Reducing throughput time of static Machine Support Frames at Mecal

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In this report several measures were taken to assure confidentiality of sensitive information. As a result, the product name, its components, material use, and related processing times are censored.

Management summary

Mecal designs, produces, and installs Machine Support Frames (MSF) for the semiconductor and imaging market on a global scale. These frames provide stability and lower vibration levels for the high-tech systems placed on top of them and make sure that these machines can operate at the best of their ability. Since Mecal is growing at a fast pace, an ongoing project aims to reduce the throughput time of one of their products. Therefore, we formulated the main research question as:

What are some of the actions Mecal can take to contribute to the goal of reducing the time needed for production and installation of the Machine Support Frame by at least 19% to achieve the set production KPIs?

We started this research by investigating the current production process of the MSF-X. Here, we concluded that both components have several overlapping types of activities and both of them are usually made to stock. Even though both are usually made to stock, Component B has a higher priority than Component A because of the outsourced steps. Additionally, Component B takes longer because of additional production steps, and is harder to produce since its specifications are stricter.

The components of the MSF-X that we consider here are typically used to fill the production schedule in case there are less ongoing projects. This way, there is room for some flexibility in production and stock levels remain sufficient for the MSF-X. Generally, the goal is to keep the production lanes occupied, given that there is enough capacity.

Once the current production process was clear, we constructed the process flows of Component A and Component B and continued with a literature review. In this literature review we aimed to find suitable research methods to improve throughput time. We concluded that we use Lean as our main framework to identify different types of waste and to use the Theory of Constraints to guide us in dealing with bottlenecks. Since mura and muri are closely related to variability and uncertainty, we used a framework that provided strategies to deal with these kinds of issues in particular.

Next, we applied these theories to identify existing issues and bottlenecks and found out how much time is spent at each stage of the production process. Since there was no historical data, we estimated the required time by providing technicians with the production quality checklist of both components and asking them for their estimations of the minimum, mode, and maximum required time for different sets of production steps. Based on this data, we created two value stream maps. Existing issues and bottlenecks were identified using the three types of waste as defined by the lean framework: *mura (lack of consistency), muri (unreasonable requirements), muda (non-value adding activities)*.

We found the main sources of mura to be the technicians that each have a different amount of experience with working on a particular frame, variability in the required process time caused by the quality of concrete, and the outsourced steps of Component B. Regarding muri we found that the throughput time of both components is not measured explicitly and that three different, non-overlapping systems exist for planning and monitoring the production process. For muda, we defined multiple smaller issues and summarized them in a table.

After identifying these existing issues and bottlenecks, we used the previously gathered data to construct a simulation model to aid us with analysing the impact of potential solutions. We described multiple potential solutions for addressing these types of waste and existing bottlenecks. Some of these solutions have been quantified using the simulation model, other solutions remain qualitative.

To reduce the throughput time of the MSF-X, our main recommendations are:

- Investigate options for reducing the number of glued parts or find different techniques of assembling these parts to the frame.

- Train technicians to use the Leica and continue making the working instructions clearer.

- Reduce variability of the quality of concrete by repairing or replacing the mould more often, and/or choosing for a different composition of concrete. Reducing the time spent on activities that are the result of lower concrete quality will improve job satisfaction and make better use of technicians' skills. According to the simulation model, this could reduce the waiting time for the first outsourced step by XXX. Also, it might be beneficial to investigate bringing some of the outsourced steps inhouse if the required resources and knowledge are available.

- Define a number of local and global KPIs to assess financial performance on a strategic level as well as operations performance on the operational level. Revise the working hours form to match the production quality checklist so throughput can be measured more accurately. Use the gathered data to detect potential improvements points and use it to improve scheduling and the production process in the future.

- To further increase capacity, new technicians should be hired over time. Given the fact that it may take a while before these technicians have enough experience, Mecal should also focus on training existing technicians to make sure that there is enough capacity to deal with the more difficult frames. We recommend training a junior technician to become a senior technician. According to the simulation model, this would reduce the average throughput time of Component A by XXX and Component B by XXX.

Following the recommendations of increasing the quality of concrete and training one junior technician to become a senior technician, we conclude that an estimated XXX could be saved in the throughput time of the components of the MSF-X. This represents a reduction of 2.85% in total throughput time (up to and including installation). The other recommendations have not been quantified and are therefore not included in this percentage. We conclude that the research objective of reducing the time needed for production and installation of the Machine Support Frame by at least 19% cannot be achieved by these quantified recommendations alone, and further measures need to be taken to achieve this reduction.

Table of Contents

1. Introduction

In this chapter we give a brief introduction to the company in Section 1.1. We continue with the problem statement in Section 1.2. In Section 1.3, we introduce the research questions of this thesis. Next, we describe the problem-solving approach in Section 1.4. In Section 1.5, we give the general outline of this thesis.

1.1. Company introduction

Mecal, headquartered in Enschede, has over 25 years of experience as (co)developer in the fields of development, engineering, and operations. Mecal has several other offices around the world employing about 125 people in total.

This project is related to the High-Tech Systems part of Mecal who engages in contracted engineering, High-tech System development and Advanced platform OEM products. The last of which this research is focused on. Mecal designs, produces, and installs Machine Support Frames (MSF) for the semiconductor and imaging market on a global scale. These frames provide stability and lower vibration levels for the high-tech systems placed on top of them and make sure that these machines can operate at the best of their ability.

Mecal is growing at a fast pace, which is why we took on the task to investigate the current production process of the MSF-X[1] and see in which way the required throughput time can be reduced.

1.2. Problem statement

The action problem, which serves as the research goal, is defined as the following:

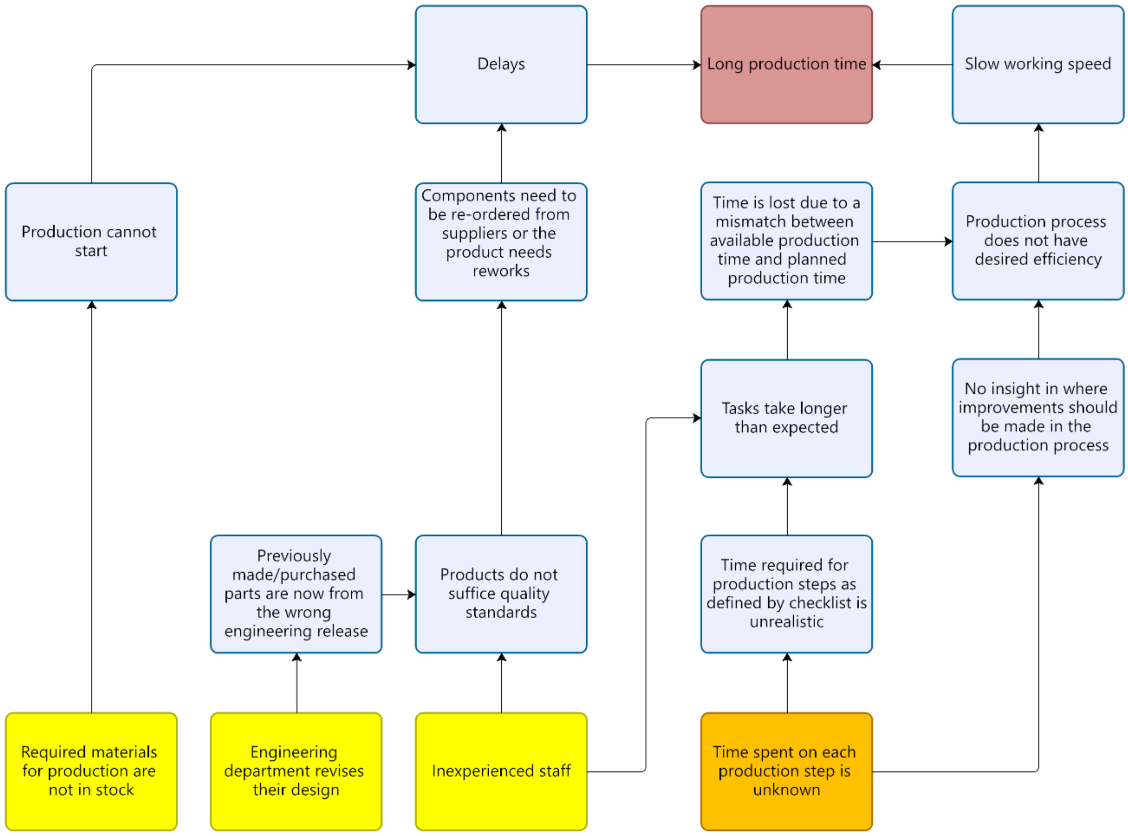
What are some of the actions Mecal can take to contribute to the goal of reducing the time needed for production and installation of the Machine Support Frame by at least 19% to achieve the set production KPIs?

Preliminary analysis has shown that on average it takes Mecal a certain number of hours to produce and install the MSF. An ongoing project in Mecal aims to reduce this by 19% by identifying the production and installation steps that are most time consuming and afterwards determine if and how the product design can be changed to reduce the time needed for production. Since this product redesign would be out of scope, we will focus on the first part of identifying the most time-consuming production steps of the two main components of the MSF-X: Component A and Component B. Afterwards we will check where production time can be reduced and provide possible solutions for it, which should help Mecal achieve their goal.

Based on interviews with employees and internal documents, an overview of current issues at Mecal is made in a problem cluster. A problem cluster contains an action problem, underlying problems, and core problems. An action problem is a gap between a desired norm, in this case a certain number of days for throughput time, and reality. This action problem is caused by underlying problems. In turn, these underlying problems are caused by other problems, or at the end, caused by core problems. Given that the core problems cause all problems that are mapped on top, these are the problems that should be addressed in order to solve the action problem.

A problem cluster helps with identifying these core problems by visually mapping the underlying causes of the action problem. Figure 1 depicts this problem cluster.

[1] Due to confidentiality reasons, this is the name used for the product in question in this report.



Action problem	Selected core problem	Other core problems	Consequences

Figure 1: Problem cluster

The action problem is the long production time of the MSF-X, this is a bottleneck for the production capacity and therefore the management of Mecal wants to reduce it. The action problem is divided into two parts: a slow working speed and delays in the production process.

Delays are caused by additional actions that should not have been necessary or because of a lack of materials. If the required materials are not present, production can only start at a later date. The other reason is additional actions caused by products not being conform quality standards. As a result, more activities need to be done, such as ordering new parts, making changes to the product, or making some parts again. All these activities add additional time towards the production process.

The reason for a slow working speed is the production process having a lower than desired efficiency. This is partly caused by a mismatch between the time it actually takes to perform the production steps and the time that is planned for them. Another reason is the lack of insight in where improvements can be made in the production process, which also relates to our core problem.

The mismatch between actual time spent and planned time happens because some tasks take longer than expected. One reason for this is that newly hired technicians do not have much experience yet and therefore do not work as fast as other technicians who have been working in production for a long time. The other reason is based on expectations. The required production time is not measured but is planned based on experience. As a result, there is a rather big range between expected minimum production time and expected maximum production time.

This brings us to the core problems in the problem cluster. The rules of thumb for selecting the core problem as defined by Heerkens & van Winden (2017) are the following:

1. The problem cluster shows existing problems and their relationships
2. The core problem does not have a cause in itself
3. The core problem can be influenced
4. If there is more than one core problem, pick the most important one

The first potential core problem is the required materials being out of stock. Although missing the required materials is bad for the throughput time of the product in question, it is not necessarily detrimental to employee utilisation. The reason for this is that in almost all cases employees can continue working on other projects and therefore still spend their time worthwhile. Fortunately, this problem does not happen that often in the first place, which is why this will not be selected as the core problem.

The second potential core problem is a revision of the design of a frame. As a result, already fabricated or ordered parts are not according to the design anymore, which will cause delays. This is mostly applicable to other products tailored to customers' specifications, and not that much to the MSF-X, making this not the most important core problem.

The third potential core problem is inexperienced staff. This is something that needs to be considered as one of the causes of the action problem, but this will not be chosen as the core problem. Inexperienced staff is partly temporary, since the technicians will gain experience over time and consequently, assumably improve the speed and quality of their work. Additionally, dealing with these types of problems is also less suited to be the subject of an IEM thesis.

All core problems meet the criteria as defined by Heerkens & van Winden (2017). The most important core problem, which will be the one we select, is the following:

Time spent on each production step is unknown.

As a result of this being unknown, some tasks will take longer than expected while other tasks are finished earlier than expected. This causes the available production time to be spent inefficiently. Another consequence of not knowing this is that it is more difficult to identify issues in the current production process and possible improvements. Additionally, it could also help with a more realistic production planning.

Currently, there are some educated guesses for the time to complete certain production steps, but these are inaccurate and completion time also varies among employees. The production orders in the ERP system use an end date that is later than the actual end date to prevent software issues. Additionally, the production quality checklists that are archived usually do not have clear start- and end dates documented on them. As a result, the actual observed production time remains unknown at a later stage.

The closest measured estimates are production phases that last several hours, as documented on the hour registration form, but these do not always include what frame has been worked on. More about this is discussed in Chapter 4, Section 4.2.2.

The desired norm would be that Mecal has some estimates of the production phases in minutes: the mode, and an indication of the range between minimum and maximum time.

