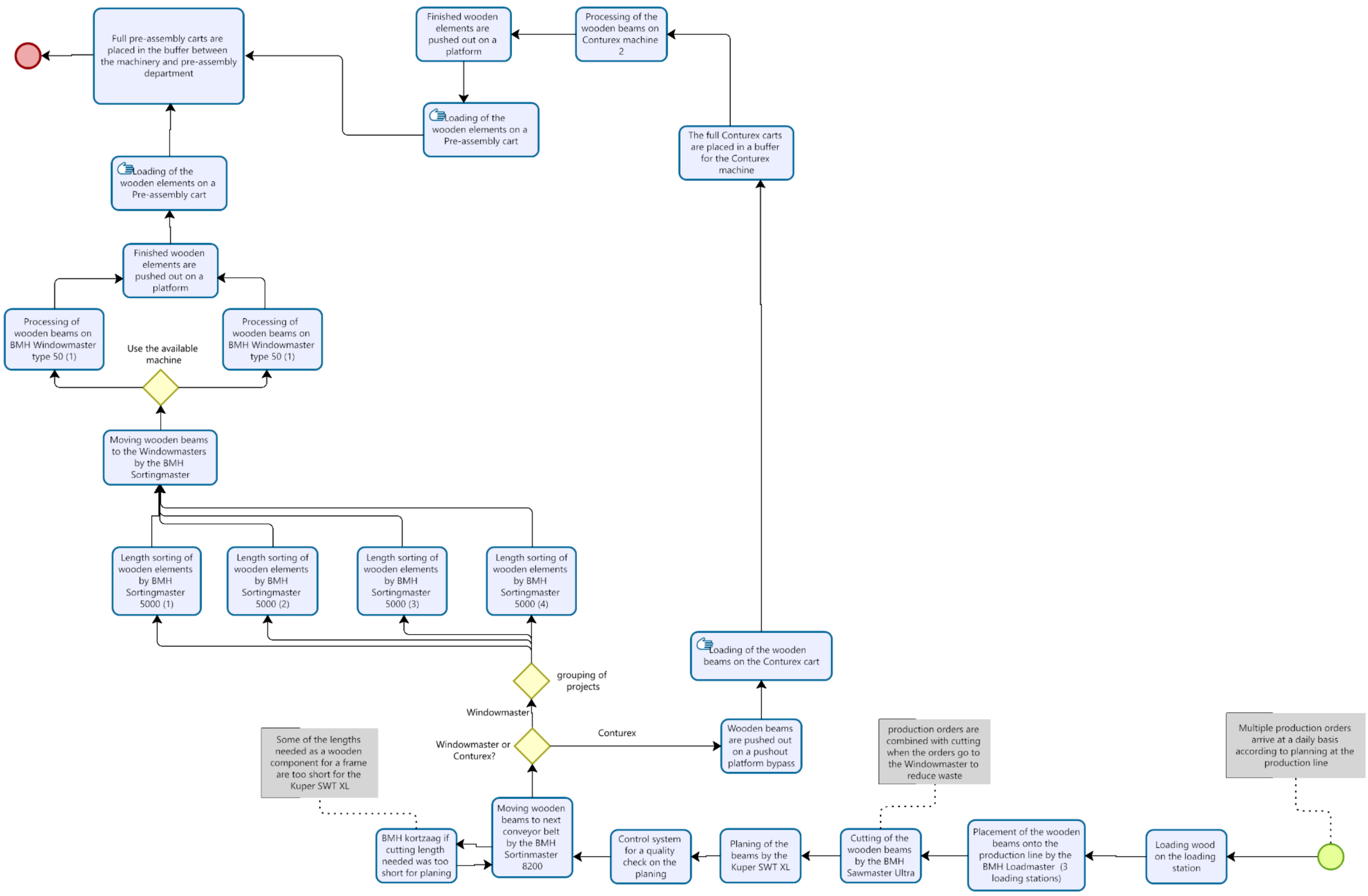
Table 21 – Elaborated Research Design

Appendix D – BMPN Models Production Line Analysis

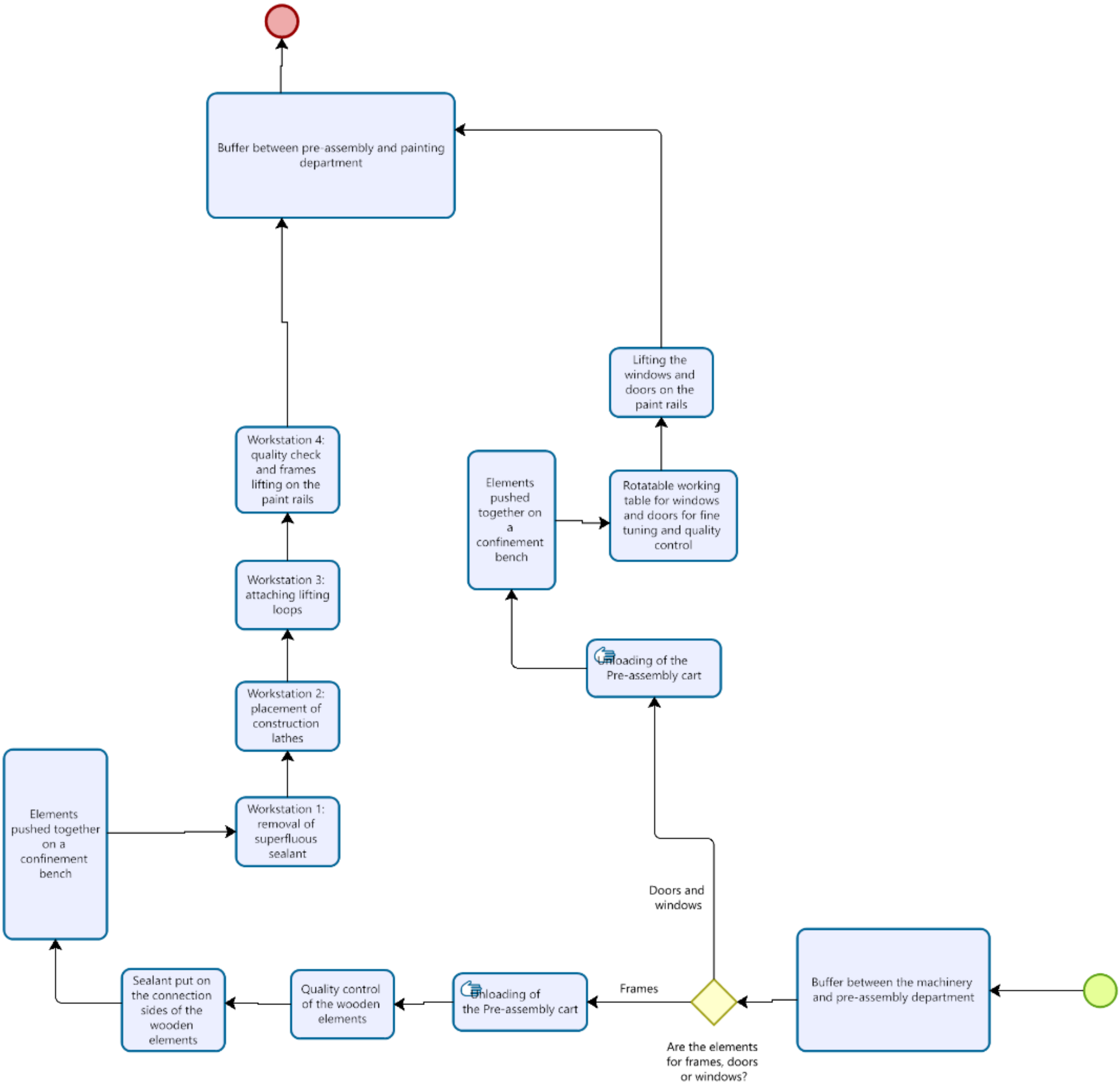
Appendix D.1 – Global overview of the production line