1.3. Research questions

In order to reduce the throughput time, we consider five research questions that need to be solved first. These research questions will guide us towards finding effective solutions to solve the action problem. The research questions are:

A. What does the current production process of the MSF-X look like in terms of process flow?

In order to improve throughput time, we first need to get a detailed overview and understanding of the current production process. Here, we define a process as "an arrangement of resources and activities that transform inputs into outputs that satisfy (internal or external) customer needs" (Slack et al., 2016, p.19). In the end, a process flow will be created of the production process (see Appendix A and Appendix B). This research question is discussed in Chapter 2.

B. What are some of the available theories in academic literature to improve throughput time and which one could be used given the context at Mecal?

By performing a cross-sectional literature study, we will investigate existing literature to choose an appropriate method to improve throughput time. Based on the context of Mecal and the scope and objectives of the thesis, we will use at least one of these theories in the solution generation process. The literature review can be seen in Chapter 3, and the detailed methods of the systematic literature review can be seen in Appendix C.

C. How much time is spent at each stage of the production process?

To investigate the production process further, we investigate in which ways time is currently spent in the production process. Together with the results of research question A, this should give some initial ideas into current issues in the production process and existing bottlenecks. This research question is further examined in Section 4.1.

D. What are the identified bottlenecks and issues in the production process?

After the previous research questions have been answered, we will investigate what the current bottlenecks are in the production process using at least one of the chosen theories from research question B. A bottleneck in a process is defined as the activity or stage where congestion occurs because the workload placed is greater than the capacity to cope with it (Slack et al., 2016, p. 205). These bottlenecks and identified issues are shown in Section 4.2, which forms the basis for the possible solutions as discussed in Chapter 6.

E. How can we model the estimated impact of possible solutions on throughput time?

To further examine the possible solutions, we make use of a simulation model to investigate the impact of them on the current system. We introduce this simulation model in Chapter 5.

F. How can Mecal address the identified issues in the production process?

The last research question investigates how these issues can be addressed and what impact they have on production in general, and throughput time specifically. The basis for this research question is formed by answering the previously mentioned research questions. Additional data collection is done where necessary. Possible solutions are discussed in Chapter 6. Since this thesis is mainly focused on the production environment, providing detailed solutions for problems in other departments is out of scope.

1.4. Problem solving approach

To solve the core problem, we define four steps based on the Managerial Problem-Solving Method from Heerkens & van Winden (2017), to go from understanding the problem to implementing the solution. These steps are:

- Understand the current production process (Section 1.4.1)
- Analyse current process (Section 1.4.2)
- Formulating possible solutions (Section 1.4.3)
- Selection and implementation of possible solutions (Section 1.4.4)

1.4.1. Step 1: Understand the current production process

To reduce the production time, we first need to understand how the production is done at the moment. This includes understanding the current layout of the production floor, the production planning, the way of working, i.e., how do employees know what tasks they need to do each day, who checks the quality, how do they keep track of progress, etc. Data collection is done by reviewing the used production quality checklists, working instructions and by interviewing technicians.

Next, business process modelling is used to create a flowchart detailing what the process looks like from order to finished product. This flowchart will show the intermediate production steps for both components. This step should deal with the core problem of not knowing the time spent at each production step. In this thesis, we will not go into detail in other departments such as sales, logistics, or the installation of the product. The process flow will be limited to the production process of the two main parts of the Machine Support Frame X, namely Component A and Component B. The other parts of the MSF-X or other products are out of scope due to time constraints.

1.4.2. Step 2: Analyse current process

After step 1 is complete, we should have a clear overview of the current production process. After performing a literature review (see Chapter 3), we will use one or more theories to investigate what the current bottlenecks and other issues are in the production process. Other core problems outside the production environment, such as missing required materials and the engineering department revising their designs, will not be investigated further. Additionally, it should become clear how the estimates of production time differ from the planned production time as well as the degree of variability. These differences can be analysed to investigate underlying problems.

Data collection for processing times is done by distributing the production quality checklists to technicians and asking them for estimates for the minimum, mode, and maximum duration of certain sets of activities. The data collection, its limitations and data validation are further discussed in Section 4.1.

1.4.3. Step 3: Formulating possible solutions

Once the bottlenecks have been identified in Step 2, potential solution will be generated. With the help of an analytical approach based on a simulation model, it will be possible to estimate changes in throughput time as a result of these potential solutions.

According to Robinson (2014), there are three reasons for choosing simulation over other methods. The most important reason is modelling variability. If systems are subject to elevated levels of variability, then simulation is often the only way to model it accurately. Therefore, the choice for an analytical approach or a simulation approach will mainly depend on the findings of the processing times distribution. If these durations have a low standard deviation, then an analytical model will suffice.

However, if these distributions have a high standard deviation, when the modelled situation is complex, or when there are significant differences between employees, we have to resort to a simulation approach.

Since we observe high variability in the system, we will use a simulation model to predict changes in throughput time based on the stochastic duration of production activities. It also gives insight into how the total production time changes if certain production steps take longer or shorter.

1.4.4. Step 4: Selection and implementation of possible solutions

In the last step, different approaches to reduce throughput time will be provided. Here, we will give some advice on which solutions are best and some recommendations for implementing them. Writing an extensive report on how to implement them is out of scope.

1.5. Outline

Following these four steps should help in reaching the goal of providing Mecal with some recommendations regarding implementing possible solutions to reduce throughput time.

In Chapter 2, we address Step 1 and research question A. Next, we discuss research question B in Chapter 3. After finding suitable theories to improve throughput time, we continue with Step 2 and discuss research question C and D in Chapter 4. After analysing the current process, we continue with discussing the simulation model, addressing research question E in Chapter 5. We use this model to estimate the impact of possible solutions in Chapter 6 and address research question F. In the end, we discuss our conclusion and recommendation in Chapter 7.

2. Current situation

In this chapter we address research question A: *"What does the current production process of the MSF-X look like in terms of process flow?"*.

Section 2.1 discusses the current production process of the MSF-X limited to Component A (Section 2.1.1) and Component B (Section 2.1.2). Section 2.2 discusses the current operational planning and control activities.

2.1. Current production process

To consider the current production process of the MSF-X, we take a look at the two main components of it, both of which are not client-specific. Due to confidentiality reasons, we will call these components Component A and Component B. The other components are either client-specific or do not have such a significant impact on Mecal's resources. Therefore, given the limited time, we will not consider the other components of the MSF-X. The distinction is made to consider the components separately, as opposed to considering the product as a whole, because these components are produced independently of each other. Only during the installation of the frame, all components are assembled, creating the MSF-X itself.

Currently, a limited amount of Components A and B is kept in stock in preparation for clients' orders. "Orders" are placed as so-called projects, which are custom-made designs according to the client's wishes and include the installation of the MSF-X on site. Since these are large-scale projects, the MSF-X as a whole has a long throughput time.

Both components have overlap to a certain extent in the types of production processes that are applied to them. To keep track of the progress, the technicians keep a production quality checklist at hand. This checklist shows what activities need to be done, in what order, and what the related quality standards are. The checklist also defines production phases, which are a set of activities that should be attainable within one day or include clearly related activities.

Both components require a significantly varying production time. For Component A, the planning generally assumes a minimum number of working days to produce them, up to a maximum of 65% more working days. For Component B, this range is approximately from the minimum number of working days up to 40% more working days at its maximum. The main given reasons for this range are twofold.

The first reason is the assigned technician: depending on the experience of the assigned technician, production might take longer or shorter. The second reason has to do with the priority of the components of the MSF-X. These components are usually made to stock, while other ongoing frames are typically made to order. Since components A and B are usually made to stock, their priority can be lower at times, causing technicians to work on other frames instead of Component A or Component B. Other additional factors are discussed in Section 4.2.1.

In Section 2.1.1 and 2.1.2, the production process of Component A and Component B is summarized. For the detailed process flows of Component A and Component B, see Appendix A and Appendix B respectively.

2.1.1. Component A

Figure 2 depicts the simplified production process of component A.

Figure 2: Simplified production process of Component A

The production process starts with an incoming goods check that contains activities such as ensuring that all required materials are present. After the incoming goods have been checked, the frame, also called the element, is set up in one of the production lanes. The production lanes are the available spots that a frame can occupy during the entire production. Once the frame is moved to the right spot using an overhead crane, production can start.

The next step is the preparation for placing the interface plates. These IF plates are treated stainless steel plates that allow the machine placed on top to be connected to the frame. In short, activities during this phase include making sure that the flatness of the frame is appropriate for the upcoming activities, cleaning the frame and degreasing it. After these activities are done, the IF plates can be glued on top of the concrete surface.

In the following step the frame is cleaned again, and the sides of the frame are sanded and degreased. After any remaining holes and irregularities in the sides have been filled, the coating can be applied to the side.

After the coating is applied, the frame is cleaned again and a flatness measurement is done again, this time with a higher precision to ensure that it suffices all tolerances during installation. Now, the frame is cleaned again, and protection rubber is added before shipment. Once the protection rubber is added, the frame is extensively quality-checked and packed for shipment.

2.1.2. Component B

Figure 3 depicts the summarized production process of Component B.

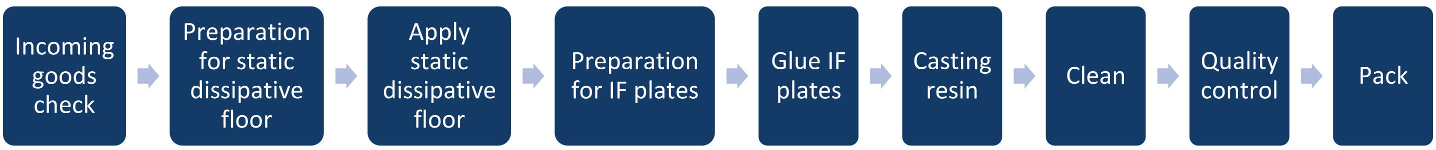


Figure 3: Simplified production process of Component B

In the same way as Component A, production starts with an incoming goods check and setting up the frame in one of the production tracks. In the next step, a brass earth bolt is added to the frame and the concrete is made level with the bumper on the side. This levelling is done to make sure that once the static dissipative floor is added on top, it will be added to an even surface with the sides being at the same height as the concrete. Consequently, this process is vital; if the flatness of the concrete is not sufficient, this will give problems at a later stage once the static dissipative floor is added. Additionally, if these issues are not resolved, it will also be problematic during the installation of the frame since the required flatness is not achieved. Once the concrete suffices the flatness specifications, the frame itself is checked to see whether it is set up correctly on the jacks and the component itself is level.

After these steps, an external company adds the static dissipative floor to the frame. The static dissipative floor makes sure that any electrostatic discharge in cleanrooms will be mitigated to increase safety and to make sure that equipment will not be damaged by any electrostatic discharge. The operations department makes an appointment with the external company, after which they come to Mecal to provide this service.

Once the static dissipative floor is added to the frame, the flatness and slope values are measured, and corrected if necessary. The next step is to prepare for applying the interface plates to the frame by marking the right dimensions and drilling the static dissipative floor. Once the right lines are drawn according to the component's drawings, the interface plates can be added to the frame. Gluing the interface plates and other parts to the frame is one of the main activities of the production process and takes multiple hours.

Now that all parts are glued to the frame, flatness and slope values will be measured again. Afterwards, an external company will come in to apply the casting resin to the frame. After the external company is done, a coating is applied to the side of the frame. Once these layers are dry, the external company comes back to apply the final layer of casting resin.

In the next step, the frame is thoroughly cleaned and made dust-free. Before shipping, the frame is extensively quality checked, packed, and put in a box with the required shipping information.

2.2. Planning and control

In this section, we consider the current planning and control systems in Mecal. With planning we mean the intended production activities in the future, which might experience changes. In turn, how to deal with these changes is the control part of "planning and control". Planning and control comprises four types of activities, which are summarised in Figure 4.

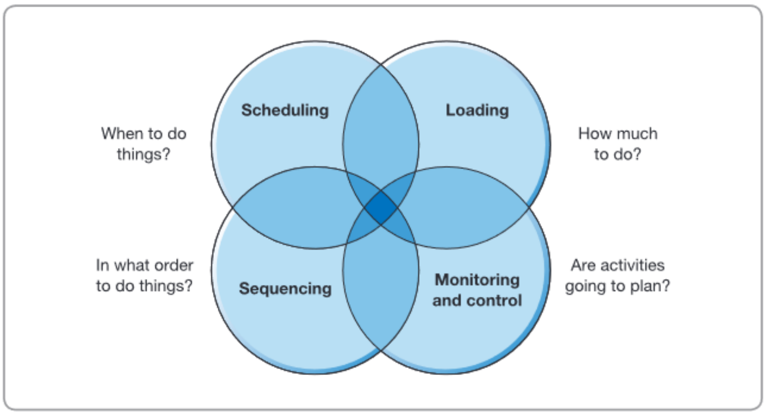


Figure 4: Planning and control activities (Slack et al., 2016, p.328)

Scheduling

At the moment, the operational planning department generates two kinds of planning: a weekly production schedule on a day-to-day level and a longer-term planning of four months with a weekly level of detail.

Most frames are only produced once Mecal receives a project from their customers. These frames form the basis for the long-term production planning. Next to the frames that are specifically tied to a customer, frames are also made to stock in preparation for customers' orders. Components A and B are often added to the production planning as make to stock products. This allows for some flexibility if for some reason the priority changes of the make to order frames.

One or two weeks before starting production, the longer-term planning changes to the short-term schedule and starts to include details on a daily level. The short-term schedule provides an overview of projects that are being finished, ongoing projects, and upcoming projects. For each day of the week, it shows which technician will work on which frame, and what activities need to be performed from a high-level view. In general, one person is assigned to work on one project, although this does not mean that only one person does the entire production of a frame. Sometimes, the assigned technician is not present for the entire duration of the production process, because the technician might be sick, working on the installation of a frame abroad, or on leave. Naturally, other colleagues help out as well sometimes.

Sequencing

The difference between make to order and make to stock frames plays a key role in sequencing. The make to order frames have a higher priority than the make to stock frames. In turn, Component B has a higher priority than Component A because of the outsourced steps in the production process. Only if stock levels are getting low, Components A and B become more important in order to make sure that stock levels remain sufficient. Priority might also change if the project planning changes. If the installation date at the customer on-site is moved, then this could have a significant impact on operations. In case the installation date is advanced, the frame in question will get a higher priority. Since the components of the MSF-X are usually made to stock, their production might need to be postponed.

Loading

In general, the goal is to keep the production lanes occupied as long as there are enough technicians to work on them. This allows the technicians to continue working on other frames if some materials used on a prior frame need time to cure or dry. Given the higher priority of make to order frames, they are loaded first and, if capacity allows for it, make to stock frames are added to the production schedule afterwards as well.

Monitoring and control

To check the actual execution of the production schedule, so-called “planning meetings” are organised with the foremen, the purchasing department, and the operational planning department. In these meetings the current progress of ongoing frames is discussed. The focus of these meetings is mainly on aligning the dates of outsourced steps and to make sure that these appointments are attainable. Additionally, they discuss when frames are expected to be finished and when they can start the production of a new frame. Often, production does not take place exactly according to the production planning. Reasons for this misalignment between actual performed activities and planned activities will be discussed in Section 4.2.2.

2.3. Conclusion

We started this chapter with research question A: "*What does the current production process of the MSF-X look like in terms of process flow?".* By interviewing technicians, reading the working instructions and the production checklists, we created the process flows of Components A and B. Figure 2 shows the simplified production process of Component A and Figure 3 for Component B. For the full process flows of Components A and B, we refer to Appendix A and Appendix B, respectively.

We find that both components have several overlapping types of activities and both of them are usually made to stock. Even though both are usually made to stock, Component B has a higher priority than Component A because of the outsourced steps. Additionally, Component B takes longer because of additional production steps, and is harder to produce since its specifications are stricter.

To generate the production planning, a minimum number of working days is considered for Component A, up to 65% more working days at its maximum. This range for Component B is approximately a longer minimum number of working days up to an additional 40% more working days.

The components of the MSF-X that we consider here are typically used to fill the production schedule in case there are less ongoing projects. This way, there is room for some flexibility in production and stock levels remain sufficient for the MSF-X. Generally, the goal is to keep the production lanes occupied, given that there is enough capacity.

3. Reducing throughput time: literature review

In this chapter we focus on research question B: "*What are some of the available theories in academic literature to improve throughput time and which one could be used given the context at Mecal?*". Many different methodologies have been formulated over the years. In this section, we aim to find some theories to reduce throughput time that are most applicable to the context of the company.

The characteristics of the product in question and the production environment also determines the scope for these theories. Any found theory needs to be compatible with these characteristics, such as make-to-stock products, a low volume - high variety product environment and also the type and layout of the production process.

For further details about the approach of the systematic literature review, see Appendix C.

3.1. The Lean framework

To identify the current issues relating to the production process, we make use of the Lean framework. Lean is focused on simplifying processes and, consequently, reducing waste and accelerating flow (Chiarini, 2011a). In turn, waste is defined as those activities in the process that do not add value (Slack et al., 2016, p. 506). Operations should continuously aim to remove any waste in the process and involve all staff in doing so. As a result, processes will add a higher fraction of their time spent on providing value to the customer and spend less time on activities that do not.

Adding value is an important proposition of Lean. We say that activities add value if they satisfy the following three criteria:

1. *They physically transform the product*: a product will only come closer to its end result if steps are performed that actually bring the product closer to its final state.
2. *The customer is willing to pay for these activities*: customers do not want a product that is different than the communicated objectives and specifications.
3. *They are performed correctly the first time*: products should not have to undergo reworks, neither the company nor the customer should have to spend additional resources on the product.

Any activity that does not satisfy all three criteria, is a form of waste. There exist three types of waste according to the Lean philosophy (Slack et al., 2016, p. 506-508):

1. *Mura*: the lack of consistency resulting in periodic overloading of staff or equipment. If tasks are not properly documented, then the results will differ based on how different staff do it at various times. This means that the required time and quality will be different. A lack of consistency leads to an overburdening of people and equipment: muri.

2. *Muri*: absurd or unreasonable requirements that will lead to poor outcomes (overloading waste). Failing to understand the priority of tasks, the required time of them and the resources that are needed will cause non-value-added activities. Avoiding this type of waste can be done by proper planning and control (see Section 2.2). This means that muri can be avoided by choosing the right priority of activities in the operations planning and understanding the required time and resources.

3. *Muda*: activities in a process that do not add value to the operation or customer, mainly because of poorly communicated objectives, or the inefficient use of resources. For activities to be effective, they must be properly recorded and communicated. Taiichi Ohno, the inventor of Lean manufacturing, defined seven types of muda (Ohno, 1988):

    - Transportation: unnecessary movement of products and employees.
    - Inventory: all inventory should be a target of elimination. High levels of inventory masks underlying problems in operations.
    - Motion: wasted motion that does not add value to the product.
    - Waiting: prevents technicians from continuing production.
    - Overproduction: producing more (or less) than needed.
    - Overprocessing: doing more than the customers asks for.
    - Defects: poor quality work or materials that leads to errors, requiring additional time to fix.

    It should be noted that often an eight waste, skills, is added to this list as well. This waste is relevant if companies do not use, or under-utilise the skills, talents, and knowledge of their employees, which is one of the main points of the Lean philosophy.

These causes of waste are related. Inconsistent processes (mura) can lead to overloading equipment and people (muri), which will cause several non-value adding activities (muda).

To identify waste and its causes, a so-called value stream map is made. Value stream mapping is visualising the entire production process including material and information flow (Singh et al., 2011). A distinction is made between activities that add value to the customer, as well as activities that do not, but are required to bring the product(s) through the flow.

3.2. Theory of Constraints

The second useful methodology to reduce throughput time is the Theory of Constraints (TOC). TOC states that each process can be seen as a chain where each step of the production process has certain constraints. Some of these constraints (but usually only one) are the weakest links that hinder an organisation or company to move towards their goal (i.e., their purpose) (Gupta & Boyd, 2008).

To reduce throughput time, these bottlenecks need to be found in the process. As before, we define the bottleneck in a process as the activity or stage where congestion occurs because the workload placed is greater than the capacity to cope with it (Slack et al., 2016, p. 205).

Consequently, to improve throughput, we can deal with the bottleneck in the process by following five steps (Goldratt, 1990; Slack et al., 2016, p. 522):

1. *Identify the system constraint*: this is the weakest link. It can be a physical constraint, but also a decision making or policy constraint.
2. *Decide how to exploit the constraint*: make as much use of the constraint as possible, preferably without expensive changes.
3. *Subordinate everything else to the constraint*: adjust the other activities of the process to a level where the constraint can operate at maximum effectiveness. Evaluate the process. If this causes the bottleneck to move, return to step 1.
4. *Elevate the constraint*: if steps 2 and 3 are not successful, the constraint needs to be eliminated by applying major changes to the system.
5. *Start again from step 1*

Goldratt argues that these bottlenecks should be the control point, making the constraints in the process a major input to planning and control. The aforementioned steps are implemented by the *drum*, *buffer*, *rope* concept (Thürer & Stevenson, 2018). The constraint represents the drum, that is, when jobs should be released. The buffer is the inventory before the constraint. The rope is the communication channel that is used to provide feedback from the drum (the constraint) to the order release. This feedback aligns the input to the system with the output of the bottleneck.

3.3. Variability & uncertainty

This section relates to the "mura" and "muri" types of waste from the lean framework. Mura, the lack of consistency, leads to variability in the production process. Muri, the "overburden or unreasonable" can be avoided by proper planning and control. In turn, proper planning and control can only be done if the duration of a set of activities is known, and lead time and uncertainty is controlled for.

Begg et al. (2014) discuss the differences between uncertainty and variability in their paper. They define uncertainty as: "*not knowing if a statement (or event), is true or false*". Under uncertainty, it is unclear what the value or outcome will be of an event. In the context of Mecal, examples of uncertainty would be not knowing if a specific customer will delay their project, if an employee will be sick next week, or if a supplier will be delayed by two days. Uncertainty can be quantified by probability distributions, stating their likelihood based on the current state of information. Variability means that a quantity can take on multiple values at different times or instances, based on observed data.

Simangunsong et al. (2012) define fourteen sources of supply chain uncertainty divided into three groups:

1. Internal organisation uncertainty
2. Internal supply-chain uncertainty
3. External uncertainty

To deal with these uncertainties, they provide two types of strategies: reducing uncertainty strategies and coping with uncertainty strategies. The first type aims to tackle the sources of uncertainty, while the second does not have this objective, but rather aims to deal with its consequences. These sources and strategies to deal with uncertainty are shown in Figure 5.

The authors have identified these sources of uncertainty based on a number of models that are presented in the literature. These sources themselves also have a number of underlying causes (see Appendix D for all dimensions). The authors argue that many of these sources need more empirical evidence to verify them. For the strategies to reduce or cope with these uncertainties, the same thing can be said. Not all strategies have strong empirical data to verify their impact on the sources of uncertainty. Therefore, we do not consider the proposed strategies without empirical data as a possible solution to help with uncertainty.

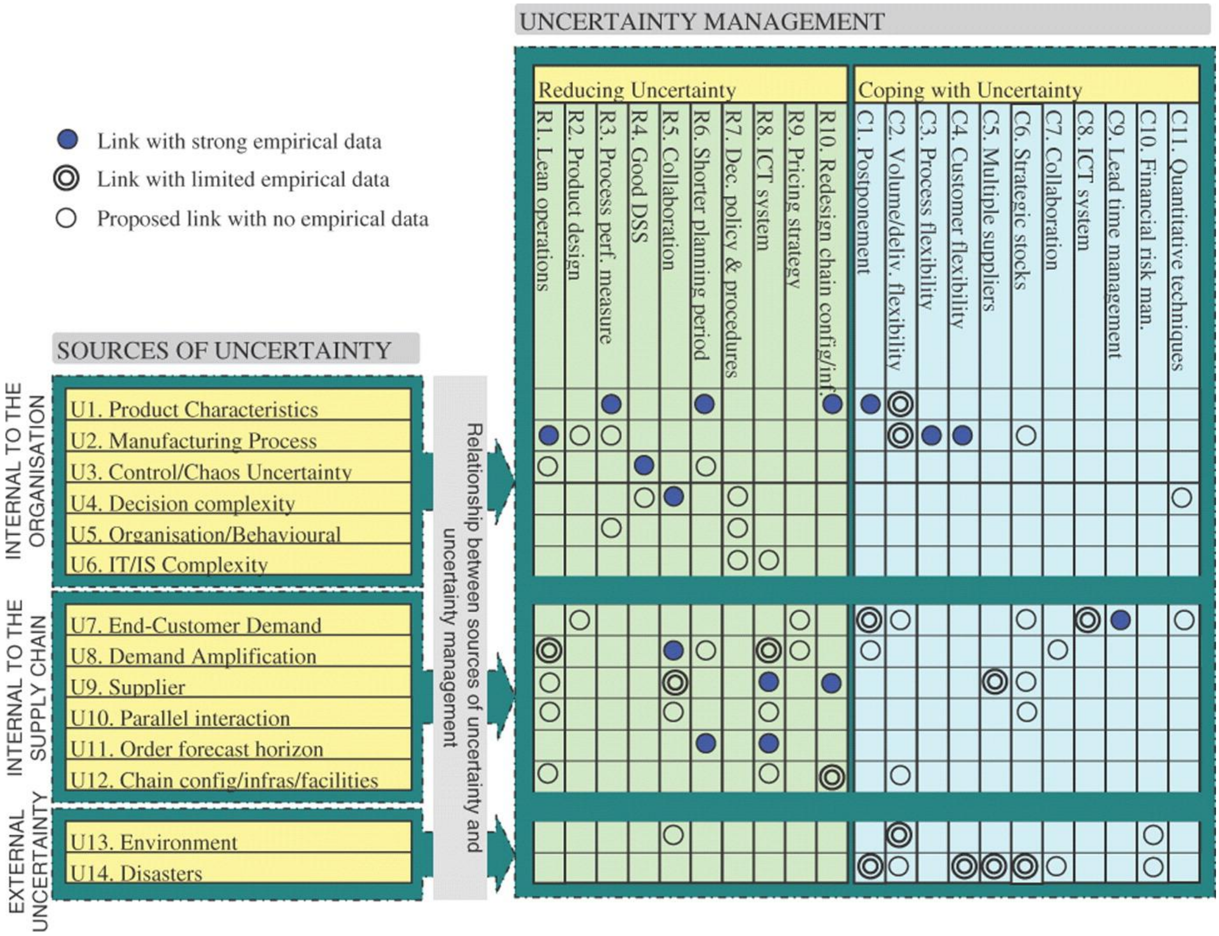


Figure 5: Alignment between sources of uncertainty- and uncertainty-management strategies (Simangunsong, 2011)

3.4. Conclusion

To reach the goal of reducing the throughput time of the MSF-X, we make use of the Lean framework and the Theory of Constraints.