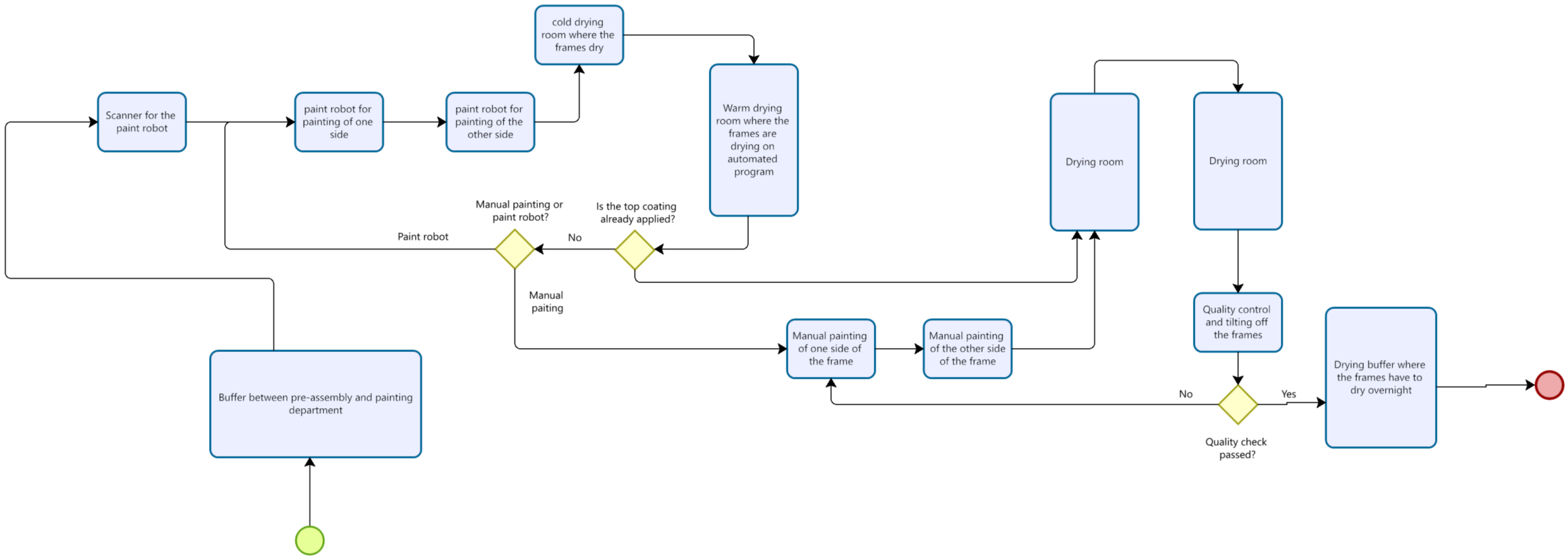
Appendix D.2 – Machinery department



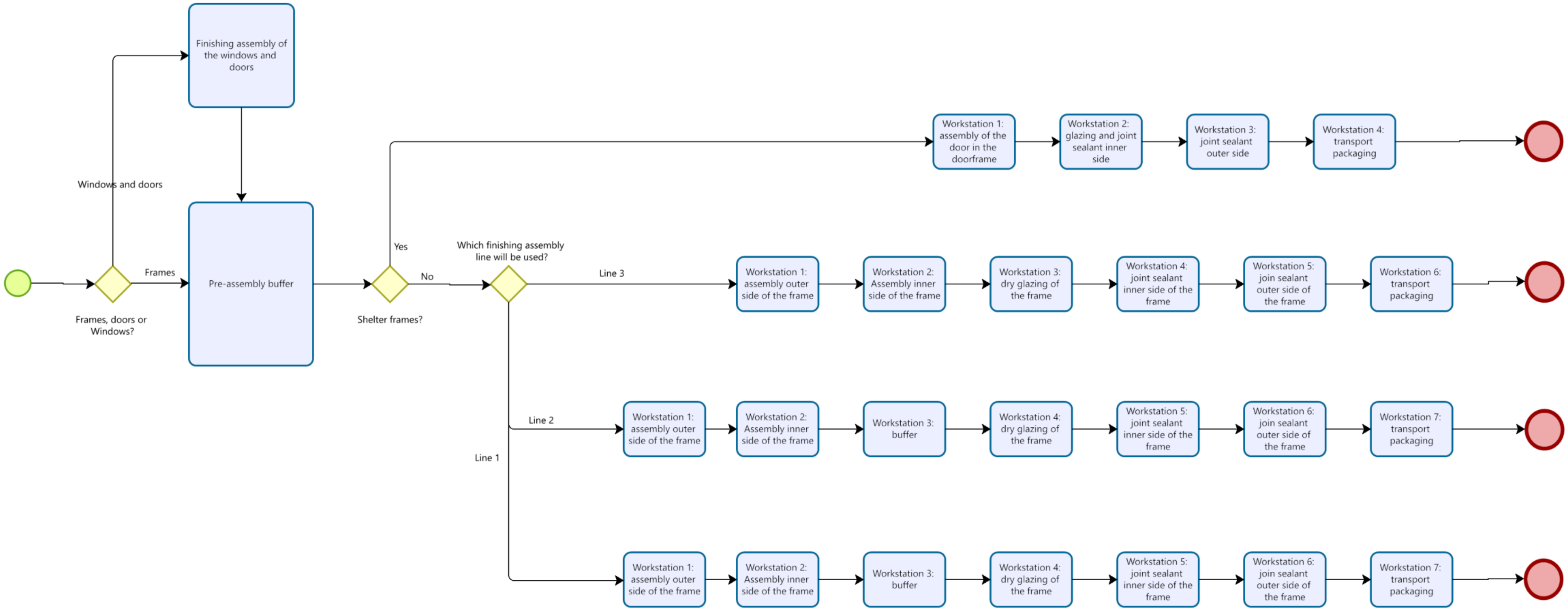
Appendix D.3 – Pre-assembly department



Appendix D.4 – Painting department



Appendix D.5 – Finishing assembly department



Appendix E – Systematic Literature Review

E.1 – Definition of the knowledge problem

As described the aim of this research project is to reduce the throughput time by looking at the layout and organisation of the production line. To achieve this, we first have to identify the possible theories that exist in the literature for reducing throughput time and identifying bottlenecks. Therefore, the research question for this systematic literature review is sub-research question 2: "*Which literature theories are available for identifying bottlenecks and improving the throughput time given the context at Nijhuis Toelevering B.V.?"*.

E.2 – Inclusion and exclusion criteria

To make sure that for this literature review, all the relevant articles are included and prevent that unrelated articles have to be reviewed, the researcher can make use of inclusion and exclusion criteria. The criteria provide a filter for the articles that are not applicable or relevant to the research question. The inclusion and exclusion criteria can be found in *Table 22*.

Nr.	Criteria	Inclusion or Exclusion	Explanation
1	Articles focused on ERP systems	Exclusion	ERP systems fall outside of the research scope, because Nijhuis Toelevering is already implementing this.
3	Sources in languages other than English or Dutch	Exclusion	English is seen as the 'language of science' and therefore represents most knowledge. Furthermore, to make sure the theories are fully understood, they need to be written in English or Dutch.
2	Articles are peer-reviewed	Inclusion	The presented theories in the articles have to be peer-reviewed to guarantee quality
3	Includes a specific methodology of theory	Inclusion	The article should follow a certain methodology or theory, since we are looking for theories to apply for this research project on how to identify bottlenecks and reduce throughput time.
4	Open access	Inclusion	The full text of the source has to be open to access for me, so the articles can be read for review.

Table 22 - Inclusion and Exclusion Criteria

E.3 – Identification of the relevant academic databases

For this Systematic Literature Research the following three academic sources:

- Scopus;
- Web of Science;
- ArXiv.org.

First of all, there is Scopus which is a multidisciplinary database, that has a large coverage and is reliable due to the peer-reviewed requirement of the scientific articles. Secondly, Web of Science is used, since it is also a multidisciplinary database with a large coverage and reliable sources. Last of all, the domain-specific source arXiv will be used for the search for familiar theories used within the research field of Industrial Engineering and Management.

E.4 – description of the search terms

Based on the knowledge question the search terms, also known as key concepts, have to be defined. From the sub-research question, "*Which literature theories are available for identifying bottlenecks and improving the throughput time given the context at Nijhuis Toelevering B.V.?*", the following search terms can be defined: 'Literature theories' and 'throughput time'. To make sure that all the synonyms and related terms can used during the search, there is a small research performed on synonyms, broader terms, and narrower terms. The broader and narrower terms can be used for finding more or less hits to the used search string. For this small research, the search tool Power Thesaurus is used (Power thesaurus, 2024). The results of this can be found in *Table 23*.

Key concepts	Related terms / synonyms	Broader terms	Narrower terms
Theory	Theoretical framework, literature studies	Theory, approach, technique	
Throughput time	throughput rate, cycle time	Throughput, duration	Process time
Production line	Assembly line, production facility	Production, manufacturing	Sequential working stations

Table 23 - Search Matrix with key concepts

E.5 – Search log

Given the key concepts, criteria and databases, the actual systematic literature review can start. For this, the key concepts are composed into search strings for the databases.

In *Table 24*, the search log for all the databases can be found, given the search date, search string, scope, number of hits, and some relevant notes. After the search, a selection of applicable articles is made, based on several removal criteria. This is also displayed in *Table 24*.

Scopus					
Date	Search string	Scope	Number of hits	Retrieved articles	Notes
10-04-2024	Theories AND “throughput time” AND “Production line”	All fields	116	0	Search string is too broad, because it gives to many unrelated articles
11-04-2024	Theories AND “throughput time” AND “Production line”	Article title, abstract, keywords	6	2 (#2 and #4)	Search string is too narrow. The amount of results do not provide enough information on multiple theories.
11-04-2024	Theor* AND (“Throughput time” OR “flow rate”) AND (“production line” OR “manufacturing line”)	Article title, abstract, keywords	25	2 (#1 and #3)	Based on titles most of the articles seem relevant, but some might not be open to access. Also some articles may be too much focused on a specific material used for production.
Web of Science					
Date	Search string	Scope	Number of hits	Retrieved articles	Notes
23-05-2024	Theory AND Throughput time AND production line	All fields	66	3 (#6, #7 and #8)	
23-05-2024	Theor* AND throughput time AND production	All fields	462	1 (#9)	
Arxiv					
Date	Search string	Scope	Number of hits	Retrieved articles	Notes
11-04-2024	Theories AND throughput time AND production line	All fields	2	0	Only 2 sources found of which only 1 might be relevant
16-04-2014	Theor* AND throughput time AND production	All fields	14	0	More sources are found, but most of them still not applicable
17-04-2024	“throughput time”	Title	3	1 (#5)	More specific results related to throughput time reduction.
Total applicable articles				**9**	

Table 24 - Search Log

E.6 – Main findings from review articles in conceptual matrix

In this section, the 9 applicable articles are reviewed for the theories used and to see if these theories can be used for this research project. The main findings and conclusion for each article can be found in Table 25.

#	Article	Title	Discrete-event simulation	Queuing theory	Lean manufacturing	Six sigma	Value Stream Mapping (VSM)	Theory of Constraints	Operation strategy: lot sizing, priority, variation	Task elimination	Flow constraint, (quick) effective utilization
1	Tébar-Rubio et al. (2022)	Conducting action research to improve operational efficiency in manufacturing: The case of a first-tier automotive supplier.			X	X	X				
2	Mc Glynn et al. (1997)	How to get predictable throughput times in a multiple product environment							X		
3	Kouikoglou et al. (1997)	A continuous flow model for production networks with finite buffers, unreliable machines and multiple products	X	X							
4	Armbruster et al. (2006)	A continuum model for re-entrant factory	X	X							
5	Schunselaar et al. (2018)	Task elimination may actually increase throughput time								X	
6	Babu et al. (2007)	Application of TOC embedded ILP for increasing throughput of production lines						X			

7	Wu et al. (2019)	A generalization of the Theory of Constraints: Choosing the optimal improvement option with consideration of variability and costs						X			
8	Sims et al. (2017)	Constraint identification techniques for lean manufacturing systems			X	X		X			X
9	Sobreiro et al. (2014)	Product mix: the approach of throughput per day						X	X		

Tabel 25 - Conceptual matrix

E.7 – Conclusion and integration of the theory

To conclude on the outcome on which theories will be used for this research project given the context at Nijhuis Toelevering B.V. and to answer the knowledge question: “Which literature theories are available for identifying bottlenecks and reducing throughput time of a production line?”. It became clear that there are many different theories that can be used for identifying bottlenecks and improving throughput time. However, given the context of the frame production line and ongoing transition at Nijhuis Toelevering, it became clear that there are two main theories which are most suitable for this research project. This is the Theory of Constraints and the theory of the Lean Framework. These two theories will be explained in *Section 3.2.* and *3.3*. However, the theory of Value Stream Mapping will also be used as a tool for the visualisation of the performance of the production line in *Section 4.1.*