The lean framework is a useful tool to reduce waste in the production process and accelerate flow. Lean defines three types of waste: mura – inconsistency, muri – unreasonable work, overburdening capacity and muda – activities that do not add value to the operation or customer. Identifying waste can be done by creating a value stream map of the production process. Consequently, solving these types of waste will make processes more efficient and reduce throughput time.

Mura and muri are closely related to variability and uncertainty. Simangunsong et al., (2012) provide a framework based on available literature. This framework identifies several sources of uncertainty and proposes strategies to tackle the source or reduce the impact of its consequences. This will help with identifying possible sources of uncertainty and providing solutions for underlying sources of mura and muri. Muda can be addressed by findings ways to eliminate or reduce the time spent on non-value adding activities. Additional knowledge might be required to do this, depending on the type of problem that needs to be addressed.

Furthermore, we have the Theory of Constraints and the drum-buffer-rope concept. TOC will provide some guidance on identifying, adapting to, and dealing with bottlenecks in the production process. Consequently, reducing the impact of bottlenecks in the production process will result in lower throughput time.

4. Value stream map and identified waste

In this chapter we discuss research question C: "*How much time is spent at each stage of the production process?*" and research question D: "*What are the identified bottlenecks and issues in the production process?*". Section 4.1 discusses the current time spent at each stage of the production process by means of a value stream map from the Lean framework. Section 4.2 discusses the identified bottlenecks and issues according to the Lean framework divided into the three types of waste (i.e., mura, muri, and muda) and their sources.

4.1. Value stream map

To provide a general overview of the duration of the entire production process of both components, two value stream maps were created. These value stream maps show the expected required minimum, mode, and maximum duration for each phase of both Component A and Component B, as well as the likely waiting time between two phases due to material use with a fixed lead time.

It is infeasible to get enough observations to provide accurate estimates of the distribution of the duration of different production steps. The throughput time of both components is rather high, meaning that only a few observations could be made in the timespan of writing this thesis. Additionally, technicians also work on other frames that we do not consider here. Therefore, we resort to creating a triangular distribution of the required time for different production steps by asking technicians for the minimum, most likely (i.e., mode) and maximum time that is required to perform a set of activities in each phase.

This data collection was done by providing experienced technicians with the production quality checklist and asking them for time estimates (minimum, mode, maximum) of the indicated sets of related activities. For Component A, three technicians were asked for time estimates of the production process, divided into twenty sets out of the fifty-nine steps that are defined on the production quality checklist. For Component B, two technicians provided estimates for thirty-nine sets out of sixty-nine steps in total. The choice for these sets is mainly based on whether these sets of activities are value adding or not. Sometimes, insignificant non-value adding activities that only take a few minutes are included with a group of value adding activities. The reasons for doing so, is because these activities do not have a significant impact on larger timeframes and likely have relatively high measurement errors. Additionally, we want to limit the burden of filling in these forms for the technicians.

Based on the previously defined criteria for value adding activities and according to the lean philosophy (Section 3.1), we differentiate between activities that are value adding and those that are not. Consequently, we are able to estimate the value-adding time (%VAT) as a percentage of time spent on each phase by calculating:

$$\%VAT = \frac{time\ spent\ on\ value\ adding\ activities}{total\ time\ spent\ on\ phase} * 100$$

Equation 1: Calculation of percentage value-adding time

It should be noted that because of this type of data collection, all %VAT as noted in the value stream map are estimates and therefore not completely accurate. To precisely measure %VAT, a different kind of data collection is required. In order to do so, all activities performed by technicians should be tracked on a detailed level over a long timeframe, which is out of scope for this thesis. Additionally, some phases are defined to be non-value adding by design.

Phase 1 of Component A and Phase 1 and 3 of Component B are examples of this. These phases only include non-value adding activities, such as quality checks and milling the top of the frame to assure sufficient flatness (for Phase 1 of Component B). As a result, these phases have a %VAT of 0%.

In the opposite case of 0% VAT, we have Phase 5 of Component A. Phase 5 is said to have an unrealistic %VAT of 100% because the non-value adding activities are minor, assumed to be subject to inaccurate measuring, and are therefore disregarded.

In Section 4.1.1, we discuss the likely waiting times between phases that are used in the value stream maps. The value stream maps for Component A and Component B are shown in Section 4.1.2 and Section 4.1.3, respectively. In Section 4.1.4 we compare the throughput time estimates from these value stream maps to the required minimum, mode, and maximum number of working days according to the production planning.

4.1.1. Waiting time between production phases due to material use

To get some estimates for the likely waiting time between phases in the value stream map, we need to consider the potential waiting time as a result of applying materials that need to dry/cure (see Table 2).

In this value stream map, the waiting time between phases (*W_between*) depends on the required application time (*a*) to apply the material to the frame, the activities that can be performed immediately without the material being properly cured (*b*), and on the required curing time (*c*). For a given working day (= 7.5 working hours while accounting for breaks), this relation is given as:

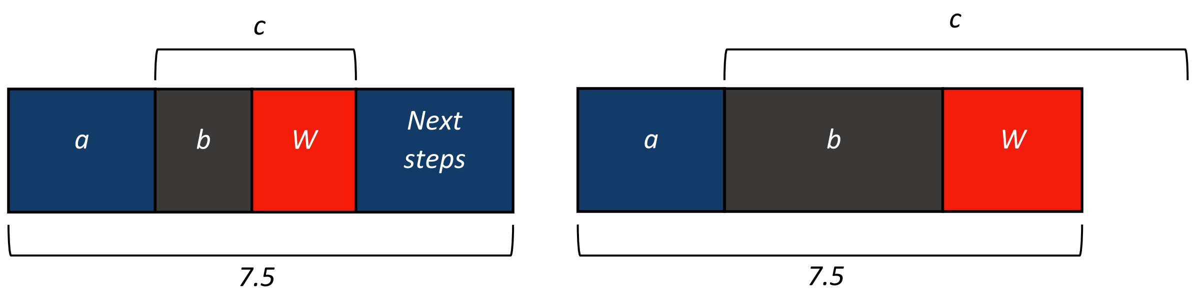
$$W\_between = \begin{cases} MIN\big(c - b, MAX(7.5 - a - b, 0)\big), & if\ b \leq c \\ 0, & otherwise \end{cases}$$

Equation 2: Calculation of production phase lead time due to material use

The waiting time between phases is said to take place if the technicians need to wait for the material to cure before the activities of the next production phase can start. This happens when all activities that can be performed while the applied material is not yet fully cured are finished, but the applied material has not cured enough yet for the subsequent activities to start.

If the activities that can be performed immediately without curing take longer than the curing time (i.e., b > c), the waiting time is zero since the next production phase can start once these activities are finished. The same thing is also true if the application of the material in question and the activities that can take place immediately after exceed the working day, since the whole day is spent on the production process and any applied material will be fully cured the next day regardless.

If the activities that can be performed immediately without curing take less than the curing time (i.e., b ≤ c), waiting time does occur. Figure 6 shows this waiting time depending on whether or not there is time left to start the next process steps.



W_between = c – b

W_between = 7.5 – a – b (≥ 0)

Figure 6: Waiting time between phases if b ≤ c

If b ≤ c then the waiting time between phases is equal to:

- *c – b*, if the technicians need to wait for the material to cure because there are still some hours left on a working day, after both *a* and *b* are finished in less than 7.5 hours and the remaining curing time does not exceed the current working day.

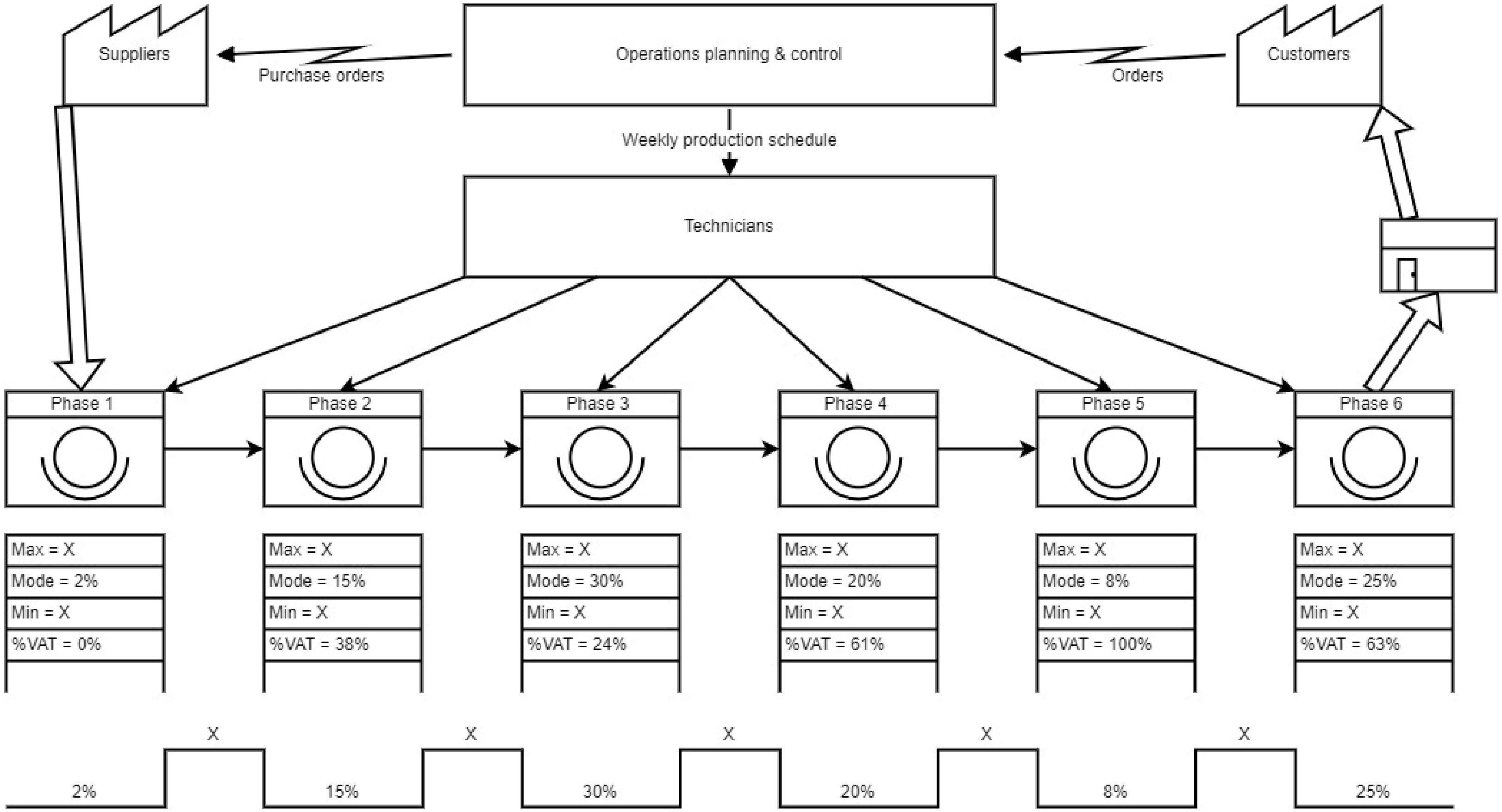
- *0*, if b = c, since the next process steps can start once the activities that can be performed immediately without curing are finished.

- *7.5 – a – b*, if the curing time exceeds the remaining working hours after both *a* and *b* are finished.

For the detailed explanation of this equation, see Appendix E.

Figure 7 and Figure 8 show the value stream maps of Component A and Component B, respectively. These figures are partly censored due to confidentiality agreements.

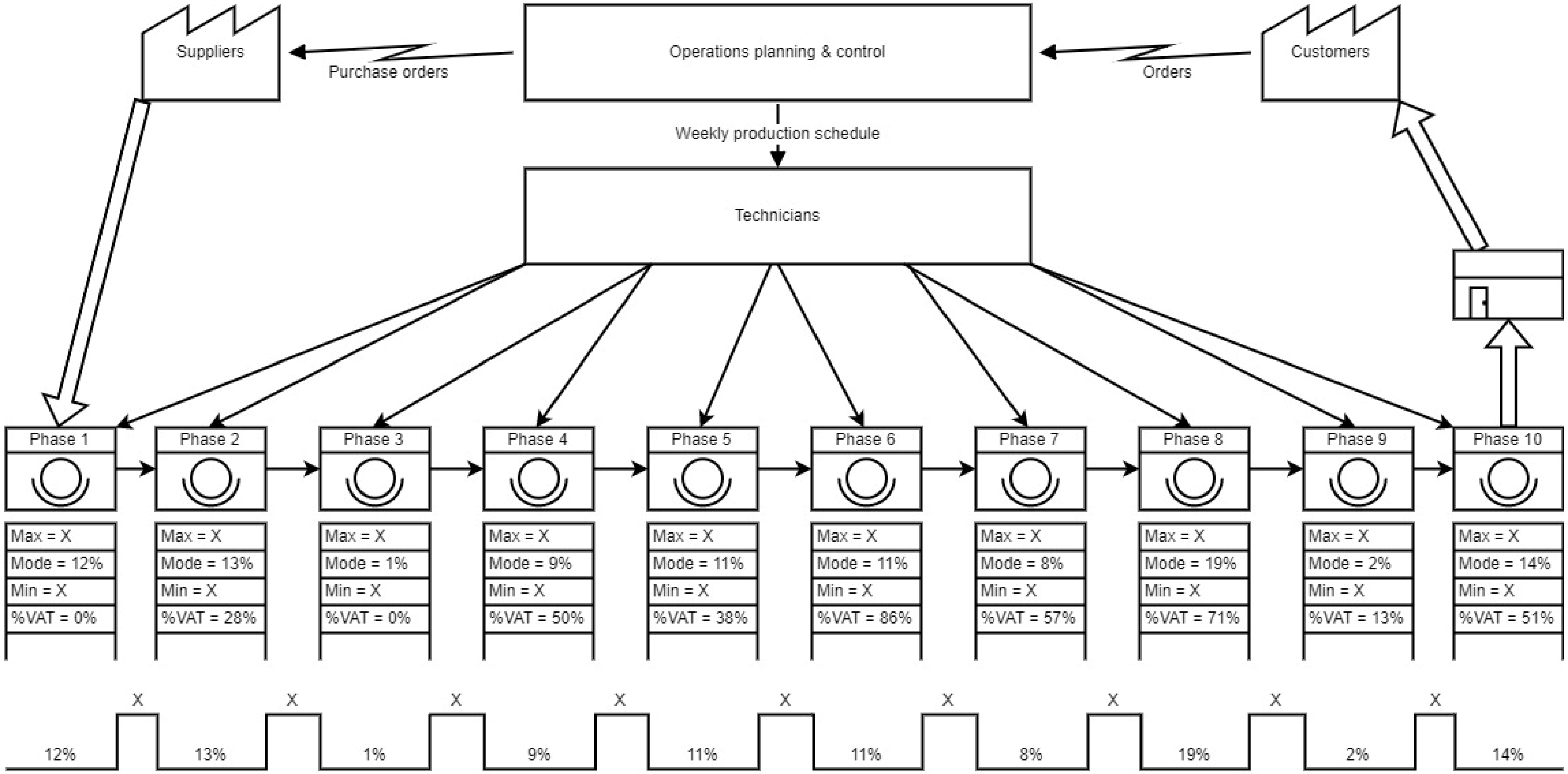
4.1.2. Component A



	Total processing time	Total lead time
Maximum:	X	X
Mode:	100%	X
Minimum:	X	X

Figure 7: Value stream map of Component A

4.1.3. Component B



	Total processing time	Total lead time
Maximum:	X	X
Mode:	100%	X
Minimum:	X	X

Figure 8: Value stream map of Component B

4.1.4. Comparison of production time estimates

We now compare the throughput time estimates from the value stream maps to the required minimum, mode, and maximum number of working days according to the production planning. Due to confidentiality reasons, we only provide differences as a percentage from the planned duration. In Table 1, a value of 100% would indicate that the reported estimates of the required number of working days, as mentioned in the value stream map, is exactly the same as the number of working days as used in the production planning.

Table 1: Comparison between throughput time in value stream map compared to planning

	Percentage difference compared to planning		
	Minimum	Mode	Maximum
Component A	94.4%	101.3%	108.3%
Component B	80.5%	97.7%	95.3%

The values used in Table 1 are the averages of the technicians who provided these estimates. It is important to note that although these values are all reasonably close to 100%, the estimates per technician are all somewhat different. In the same way, the estimates used in the production planning are more nuanced in reality and are not strictly given as a set number of working days. Instead, they would also account for current workload, amount of experience from the designated technician, possible help from other colleagues etc.

As an example, the indicated 80.5% for Component B of the minimum throughput time comes from experienced technicians. It would be unreasonable for the planning department to always use this number of working days, since you would want to provide more time for inexperienced technicians. Perhaps, this table might suggest that the production department could simply lower the number of required working days in the schedule, which is not the case in general, but depends on the specific circumstances.

Further discussion about data quality can be seen in Section 7.3.

4.2. Waste

Now we turn to the identified sources of waste according to the three types of waste from the Lean theory: mura, muri and muda. In Section 4.2.1, we discuss mura. In Section 4.2.2, we discuss muri. In Section 4.2.3 we give a short overview of muda.

4.2.1. Mura

The lack of consistency leads to variability in the production process. Variability in processes results in waiting time and resource under-utilization (Slack et al., 2016, p. 209,210). As defined by the Lean philosophy, waiting time is a non-value adding activity, which is why variability should be reduced where possible. In the context of Mecal, a high variability in processing times means that a frame occupies one of the production lanes for a longer period than expected and, additionally, it prevents the next frame from starting production. Moreover, having high levels of variation makes it more difficult to detect changes in process performance (Slack et al., 2016, 608). This is because it remains unclear if observed differences from expected levels, in terms of speed or quality, are the result of natural variability, or whether they are the result of (potentially structural) process changes. Additionally, reducing levels of variability will lead to a better understanding of how and why a process is behaving a certain way. Therefore, reducing variability in the production process has several benefits, including the indirect reduction of throughput time.

The sources of mura within the production process are discussed below. In Section 4.2.1.1, we discuss the experience of staff. Next, we discuss the craftmanship of ongoing frames in Section 4.2.1.2. In Section 4.2.1.3, we proceed with the quality of concrete. Last, we discuss the outsourced steps in Section 4.2.1.4.

4.2.1.1. Experience of staff

Once technicians gain more experience by working for longer periods of time in production, they understand the production process better and assumably become faster and deliver better quality work. Since the frames made at Mecal each have a relatively long throughput time, it could take some time before employees become familiar with working on them. Additionally, there are multiple types of frames that are alternatively produced, meaning that gaining much experience with one frame in particular could take a while. Experience also plays a role in the equipment used and the activities that are performed since technicians have to learn how to use the tools and materials correctly. In the beginning, experienced technicians help the new technicians and provide some guidance on how to do the production steps.

Additionally, Mecal created several working instructions that explain how some of the production steps should be performed. The goal of these working instructions is to attain a uniform way of working and achieve a similar result in terms of quality and productivity levels for all technicians. Additionally, these working instructions are also used to train new technicians and to make sure that they have a manual laying around if they need it. For Components A and B there are working instructions for the gluing activities and for applying the protection rubber to the frame, but not for other activities in the production process.

4.2.1.2. Craftmanship of ongoing frames

The difficulty of ongoing frames is closely related to the experience of the technicians. Some frames include more complex steps to produce them. These steps often have a certain level of craft to them and consequently, they are more susceptible to the amount of experience the assigned technician has. As a result, certain steps in the production process require more time and care before they meet the set quality standards, which is especially the case for Component B. Since Component B has stricter specifications compared to Component A, it becomes more important to deliver high quality work in order to reach them. Additionally, technicians need to have sufficient knowledge and experience before they can start working on Component B. As an example, technicians need to learn how to do flatness measurements in the right way and how to work with the related software.

4.2.1.3. Quality of concrete

Another variation in the production time is caused by the quality of the used concrete. A significant amount of time is spent into assuring the right flatness and slope values and filling any irregularities or remaining holes in the concrete. It takes some time to measure these flatness and slope values in the first place and, additionally, it takes a while to ensure the set quality standards if these values are outside their tolerances. The quality standards for concrete as set by Mecal are higher than the set specifications as ordered from the supplier. As a result, one of the first production activities for Component B is to ensure these higher internal quality standards. The amount of work these activities take mainly depends on the quality of the concrete, which is one of the sources of mura in the production process.

4.2.1.4. Outsourced steps

The lead time from the outsourced steps can occur at two points in time. Either the frame is ready for the outsourced step, but the appointment is scheduled at a later date, or the frame is not yet ready, and the appointment has to be rescheduled.

The choice for outsourcing these steps was made when Mecal was much smaller and had a smaller team. Since Mecal lacked the expertise and these steps were not routine tasks at that time, they were outsourced to an external company. After all, an external company already has the knowledge and experience to do this quickly.

The first case where unnecessary waiting time occurs is when the frame is ready for the outsourced step (static dissipative floor or casting resin), but the external company only comes to Mecal at a later date. In the production phase that precedes the application of the static dissipative floor, Glue B or Material D is applied to the frame. Most technicians prefer working with Glue B since it is more convenient to work with than Material D (Material D comes in smaller containers). Given the longer lead time, this option can only be chosen if there is enough time left for the glue to cure. If there is not, then the technicians will have to use the Material D to make sure that the frame is ready for the appointment in time.

For applying the static dissipative floor, the technicians can only work on the sides of the frame while waiting for the appointment. This still takes several hours, but after that, they can only continue production once the static dissipative floor is added to the frame. The technicians cannot perform other activities while waiting for the casting resin, so any time between the frame being ready for the appointment and the actual appointment, will always be waiting time. Therefore, not scheduling these activities efficiently can be a source of mura and waiting time.

However, in practice, coordinating this can be difficult due to the (in)flexibility of the external party, scheduling changes, and variability in the production process. Factors such as supplier delays, employee sickness or unexpected leave, and changes in project planning of customers, can influence the available workforce and priority of ongoing frames. As a result, there might be too many technicians for the available work causing Component B to be finished way before the appointment, or in the other case, the appointment needs to be rescheduled since working on other frames has become more important.

This exemplifies the second reason of lead times and mura from outsourced steps. Needing to move the appointment since the frame is finished way ahead of planning, or because the frame is not yet ready, introduces another aspect of variability. Now, the required waiting time depends on the flexibility of an external party that cannot be controlled directly. Operations can make a schedule for the internal production, but the external company still needs to be available on the desired dates for this schedule to fully work out, in addition to the internal production going according to plan. Of course, the external company also prefers to work on multiple frames at once if they are at Mecal, in order not to come back that often. Another factor that needs to be considered is that by deciding to outsource these steps, the quality is in the hands of an external party.

4.2.2. Muri

After discussing the lack of consistency, we now discuss muri: the “overburden or unreasonable” type of waste. This is a result of demanding unreasonable or unnecessary work, resulting in bad outcomes. Scheduling is an important factor of this type of waste since a bad schedule causes resources to be spent inefficiently and contributes to longer throughput times. Prime examples include the usage of materials with a fixed lead time and the outsourced steps for Component B that need to be considered while scheduling.

In the following sections we introduce the sources of muri. Section 4.2.2.1 elaborates on the current situation and consequences of (missing) measurements of throughput time. In Section 4.2.2.2, we discuss some factors that introduce variability to the scheduling process. In Section 4.2.2.3, we consider the lead times of used materials during daily production. In Section 4.2.2.4, we give some examples of factors that cause unforeseen scheduling changes.

4.2.2.1. Throughput time is not measured

The actual production time of Component A and Component B is not measured. The observed production time is measured on the MSF-X level, which includes all components. However, the production time of these components on an individual basis is not tracked explicitly. As a result, the planning is based on past experience. Additionally, the actual production time varies a lot due to the variability in the production process and the reliance on external parties, as discussed in 4.2.1.

At the moment there are three different systems for planning and monitoring the current production progress. The first one is the previously discussed production quality checklist that defines phases for production (see Appendix A and Appendix B). In total, there are six defined phases for Component A and ten for Component B.

The second can be considered to be the hours registration form. To register the production hours, the technicians fill in this form that is used for all products. On this form there are also phases defined, but since this form is used for all products, these phases are rather general and not every phase is applicable to every product. These phases are: “Bottom Site”, “Marking Heartlines – Holes”, “Glue Sleeper”, “Top Plate + Sides” and “QC & Packing”.

Preliminary analysis of the MSF-X has shown that most of the production activities fall into the “Top Plate + Sides” phase. Since this is also the broadest category, it makes sense that most production activities can be attributed to this phase.

When registering the working hours on this form, the related production order, which specifies the type of frame that has been worked on, is usually included as well. However, registering the production order is also often forgotten. As a result, it remains unclear at a later stage if these times relate to Component A, Component B or to a different component of the MSF-X. Currently, the end dates of these production orders are also registered incorrectly on purpose in the ERP system, to prevent the software from placing purchase orders for the required components again.

The last system used is the one that is used by the operational planning department for the weekly production schedule. In the weekly production schedule, neither the terms from the working hours form, nor from the defined production phases are used. Instead, the operational planning department uses more general terms such as gluing / static dissipative floor / casting resin / interface plates / pack etc. to communicate the focus of certain days to the technicians.