Appendix F – Value Stream Maps

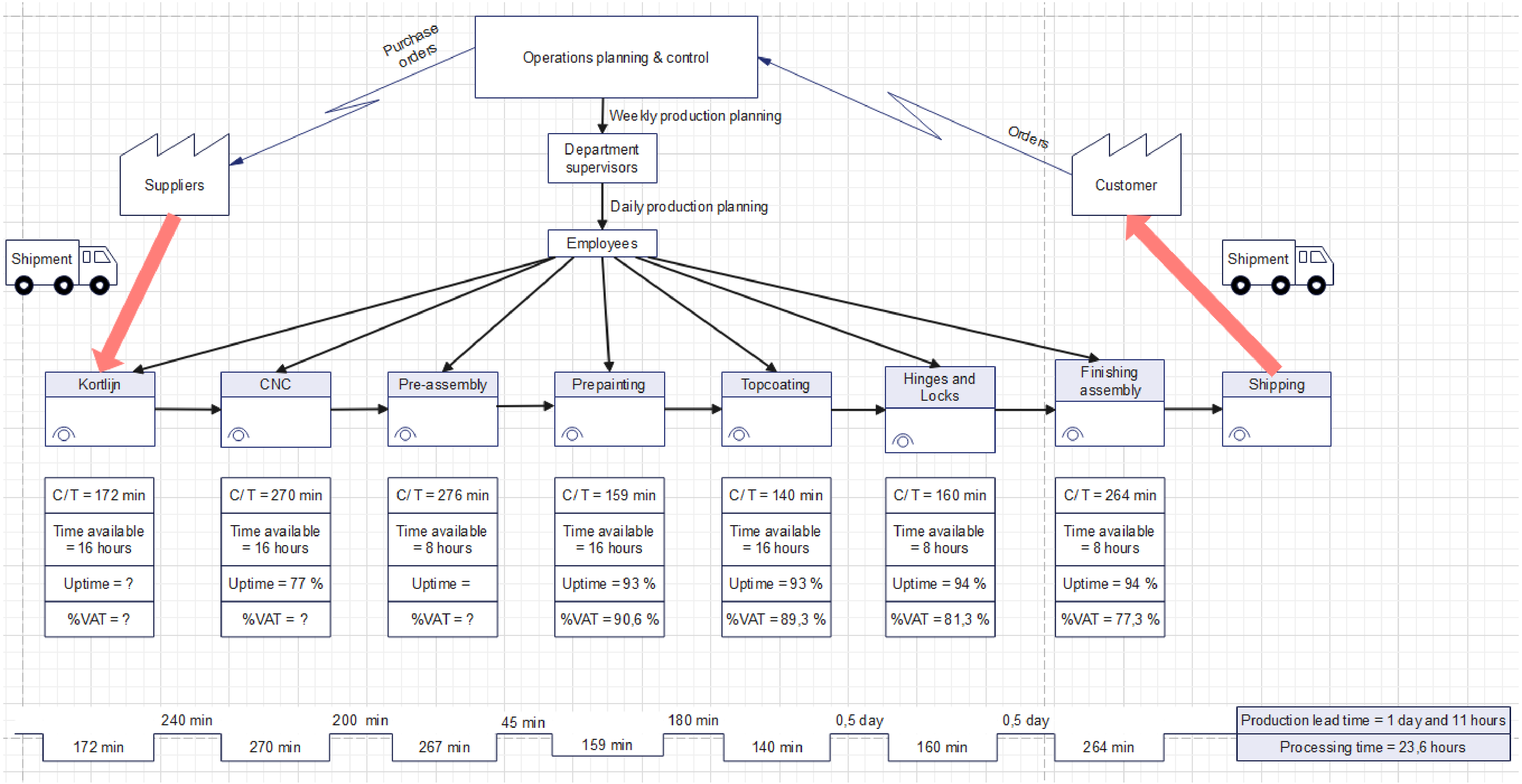


Figure 13 - Value Stream Map construction project batches

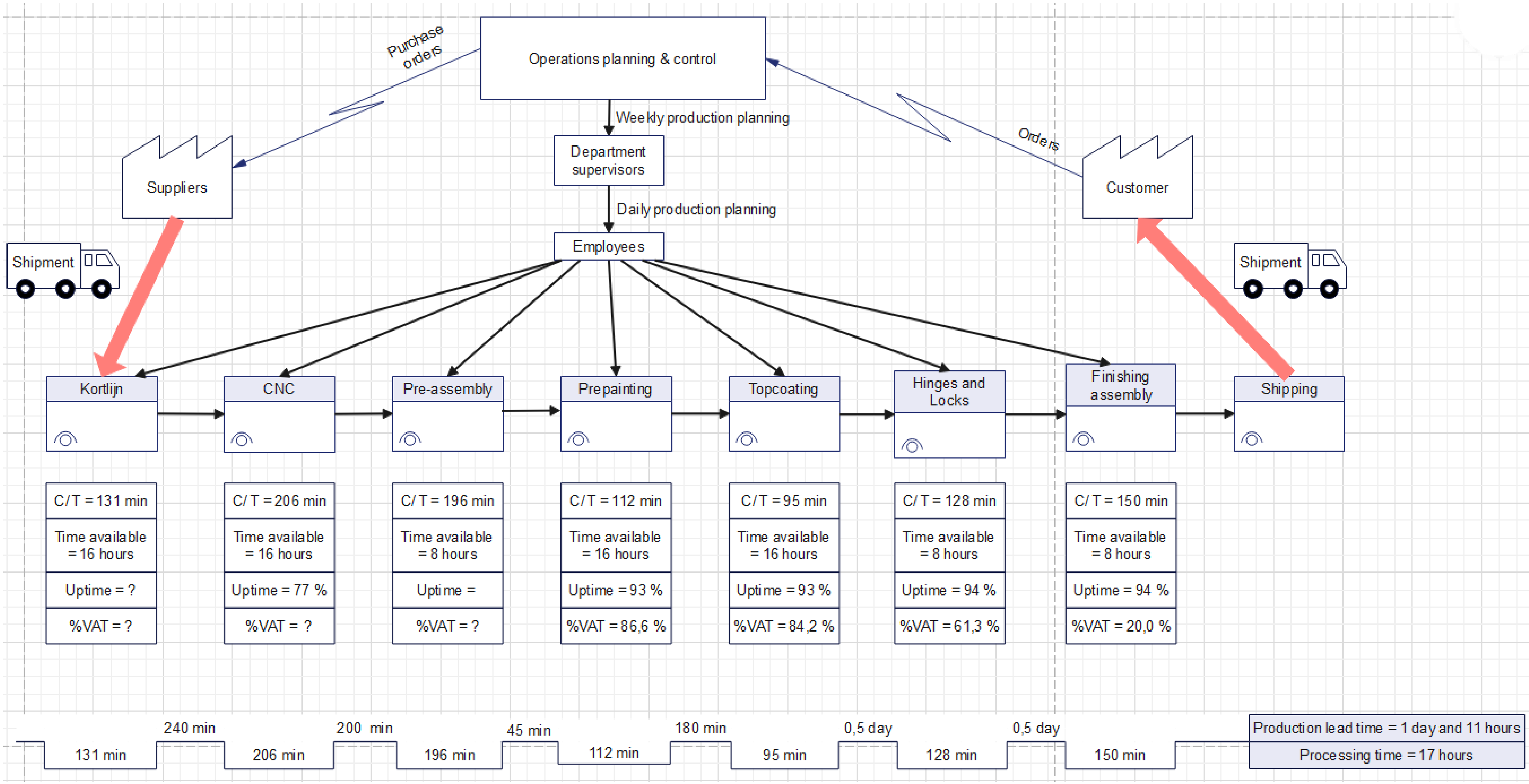


Figure 143 - Value Stream Map online batches

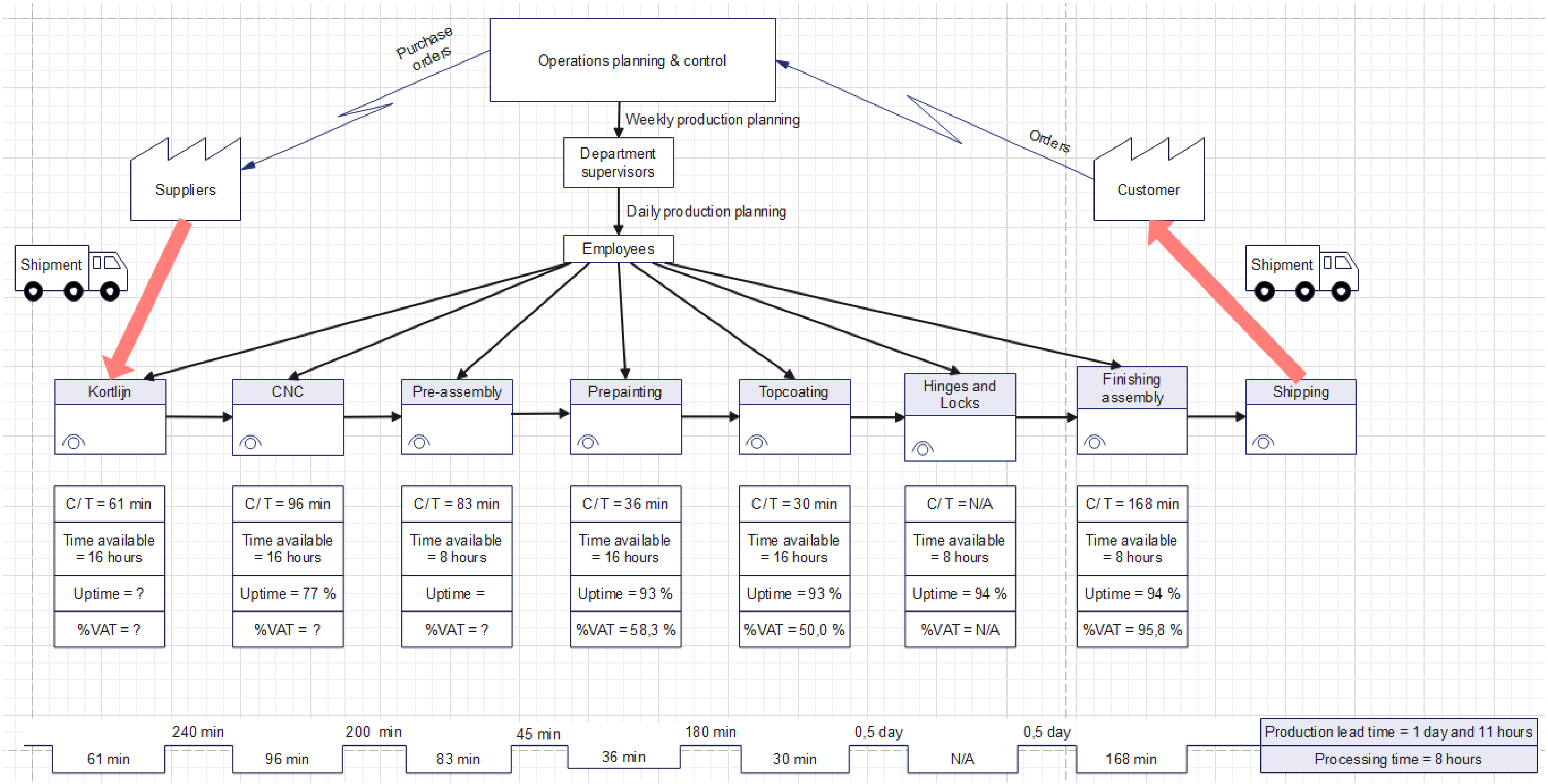


Figure 15 - Value Stream Map shelter frame batches

Appendix G – Conceptual Model

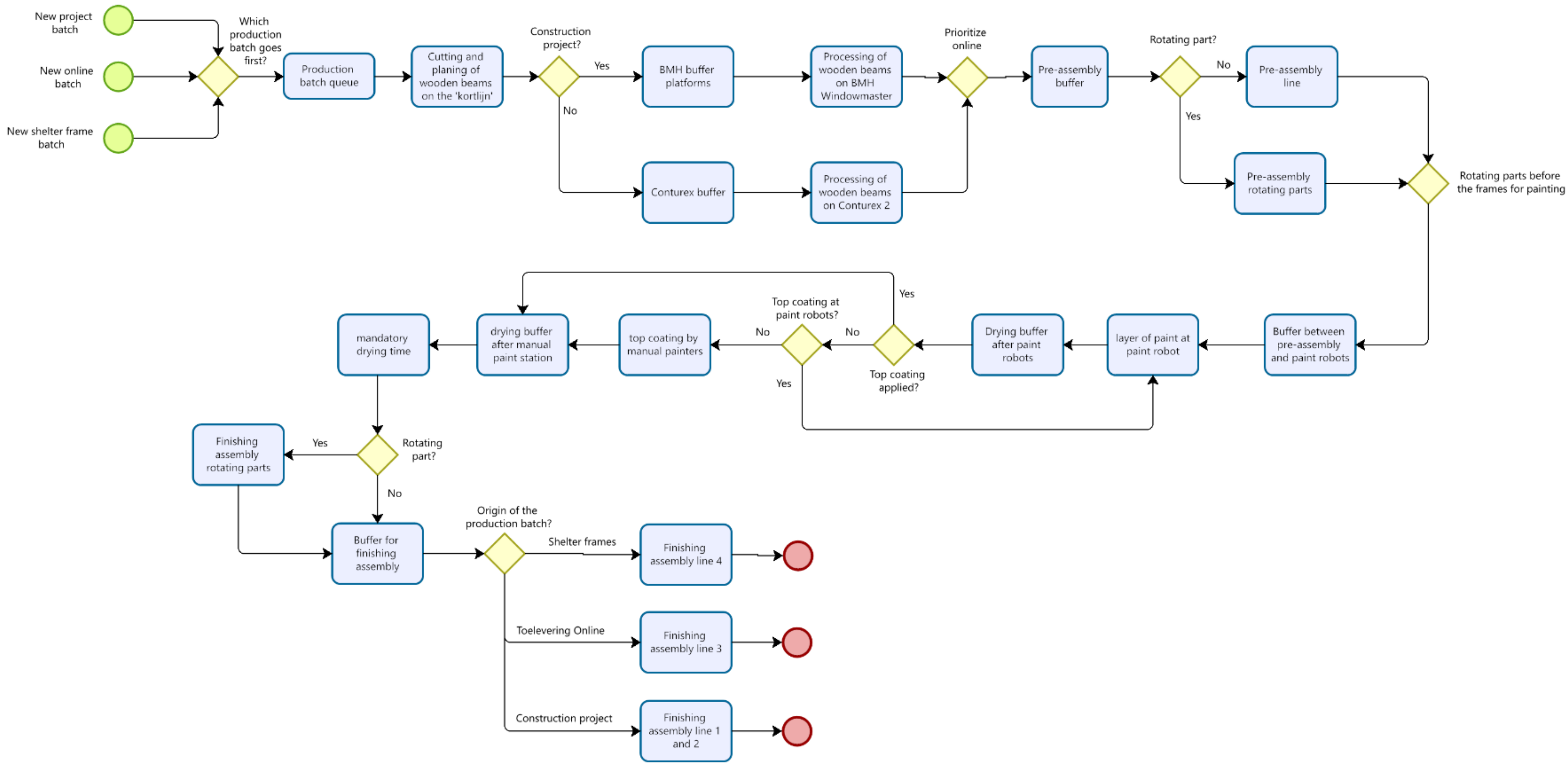


Figure 165 - Conceptual Model

Appendix H – Collected data

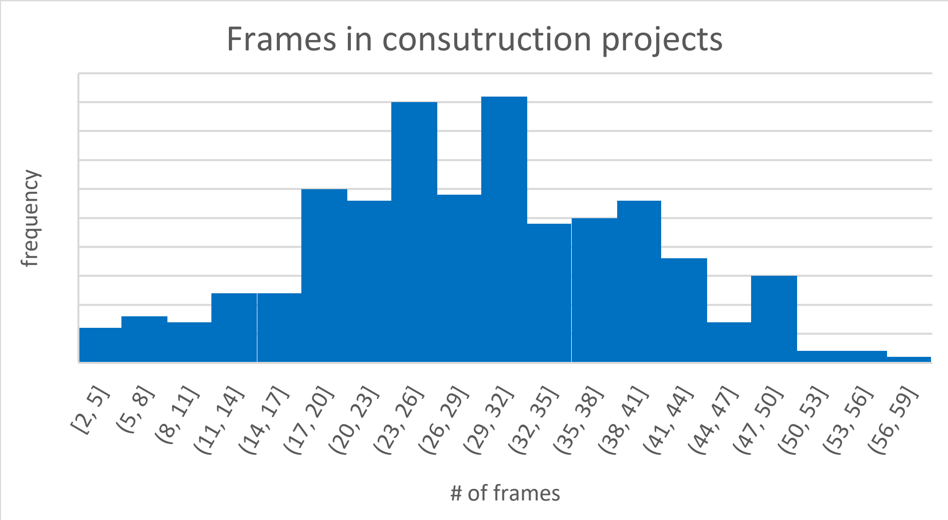
Name of process	type data	data Distribution	Desciption	Assumed data according to observation of (333300-01/02/03)	Data according to ERP research	Data according to supervisors	Data analytics	unit
project arrival	arrival rate (numbers)	uniform	at what rate do construction projects arrive at the factory	3 project batches per day	N/A	?		
online arrival	arrival rate (numbers)	uniform	at what rate do online orders arrive at the factory	2 online batches per day	N/A	?		
Batch size	fixed size	uniform	the number of frames, doors and windows for a production batch	20 frames, 5 doors and 12 windows on average	1 frame	?	See product mix	