The production phases of the production quality checklist and the phases on the hour registration form do not overlap one-to-one with these terms used by the weekly production schedule. As a result, there is an unused potential of data that could be used to improve the scheduling process.

4.2.2.2. Variability factors that influence scheduling

The aforementioned sources of mura all affect the expected duration of producing Component A or Component B. In the planning, the approximate required production time of Component A could range from a minimum number of working days up to a maximum of 65% more working days. For Component B this range is approximately the minimum number of working days up to 40% more working days at its maximum. Here, it also plays a role which technician to assign to a frame. If a technician who has been working at Mecal for a long time is assigned to a frame, you could expect to be on the lower end of this spectrum. Conversely, by assigning newer technicians, you might need more time, but they also gain valuable experience. This decision applies more to Component B than Component A since Component B has stricter specifications.

Next to the time spent at Mecal and the difficulty of frames, the raw material quality also plays a role. If the concrete is of lower quality but still within acceptable limits, more time needs to be spent on assuring appropriate flatness and filling any remaining holes in the concrete. These activities can be quite time-intensive if the quality of the concrete is not as high.

Depending on when tasks are exactly finished, in which way technicians plan to perform remaining production steps, and potential other sources of variability (e.g., absence of technicians, delayed deliveries, scheduling outsourced steps etc.), used materials might introduce additional waiting time if they are applied to the frame at inconvenient times. The same can be said for planning the outsourced steps for Component B. Scheduling these appointments can be difficult. If Component B is not yet ready on time, then the appointment needs to be rescheduled, but scheduling it too late will cause a lot of waiting time. Additionally, Mecal also relies on the flexibility of the external company.

4.2.2.3. Lead times of materials

There are multiple sources of lead time from the used materials as a result of the required drying and curing time. The most common one is from the glue that is used during the production process. Table 2 displays these materials, their lead time, and in what production phase they are used.

Table 2: Lead times of used materials (adjusted for confidentiality)

Material type	Lead time	Used in phase #	
		Component A	Component B
Glue A	XXX	-	5, 6, 7
Glue B	XXX	3	2, 6
Glue C	XXX	3, 4	7
Mortar	XXX	4	-
Material D	XXX	4	1,2
Coating	XXX	4	8
Final layer of casting resin	XXX	-	9

Since some of these lead times take up a large portion of the daily production hours, it is vital that activities that include glue, coating or casting resin are finished at the end of the day so the used materials can cure overnight. The technicians are aware of this fact, but given the variability in the production process, it is not always possible to achieve this. As a result, technicians might need another day for gluing if they glue the last parts of the frame on a new day and need to wait for the glue to cure to start the next set of activities.

4.2.2.4. Unforeseen scheduling changes

It is inevitable that scheduling changes have to be made. We consider three factors that cause unexpected changes to the production schedule.

Changes in the planning of customer's projects
The first factor has to do with the fact that the organised production activities largely rely on customers' projects. This means that if their planning changes, for example, because they want the installation to happen at a different date, the production schedule might change as well. As a result of these external planning changes, this could cause certain frames to have a higher priority. Consequently, the production of frames that have a less strict deadline, usually those that are made to stock, will be postponed.

Supplier delays
The second reason relates to supplier issues. If the purchasing department ordered parts that are needed to start production, but the supplier cannot deliver at the agreed date, then production might need to be postponed. This also applies to the outsourced steps if the external party has to cancel.

Sickness or unexpected leave
The last factor has to do with technicians becoming unavailable. This could be because they get sick or need to go on unexpected leave, which is something that cannot be controlled. However, it should be kept in mind while making the production schedule.

4.2.3. Muda

From a Lean perspective there are also a number of time-intensive activities that do not add value to the product. As previously discussed, activities add value if they physically transform the product in a way that the customer is willing to pay for, and additionally, if they are performed correctly the first time. All these non-value adding activities could potentially be removed, or if that is not possible, the time spent on them should be minimized since they preferably should not happen in the first place. Table 3 displays these activities, the reason for including them, and the components they relate to. All non-value activities are a target for elimination. We discuss possible solutions to deal with these activities in Chapter 6.

Table 3: Non-value adding activities

Non-value adding activity	Reason	Applicable to Component	
		A	B
Measuring and ensuring flatness and slope values of concrete.	Measuring flatness does not add value to the product. Flatness and slope values should be as good as possible right from the start. This means that the technicians should not have to perform these tasks if the supplier has the equipment to deliver this at a lower cost than Mecal.		X
Setting up the concrete elements.	Does not add value to the product	X	X
Filling holes/irregularities in concrete.	Should be absent as much a possible from the start.	X	X
Placing interface plates on concrete, lifting them, and placing them again.	Does not add value to the product.	X	
Marking centre lines before gluing.	Does not add value to the product.		X
Waiting for drying/curing time of used materials.	Does not add value to the product.	X	X
Waiting for outsourced steps.	Does not add value to the product.		X
Removing glue residues.	Removing glue residues after the glue has cured is a time-intensive process. Removing glue residues should be done correctly the first time, during gluing.	X	X
Checking and removing burrs from threads	Should not be present in the first place.	X	
Checking if plugs fit in interface plate.	Does not add value to the product	X	

4.3. Conclusion

In Section 4.1 we discussed research question C: "*How much time is spent at each stage of the production process?*". By asking the technicians for estimates containing the minimum, mode and maximum time spent, we created a value stream map to visualise the time spent on the current production process.

Next, we discussed research question D: "*What are the identified bottlenecks and issues in the production process?*". In Section 4.2 we looked at the current sources of waste according to the Lean framework.

First, we found the following main sources of mura:

- Not every technician has the same experience with working on a particular frame. A lack of experience and knowledge are a barrier for a technician to start working on Component B.
- The quality of the concrete causes significant variability in the required process time.
- It can be difficult to coordinate the outsourced steps of Component B with the external company due to their (in)flexibility, production variability and unexpected schedule changes.

Second, the main sources of muri, the "overburden or unreasonable" type of waste are:

- The throughput time of Component A and Component B is not measured explicitly but is only available on the MSF-X level. Technicians often forget to document the production order while filling in the working hours. The end date of a production order is registered incorrectly in the ERP system and dates are usually forgotten on the production quality checklist.
- Three different, non-overlapping systems are used for planning and monitoring the production process.
- The types of material used in production have the potential to cause a significant waiting time on a day-to-day basis. This waiting time depends on when the materials are applied and potential tasks that can be done in the meantime. This factor, together with the outsourced steps in Component B, should be important focus points in scheduling according to the Theory of Constraints.

Third, we looked at muda and identified multiple non-value adding activities as seen in Table 3. Most of these activities are included because they do not add value to the product itself, but there are also a number of activities that need to be performed since they were done incorrectly the first time, i.e., reworks.

5. Simulation model

In this chapter, we discuss research question E: "*How can we model the estimated impact of possible solutions on throughput time?*". We discuss the simulation model that we use in Chapter 6 to evaluate different solutions. In Section 5.1, we introduce the conceptual model. In Section 5.2, we discuss the different types of data used in the simulation model and the verification and validation of the simulation model. In Section 5.3, we determine the required warm-up period for the model, the run length, and the required number of replications. We end this chapter by stating our conclusions in Section 5.4.

5.1. Conceptual model

In this section, we discuss the conceptual model of the simulation model that was made in Tecnomatix Plant Simulation. Conceptual modelling is the abstraction of a simulation model from the part of the real world it represents. The conceptual model describes the objectives, inputs and outputs, content, assumptions, and simplifications of the model (Robinson, 2014). Figure 9 displays the framework by Robinson that we use to create the conceptual model.

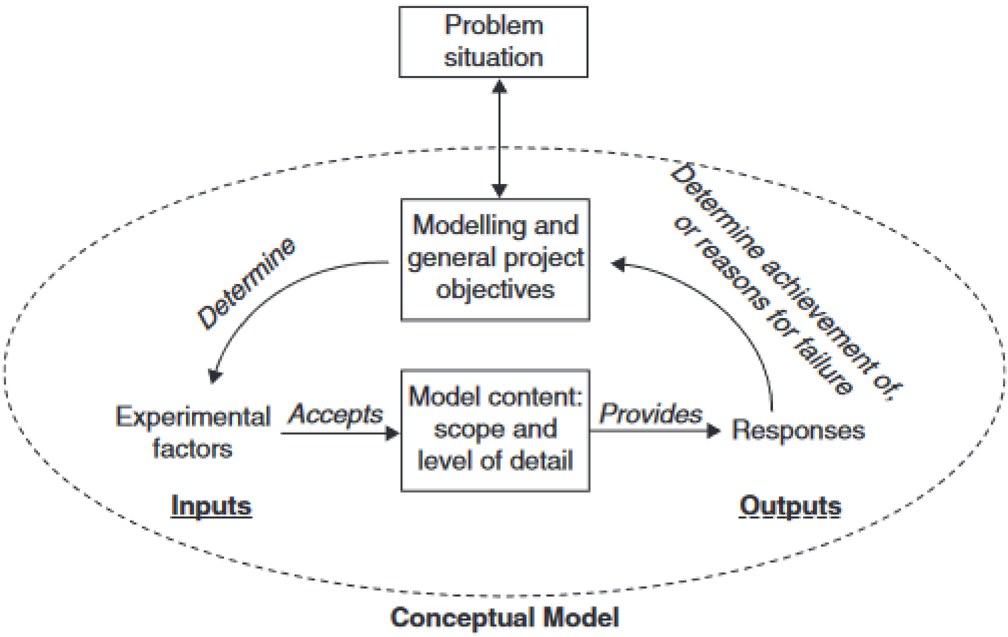


Figure 9: A framework for designing the conceptual model (Robinson, 2008a)

After having discussed the problem situation in the previous chapters, we describe the objective of the simulation model in Section 5.1.1, the model outputs and model inputs in Section 5.1.2, the assumptions and simplifications in Section 5.1.3, the content of the model in Section 5.1.4, and the flowchart demonstrating how we modelled the simulation model in Tecnomatix Plant Simulation, as well as the dashboard of this simulation model in Section 5.1.5.

5.1.1. Objective

The objective of this chapter is to answer research question E: "*How can we model the estimated impact of possible solutions on throughput time?*". Therefore, we first have to create the conceptual model, as will be done in the following sections. Afterwards, we need to implement the conceptual model in Tecnomatix Plant Simulation.

The primary objective of the simulation model is to assess the impact of possible solutions on the throughput time of the components of the MSF-X. While the overall goal is to reduce the throughput time by 19% in total, it is unclear to which extent this reduction should come from production or from other parts in the process. Next to the primary objective, we have the secondary objective. The secondary objective is to see how these changes influence capacity in terms of utilisation and waiting times.

5.1.2. Inputs and outputs

We now turn to the inputs and outputs of the simulation model. The model outputs are statistics to check whether or not the objectives are being met. If the objectives are not met, then the outputs should indicate why objectives are not being achieved. The input variables are the experimental factors in the model that are changed in an attempt to reach the set objectives (Robinson, 2014).

The model contains the following outputs:

1. Throughput in working days for each frame, as measured from the day that a frame was set up in one of the production lanes up until the day that it left the system. This metric is also given as a running average for all frames.
2. Difference between observed throughput time and the required number of days (depending on the type of technician) as defined by the schedule.
3. The running average difference between observed number of required working days and the planned required number of working days (of all finished frames).
4. Waiting time of frames, in terms of waiting for a technician and waiting to use the crane.
5. Capacity utilization, in terms of "*waiting empty"* (no frame is present), "*waiting occupied"* (there is a frame present, but there is no technician available to perform any work on it), and "*working"* (both the frame and the technician are available).

Output 1 is the main output used to determine if the objective can be reached. Output 2 can be used to detect outliers and incorrect estimates of the required number of production days once throughput time is measured more precisely. Output 3 relates to the same objective and should approach a value close to 0 over longer time periods once the estimates of the required number of working days become more precise. Next, we have the waiting time in output 4. These waiting times indicate shortages in capacity in technicians as well as the overhead crane. The last output, output 5, is also concerned with capacity. This time, it is about the utilization of the production lanes and the overhead crane.

Next to these outputs, the following inputs are used:

1. Number of junior technicians
2. Number of senior technicians
3. Efficiency of technician type
4. Number of used production lanes
5. Total processing time given as mode (for non-MSF-X components)
6. Upper-and lower bounds for processing time, defined as a factor of the mode
7. Phase-specific processing time (for components of the MSF-X)

Input 1 and 2 determine the number of technicians that are present in the system, both types having a different efficiency as defined in input 3. The efficiency of a technician is the factor that is considered in the model when calculating the required processing time. As an example, if a task takes 60 minutes (with 100% efficiency), a technician with an efficiency of 60% will take 60/0.6 = 100 minutes. Input 4 determines the number of production lanes in the system that are filled with frames.

To generate the processing times of each frame, we make use of the triangular distribution. The triangular distribution is a continuous probability distribution using a minimum (lower bound), mode, and maximum (upper bound) where the highest probabilities are given to values near the mode. Input 5 states the mode processing times of each type of frame, together with the lower and upper bounds as defined in input 6. The model uses one factor for the lower bound (e.g., 0.9) and one factor for the upper bound (e.g., 1.1) for all frames (Assumption 7). The mode processing times are multiplied by these factors to determine the minimum and maximum values as used in a triangular distribution to generate the required processing time of a frame. For Components A and B, processing times on a phase level (minimum, mode, and maximum) were estimated to get more accurate estimations of the required processing time. Input 7 includes these phase-specific processing times.