processing time "Kortlijn"	time	constant	how long does it take to process a production batch at the the "kortlijn" which consists of the BMH loadmaster, sawmaster, Kuper SWT XL and first sorting master	moet nog geklokt worden	13,27 minutes	theoretical about 2500 parts per day realisticly currenlty on 1300-1500 parts per day	61,3163265	parts per hour
Filling time BMH buffer	dwell time	constant	how long does it take to fill the BMH buffers	moet nog geklokt worden	240 minutes	240 minutes, but might differ when fully opertional		
Capacity BMH buffer	numerical	fixed	What is the capacity of the BMH buffers in terms of production batches	4 production batches	N/A	320 parts per buffer, but dependent on variation of the parts	N/A	
Filling time conturex carts for buffer	dwell time	constant	How long does it take to fill the Conturex Machines carts for a production batch	moet nog geklokt worden	N/A	?	N/A	
Capacity Conturex buffer	numerical	fixed	how many carts are there available for Conturex Machine 2	15 carts with 8 layers that eah hold 10 beam positions	N/A	?	N/A	
Processing time BMH windowmaster	time	constant	What is the production rate of the BMH Windowmaster	810 minutes (opnieuw klokken vanwege storingen)	17,54 minutes (WM of Conturex?)	theoretically 20 seconds per part, but not sure yet		