5.1.3. Assumptions and simplifications

As with any model, there are a number of assumptions and simplification that were made under the scope and time constraints of this thesis. Assumptions are made under uncertainties or beliefs about the real system. The assumptions fill the knowledge gaps if there is limited knowledge about the real system. Simplifications are choices that are made in order to create simpler models and enable more rapid model development and use, and to improve transparency (Robinson, 2008b).

In the simulation model we have the following assumptions:

Assumption 1: All lanes (as determined by the input) will be filled with frames.

Since Mecal is growing at a fast rate, this resembles the situation where demand is sufficiently high to fill all production lanes.

Assumption 2: If a frame finishes production, a new frame is available and will be set up on the following day.

Technicians will not set up a new frame on the same day that the previous frame finished production but will only do so on the next day.

Assumption 3: The set-up time does not depend on the type of frame.

In this case, set-up time refers to the process of putting a frame in one of the production lanes. It is unclear what the impact of the type of frame is on the set-up time, which is why we assume a similar duration for all frames.

Assumption 4: Each technician works independently on one frame.

In other words, technicians keep working on their assigned frame and do not switch after some time or work together on the same frame. The model assumes that the assigned technician can work independently on the frame.

Assumption 5: All technicians have the same fixed efficiency respective to their type (60% for junior technicians, 100% for senior technicians)

In the model we assume that there are no efficiency differences among technicians with the same type. In reality this percentage would vary among technicians, available help from other technicians, type of frame, type of tasks and other factors. This percentage is difficult to estimate and would also increase over time once a technician becomes more familiar with the production process. Since the impact of these factors is unknown, we assume a fixed percentage as will be explained in Section 5.2.

Assumption 6: All technicians always work from Monday to Friday from 8:00 to 16:30 with three breaks in between (net working day = 7.5 hours), without any expected or unexpected leave.

The simulation model assumes that all technicians as stated in the input are available on all working days and said working hours. Technicians immediately start working on the frame after a break is over, neglecting any travel time between locations (although arguably this is included in the processing times already).

*Assumption 7: The base model assumes 1.10 * mode, as maximum processing time, and 0.9 * mode, as minimum processing time for all non-MSF-X frames.*

These bounds apply to the non-MSF-X frames since we do not have phase-specific data for these frames. This is the lower- and upper bound of a frame for a technician with 100% efficiency (e.g., a frame processed by a junior technician would have the processing time divided by 0.6). These constants can be changed in the input settings.

Assumption 8: The required materials are always present.

Technicians in the simulation model do not need to wait for materials but can continue working on the frame.

Assumption 9: The overhead crane does not break down.

Since breakdowns are infrequent events, we assume that the overhead crane stays fully operational during the simulation run.

Next to these assumptions, we have the following simplifications:

Simplification 1: Any type of frame can be set up in any lane.

In reality, putting bigger types of frames next to each other is unlikely to happen since doing so would leave an impractical amount of space in between them. The model just fills the first available lane, so it does not take this logic into account.

Simplification 2: Activities performed in a lane do not influence the activities that can be performed in the lane next to it.

Since processing times are not modelled on an activity basis, the model implicitly assumes that all activities that are performed on a frame do not depend on the performed activities in the lane next to it. For example, in reality, if a frame is being sanded, coating the frames in the adjacent lanes will be unattainable. These situations are not accounted for in the model.

Simplification 3*: Junior technicians do not become senior technicians over time.*

To gather enough data, the simulation model runs for longer periods of time. In order to clearly assess the impact of a changed workforce (more seniors / more juniors), we do not consider that junior technicians gradually become senior technicians.

Simplification 4: Only senior technicians work on frames with type 2 (Component B), 7, 10, 11 (other frames)

In reality, this is not a viable option for the long run since junior technicians have to be trained to deal with the more difficult frames as well. Junior technicians could do these frames as well, but it would require the help of other, more experienced technicians, which is excluded from this simulation model.

Simplification 5: The generated processing times of the phases of Components A and B are independent

The simulation model assumes the (pseudo)randomly generated processing times of a certain phase to be independent of the processing times of previous phases. This means that if a high processing time is observed in one phase, it will not cause another phase to have a high(er) processing time as well. In reality, this may not always be applicable. Previous examples indicate that if the quality of concrete for a given frame is lower, technicians would require more time in all phases that are linked to the quality of concrete. This element is neglected in the simulation model, and processing times of production phases are said to be independent.

Simplification 6: The time required to set up a frame takes the same amount of time to load the frame once it is finished

The simulation model does not make a distinction between using the crane to set up a frame and using the crane to remove a frame from the production lane.

5.1.4. Content

We now discuss the content of the simulation model, divided into the scope and the level of detail. The scope determines the boundary of what is going to be modelled from the real system. In turn, the level of detail clarifies which details of these elements are going to be included. Table 4 shows the scope of the simulation model and Table 5 the level of detail.

Table 4: Scope of the simulation model

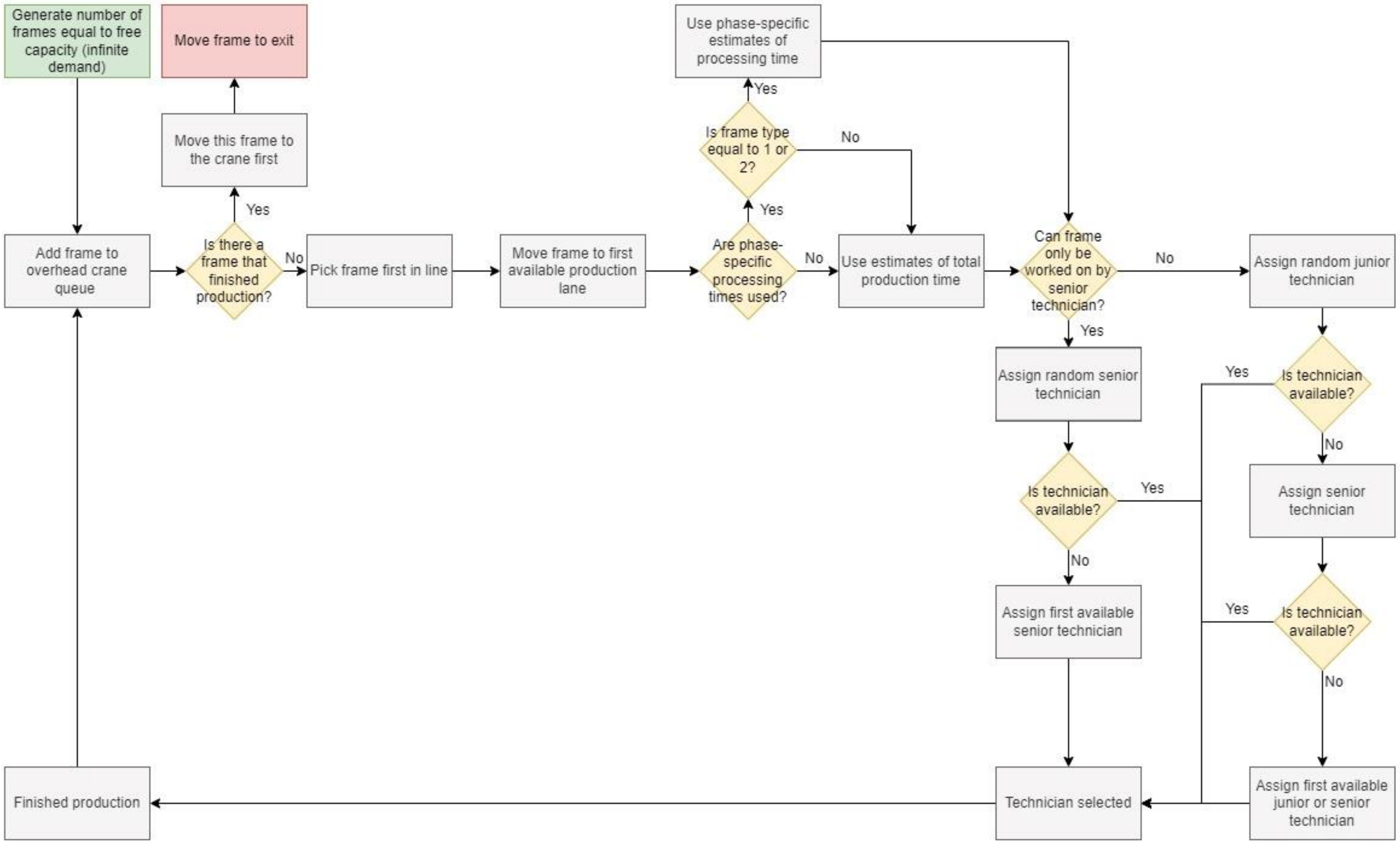
Component	Include/Exclude	Justification
Entities:		
Frames at the production location of Components A and B.	Include	Main object of the study
Products at other production location	Exclude	Not the focus
Activities:		
Transport	Exclude	Not the focus
Processing	Include	Main focus
Queues:		
Production lanes	Include	Each frame requires a production lane to be processed
Queues to use the crane	Include	There is only one overhead crane, might be a limiting factor
Queues to use flatness/slope measurement tools	Exclude	Assumed to be available
Queues of new frames in storage	Exclude	New frames assumed to be available
Resources:		
Internal logistics	Exclude	Material shortages do not play a significant role on throughput time: Assumption 8
External logistics	Exclude	Not the focus / done by external party
Technicians	Include	Required to process frames

Table 5: Level of detail of the simulation model

Component	Detail	Include/exclude	Justification
Entities:			
Frames	Twelve most frequently used types of frames. Each type specified to be processed by “junior technicians” or “senior technicians” Empirical distribution based on the past ~1.5 years (January 4th, 2021 – June 16th, 2022) FIFO processing rule	Include	Assumption 4 Simplification 4
Activities:			
Processing	MSF-X frames: processing times on phase level (phases as defined by Appendix A and Appendix B) Triangular distribution	Include	Simplification 5

	Non-MSF-X frames: processing time as a whole Triangular distribution with minimum and maximum values being a certain factor of the mode (input 6)	Include	Other frames are included to increase the accuracy of capacity utilization, but at a decreased level of detail / Assumption 7
Queues:			
Production lanes	Capacity of lane: 1	Include	Assumption 1
	Queue discipline: FIFO, priority given to senior only frames	Include	Assumption 2
	Set-up / changeover	Exclude	Not explicitly stated, part of processing times
	Routing: random	Include	Simplification 1
Queues to use the crane	Capacity of crane: 1	Include	At most one frame at a time can be hoisted by the crane
	Queue discipline: FIFO, priority given to frames that have finished production	Include	If there are multiple frames in the queue, finished frames are removed before the production of new frames start.
	Breakdowns	Exclude	Assumption 9
	Set-up / changeover	Exclude	Not explicitly stated, part of the service time of the crane / Assumption 3
Resources:			
Technicians	Two types: senior and junior	Include	Assumption 5
	Experience per frame	Exclude	Assumption 5 / Simplification 3
	Absenteeism	Exclude	Assumption 6

5.1.5. Flowchart and dashboard



Legend:	
Start	
End	
Event	
Decision	

Figure 10: Flowchart of the simulation model

Removed due to confidentiality

Figure 11: Dashboard of the simulation model

5.2. Used data, verification, and validation

In this section we take a closer look at the data that was used as input, and model verification and validation. Model verification can be defined as: "ensuring that the computer program of the computerized model and its implementation are correct". Model validation can be defined as: "the substantiation that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Sargent, 2013). Before discussing model verification and validation, we first consider the data that was used as input.

The first type of data is the number of technicians and the number of production lanes. In the simulation model we use six production lanes with three junior technicians and two senior technicians as baseline. The baseline number of technicians was made in consultation with the planning department together with the internal capacity planning. While the available number of technicians varies, we decided that two senior technicians and three junior technicians is a reasonable average. We use six production lanes since the seventh production lane is not in the same row as the other production lanes and is therefore harder to use. Additionally, it is more common that the first six lanes are filled, while the seventh lane remains empty. Since the simulation model fills all available lanes as determined in the input, we decided to use six production lanes as baseline.

The second type of data is the assumed efficiency for each technician type. The model assumes 100% efficiency for senior technicians and 60% for junior technicians (Assumption 5). This percentage for junior technicians was chosen in consultation with the planning department. In the same way, a general upper- and lower bound was chosen: 1.1*mode and 0.9*mode, respectively. Afterwards, by comparing the theoretical minimum, mode, and maximum throughput time of the frames in the simulation model to the typically observed throughput times at the production site, these percentages were assumed to be reasonable. Preferably, this should have been done by using historical data to ensure a higher validity, but since the required data is not available, this method is used.

The third type of data is the total processing times. The non-phase specific processing times came from an internal Excel file, estimating the required number of hours for each type of frame. These hours are used as the mode processing times for each frame in the simulation model. The phase-specific processing times for components of the MSF-X came from the data that was gathered in order to make the value stream map in Section 4.1. This data is also used as input for the processing time of the overhead crane, which is the time to set up a frame in the production lane as well as the required time to remove the crane from the production lane (see Assumption 3 and Simplification 6).