Processing time Conturex 2	time	constant	What is the production rate of the Conturex 2	moet nog geklokt worden	^	1,5-2,0 hours per cart	32,74	parts per hour
Loading of carts for the pre-assembly line	time	constant	How long does it take for a machinery employee fo fill a cart for the pre-assembly line after the BMH windowmaster or Conturex 2	moet nog geklokt worden	200 minutes	1,5 - 2 hours	N/A	

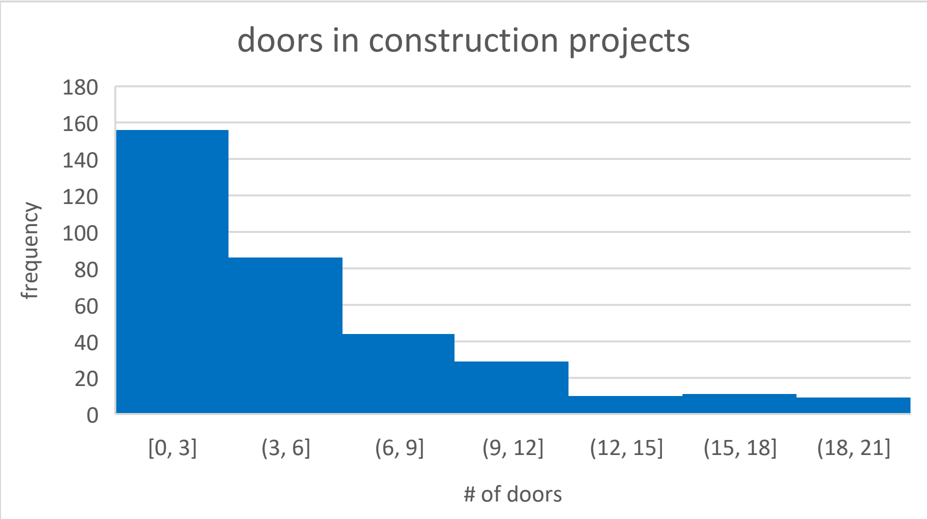
Capacity of pre-assembly buffer	numerical	fixed	How many carts are there available to fill for the pre-assembly line		19 carts (?)		N/A		11 carts for the frames 10 carts for the doors/windows		N/A	
Processing time on pre-assembly line	time	Normal	What is the production rate of the pre-assembly line		120 minutes		51,7 minutes		13-15 frames per hour		12,9646739	frames per hour
Processing time on pre-assembly line for doors and windows	time	Normal	what is the production rate of the pre-assembly line for door and window frames		224 minutes (opnieuw klokken)		9,9 minutes		61 windows per day 21 doors per day		12,3698157	Doors/windows per hour

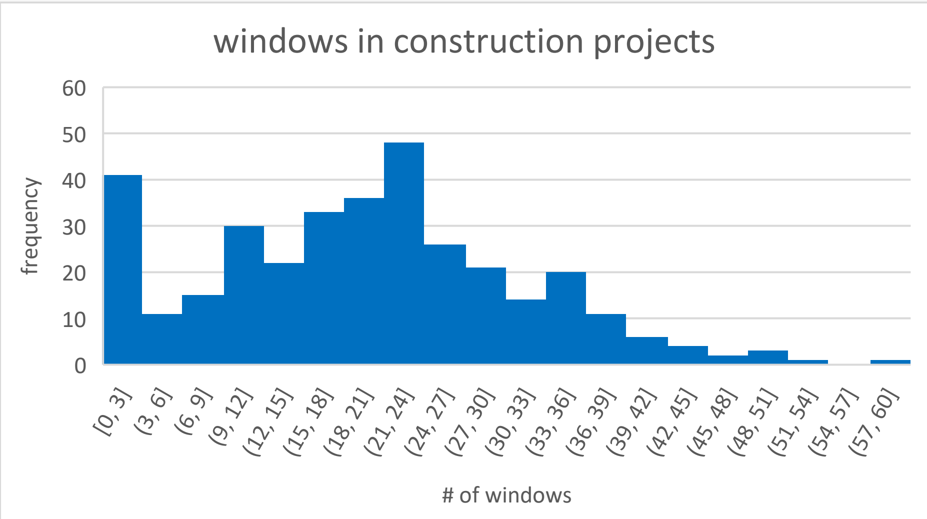
Capacity of the buffer before the painting department	numerical	fixed	How many production batches can be loaded onto the rails of the buffer before the painting robots		N/A		N/A		17-20 traversen for the 3 buffers from the pre-assembly then followed by 12 traversen for the first layer of paint buffer and 12 traversen for the topcoating		N/A	
Processing time of the painting robots	time	constant	what is the production rate of the painting robots		72 minutes		9,9 minutes		13-16 traversen per hour		10,3383811	traversen per hour
Capacity of the first drying chamber at the painting department	numerical	fixed	what is the capacity of the first drying chamber in terms of frames		40 traversen that each hold 1-3 frames		N/A		40 traversen		N/A	
drying time in the first drying chamber	dwell time	constant	how long does it take for a frame to go through the first drying chamber		122,5 minutes		120 minutes		2 to 2,5 hours		N/A	
processing time of the manual painting station	time	constant	what is the production rate of the manual painting station		N/A		16,4 minutes		15-20 traversen per hour		16,8822409	traversen per hour
Capacity of the second drying chamber at the panting department	numerical	fixed	what is the capacity of the second drying chamber in terms of frames		45 traversen that each hold 1-3 frames		N/A		?		N/A	
drying time in the second drying chamber	dwell time	constant	how long does it take for a frame to go through the second drying chamber		122,5 minutes		120 minutes		2 to 2,5 hours		N/A	
offloading of the frames onto the carts for the finishing assembly	time	constant	what is the production rate of the offloading of the frames onto the carts for the finishing assmebly line		87,5 minutes		4,2 minutes		?		N/A	
Dryingtime that is mandatory before the frame can move to the finishing assembly	dwell time	constant	what is the mandatory drying time after offloading the frames onto the carts (prequisite from the paint supplier)		20,21 hours		24 hours		The frames have to stay within the painting department overnight (the mandatory 24 hours start directly after the topcoating		N/A	
capacity of the drying buffer	numerical	fixed	how many carts are there available for the frames		same carts used as the pre-assembly buffer		N/A		?		N/A	

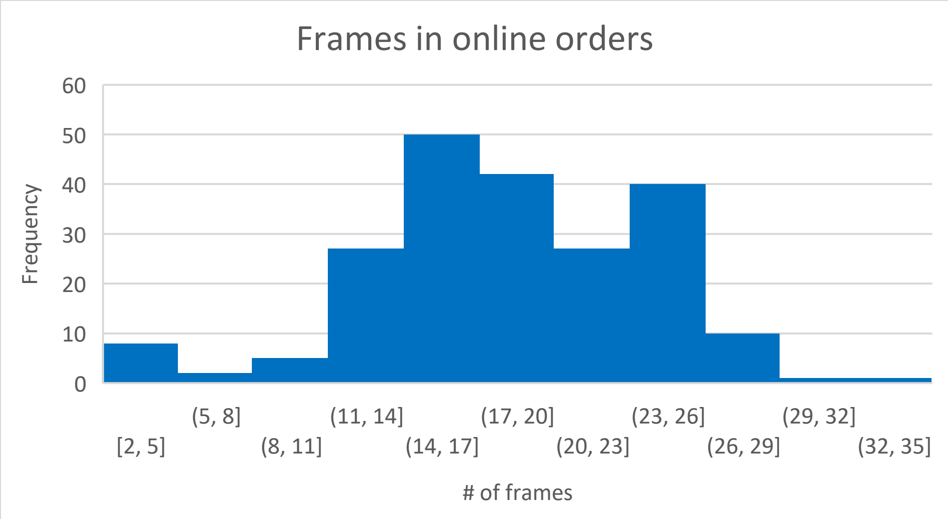
processing time of the hinges and locks station of the finishing assembly department	time	normal	what is the production rate of the hinges and locks station of the finsihing assembly department		131,7 minutes		13,1 minutes		daily average is 55 windows and 23 doors		9,425	windows/doors per hour
capacity of the finishing asembly buffer	numerical	fixed	how many carts are there available for the frames		45 carts for frames 40 carts voor windows, doors and shelterframes		N/A		?		N/A	
Processing time of finishing assembly line 4	time	poisson	what is the production rate of finishing assembly line 4		N/A		38,77 minutes		Line 4: 15 frames		1,875	shelterframes per hour
Processing time of finishing assembly line 1,2 and 3	time	Normal	what is the average production rate of finishing assembly line 1, 2 and 3		381,7 minutes		122,7 minutes		Line 1: 32 frames Line 2: 35 frames Line 3: 23 frames	1	4,03571429	frames per hour
										2	4,41620879	frames per hour
										3	2,99587912	frames per hour

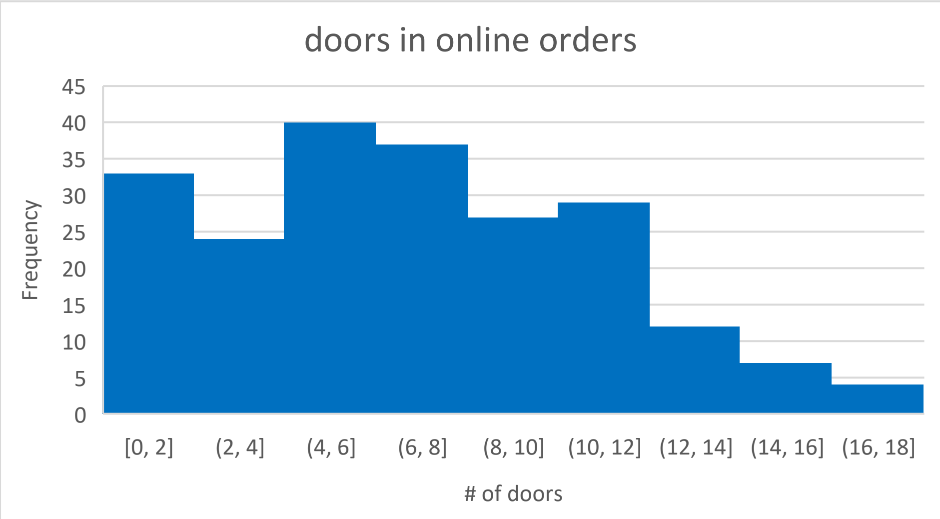
Appendix I – Data Distributions

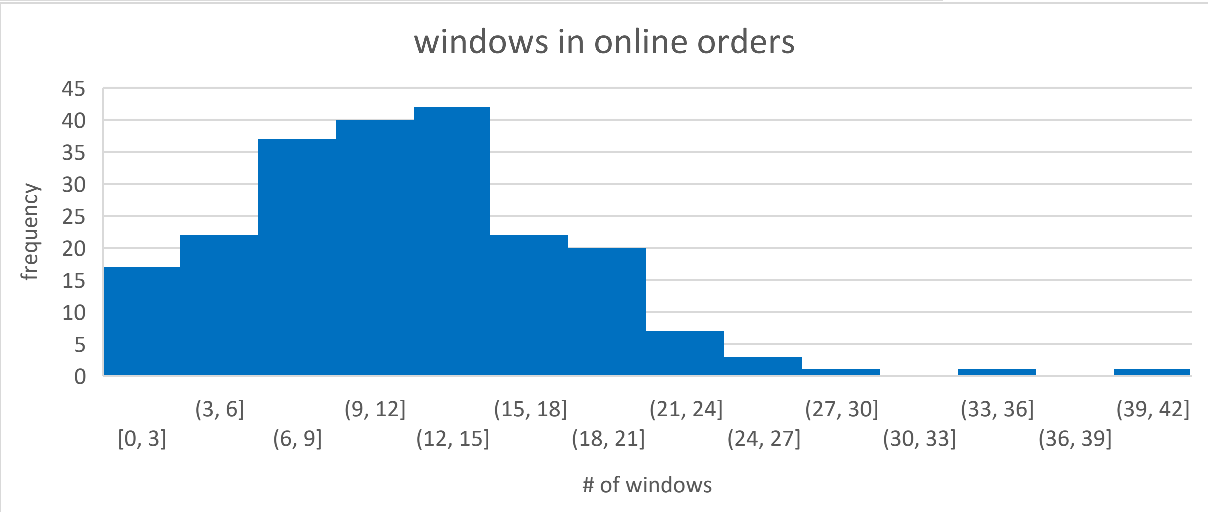


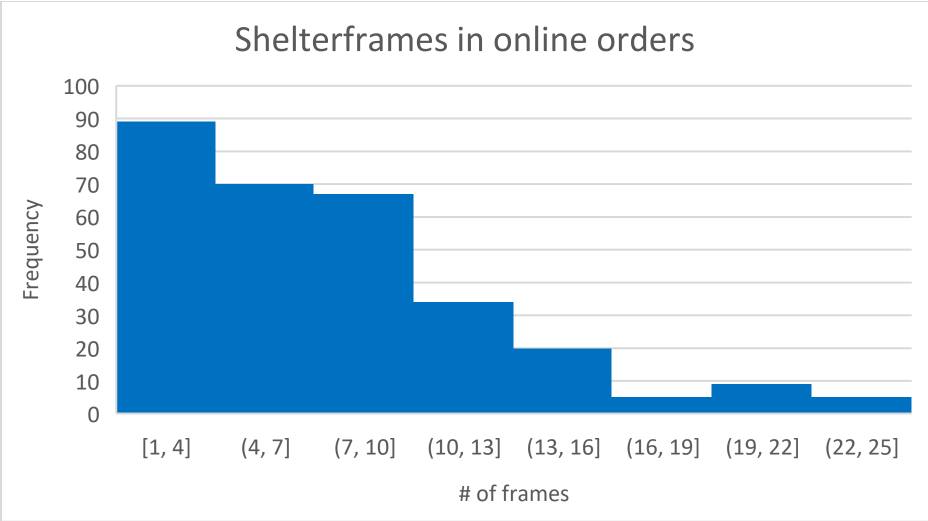





Frames in online orders
Frequency
60
50
40
30
20
10
0
[2, 5]
(5, 8]
(8, 11]
(11, 14]
(14, 17]
(17, 20]
(20, 23]
(23, 26]
(26, 29]
(29, 32]
(32, 35]
# of frames


doors in online orders
Frequency
45
40
35
30
25
20
15
10
5
0
[0, 2]
(2, 4]
(4, 6]
(6, 8]
(8, 10]
(10, 12]
(12, 14]
(14, 16]
(16, 18]
# of doors


windows in online orders
frequency
45
40
35
30
25
20
15
10
5
0
[0, 3]
(3, 6]
(6, 9]
(9, 12]
(12, 15]
(15, 18]
(18, 21]
(21, 24]
(24, 27]
(27, 30]
(30, 33]
(33, 36]
(36, 39]
(39, 42]
# of windows


Shelterframes in online orders
Frequency
100
90
80
70
60
50
40
30
20
10
0
[1, 4]
(4, 7]
(7, 10]
(10, 13]
(13, 16]
(16, 19]
(19, 22]
(22, 25]
# of frames

Appendix J – Logic Flow Diagram of Simulation Methods

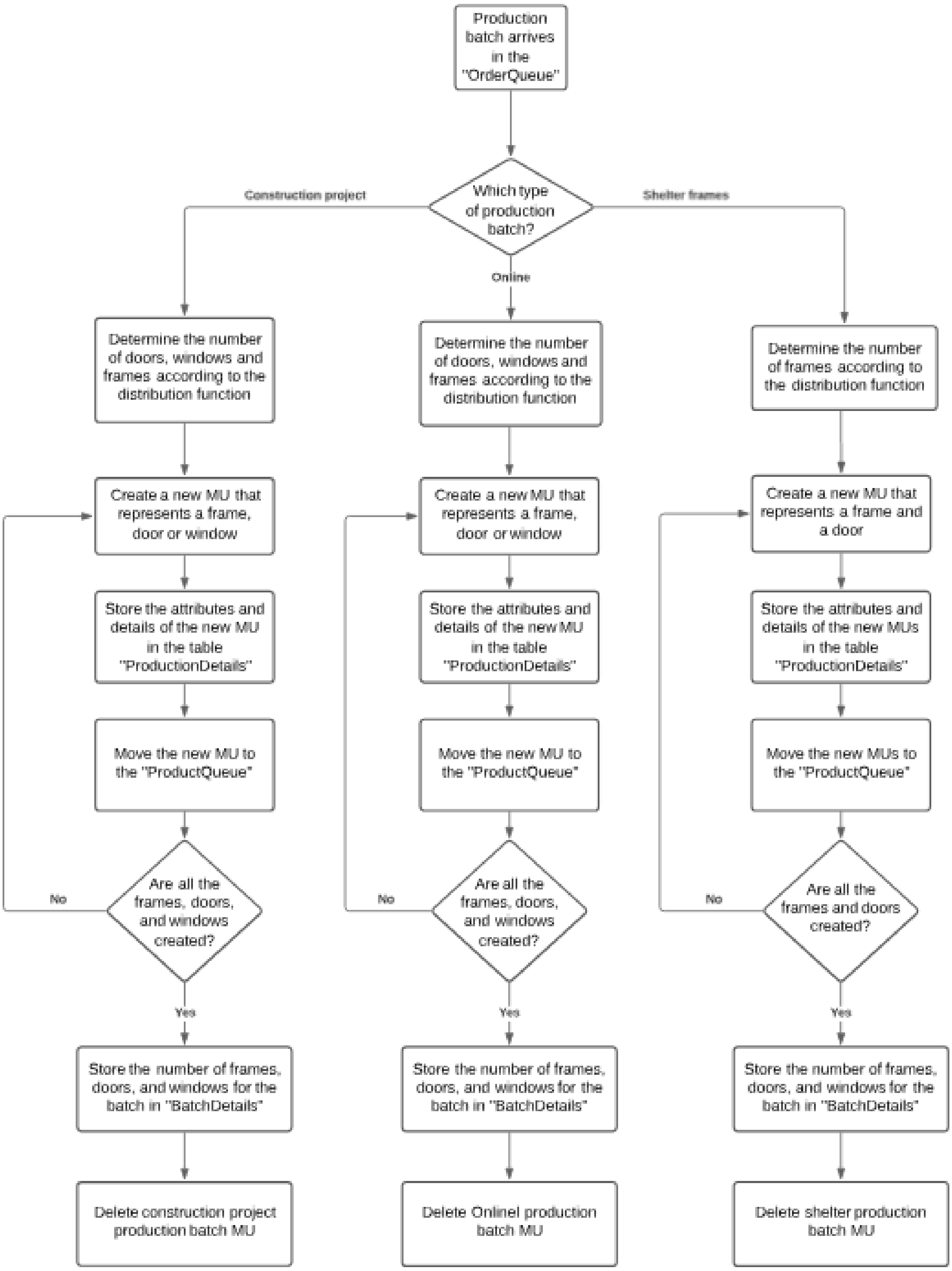


Figure 16 - Logic flow chart of method BatchSizing