While making the simulation model we performed several checks to assess model verification. We often checked the code and used plenty of comments to make sure that the required logic is programmed correctly. By following frames and technicians step-by-step we made sure that the system is behaving according to the conceptual model, and no unexpected things happen. We perform another verification check at the end of the simulation run, where for all production lanes and the overhead crane, the following equation must hold:

$$WaitingEmpty + WaitingOccupied + Working = total\ operating\ time$$

Equation 3: Verification check for collected statistics

Here, the total operating time is the time in the technicians' shift excluding breaks (= 7.5 hours for one working day). Since the crane and the production lanes must always be in one of these three states, it will flash if it does not hold, indicating that statistics are collected incorrectly, and the model is wrong. By checking these things, we find the conceptual model to be turned into a simulation model with sufficient accuracy.

Next to this, black box validation is also an import part of validating simulation models. The objective of black box validation is to determine if the overall model represents the real world with sufficient accuracy for the purpose at hand (Robinson, 2014). Unfortunately, since there are no historic records of observed throughput time, it is impossible to assess whether or not the observed throughput times in the simulation properly resembles the observed throughput times in the real system. For that reason, we need to skip this type of validation for now. It is important, however, that Mecal checks the set processing times in the model to the actual observed throughput times once this data is available. These settings can be easily adjusted at a later date.

5.3. Warm-up period, run length and number of replications

Since the simulation model starts without any frames being present in the production lanes, we need to determine a warm-up period to remove initialisation bias. This bias is formed since the throughput time of a frame depends on the state of the system, for example, the number of available lanes and the number of available technicians. The initial state is not representative for the real system, which is why we need a warm-up period. To determine the warm-up period, we use the Marginal Standard Error Rule (Robinson, 2014):

$$MSER(d) = \frac{1}{(m-d)^2} \sum_{i=d+1}^{m} (Y_i - \bar{Y}(m,d))^2$$

Equation 4: Marginal Standard Error Rule calculation

Where:

- d = the proposed warm-up period
- m = the number of observations in the time-series of output data
- $\bar{Y}(m, d)$ = the mean of the observations from Y_{d+1} to Y_m

The aim of the MSER is to minimise the width of the confidence interval about the mean of the chosen output data after the set warm-up period. The chosen warm-up period is the value of *d* that minimises the MSER. After running ten replications with the baseline settings (three junior technicians, two senior technicians, six lanes etc.), we calculate the MSER using the averaged throughput time in days. Figure 12 shows the values of the MSER for given values of *d*.

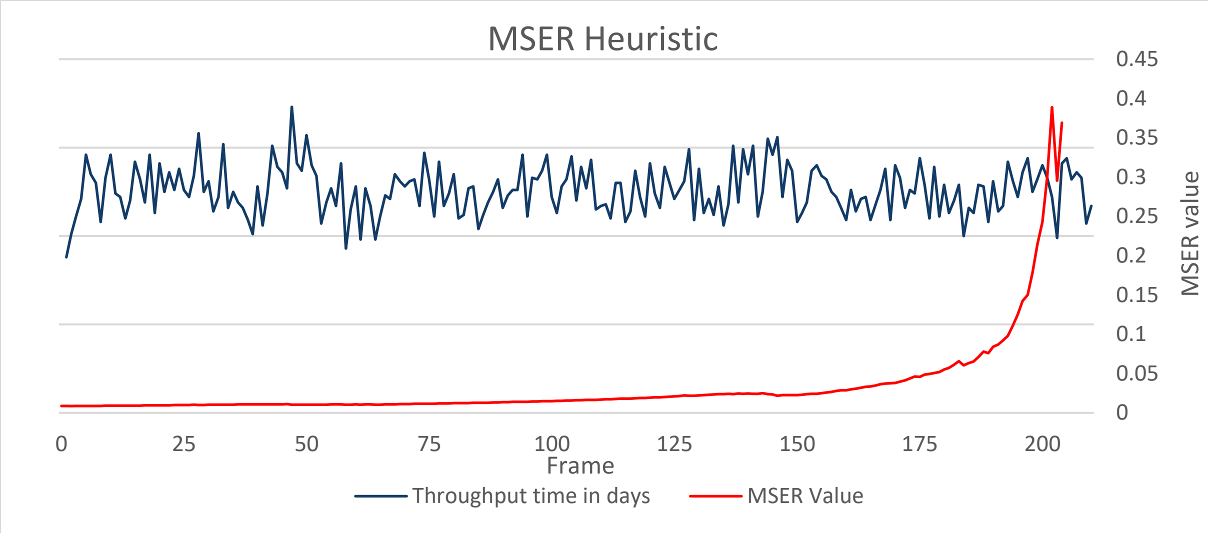


Figure 12: MSER Heuristic (adjusted for confidentiality)

From this calculation, we find that a warm-up period of d = 2 minimizes the MSER value. This means that having two frames as warm-up period yields the smallest width of the confidence interval about the mean of the simulation output. The result is the same if we use the difference between planning instead. If we use another frame as a margin for safety, we conclude that we need to use three frames as the warm-up period.

The run length needs to be much longer than the warm-up period to prevent initialisation bias as much as possible. Banks et al. (2009), recommend using a run length that is at least ten times the warm-up period. Since the warm-up period is not that long, we can be fairly confident that the initialisation bias is not that severe over a longer time period. Consequently, we let the model run for sixty-three frames (including three warm-up frames). This run length should make any remaining initialisation bias negligible.

Next to the run length, we also need to decide on the number of replications. Each replication uses a new stream of random numbers, making the outcomes of random processes in the simulation runs different each time. As a result, we gather better estimates of the performance metrics. Law & McComas (1991) recommend using at least three to five replications. Robinson (2014) notes that this rule of thumb does not consider the characteristics of model output, indicating that models with more varying output data need more than five replications to give sufficiently accurate performance estimates. A simple graphical plot of the cumulative mean of the mean throughput time per replication points to the same conclusion. The cumulative mean is the average over the first n replications as a function of n. Figure 13 shows this plot, indicating that the mean throughput time becomes stable at around seven replications, making this the lower bound for the number of replications. Equation 5 shows how the cumulative mean is calculated:

$$CM_r = \frac{X_1 + \cdots + X_r}{r}$$

Equation 5: Calculation of cumulative mean

Where:

- r = the replication number (1, 2, … , 25)
- X_r = the mean throughput time in replication r

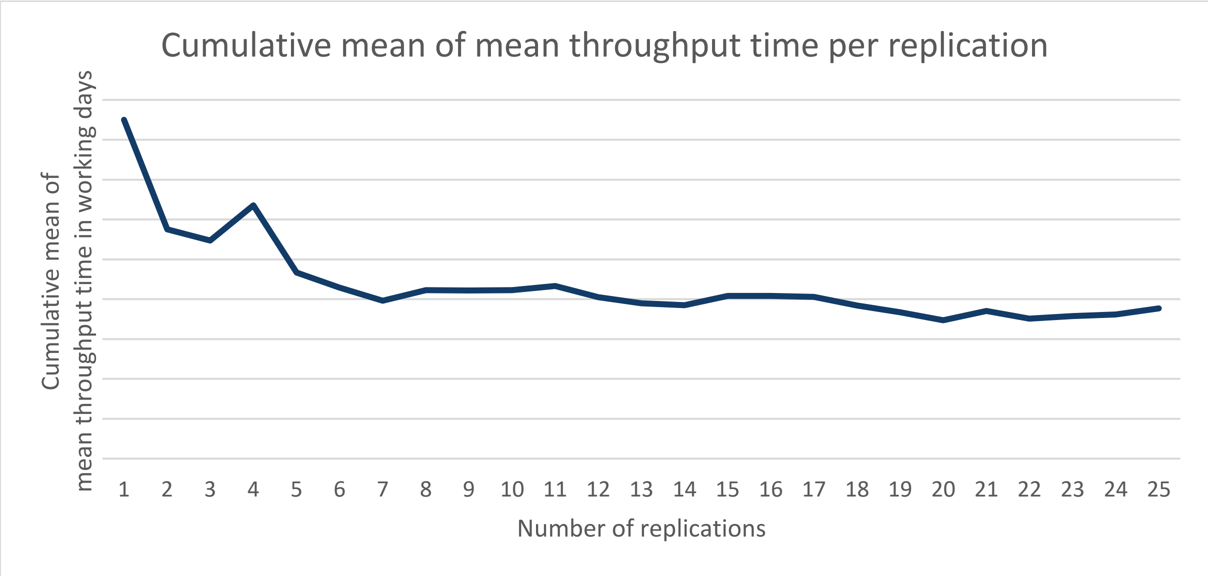


Figure 13: Cumulative mean of mean throughput time per replication (adjusted for confidentiality)

Performing more replications will only provide marginal improvements for estimating the mean value of this performance indicator. Although performing more replications will provide more accurate results, we limit the simulation model to perform ten replications. This number should provide sufficiently accurate results while not causing excessively long computation time.

5.4. Conclusion

In this chapter, we answered research question E: "*How can we model the estimated impact of possible solutions on throughput time?*", and introduced the simulation model that we use to analyse potential solutions. In Section 5.1 we discussed the conceptual model, showing the objective, the inputs and outputs, the content, the assumptions and simplifications, and the flowchart and dashboard of the simulation model. In Section 5.2 we discussed the different types of data that we used and model verification and validation. We conclude that we use six production lanes in the model with two senior technicians and three junior technicians. The efficiency of a junior technician is assumed to be fixed at 60% for all junior technicians. Processing times of non-MSF-X frames are assumed to have a lower bound of 0.9 * mode and an upper bound of 1.1 * mode. In Section 5.3 we used the MSER to determine the required warm-up period and decided to set this value to three frames. Afterwards, we decided to set the run-length to sixty-three frames including three frames used for the warm-up period. At the end of this section, we plotted the cumulative mean of mean throughput time and concluded that we use ten replications.

6. Overview of potential solutions

In this chapter, we discuss research question F: "*How can Mecal address the identified issues in the production process?*". In the following sections we discuss solutions to address the previously identified types of waste. Some of these solutions are only qualitative, other solutions are quantified by means of the simulation model as introduced in Chapter 5. The solutions that make use of the simulation model are indicated by the used input values for the experiments. On a side note, all output from the simulation model is given in working days to account for potential inaccuracies in the estimated processing times.

Section 6.1 introduces solutions to address mura, Section 6.2 for muri, and Section 6.3 for the muda type of waste. After discussing these solutions, we end this chapter with providing our conclusions in Section 6.4.

6.1. Mura

In this section we discuss solutions to address variability in terms of quality and speed in the production process caused by a lack of consistency. We previously identified that there are four main factors of mura in the production process: difficulty of frames, technicians, quality of concrete, and the outsourced steps of Component B.

The first factor, the difficulty of frames, is hard to address short-term. Most of the difficulty of the product comes from the required tolerances and used production techniques. Therefore, reducing this type of variability would be achieved by redesigning the product in such a way that the required production steps are less error prone and required processing times become more stable.

As an example, parts are currently glued to Component B, which requires experience to do so correctly. Technicians who do not have this experience might need a lot longer before all tolerances are achieved. For future iterations of the product, it would be useful from a production point of view to find alternative assembling techniques for this step, or to reduce the number of parts that need to be glued. Additionally, it might be beneficial to invest in machines that can aid with positioning these parts, making it easier to achieve the set tolerances.

The second factor is the number of available technicians and their experience on a given set of frames. Closely related to the difficulty of frames, not every technician can work on every frame. Technicians need to have enough experience and knowledge before they are able to do so. In that regard, a faster, more accurate tool that is referred to as the Leica, is available for flatness and positioning measurements, but not everyone knows how to use it. This tool is typically used for the frames that have stricter tolerances. The other tool that is commonly used does not have such a barrier to use it, although it has a longer set-up time and a lower accuracy. Therefore, we would recommend that all technicians learn how to use the Leica since it is faster and more accurate. In this case, technicians already know how to use it in case they also start working on Component B. Additionally, the throughput time of other frames should improve as well. At the moment, the Leica is usually available, but this might change in the future if other technicians start using it as well. Therefore, it might be necessary to keep its utilisation in mind with the production schedule if a lot of production lanes are occupied. The remaining equipment could be kept as a backup in case there are no Leicas available and such a high accuracy is not required.

Another improvement could be made in the working instructions. At some points there are multiple choices for using a certain type of material. Apart from the obvious differences in material characteristics and impact on the quality of the frame, they also differ in the required curing time.

New technicians might not be aware of these differences and situations where they should choose one material type over the other (e.g., material that cures faster, but should only be used if there is time pressure). Not clearly stating to use only one material type, or the limitations that apply if there are multiple options, might lead to situations where technicians use different kinds of materials in certain steps and potentially introduce variability in throughput time and quality.

The third factor is the quality of concrete. As discussed in Section 4.2.1, there is quite some variability in processing times in certain parts of the production process as a result of differences in the quality of concrete. Reducing this variability, or more specifically, the outliers near the maximum, would lead to spending less time on measuring / assuring flatness and filling holes / irregularities in concrete. These tasks can be rather tedious, so spending less time on this would be beneficial for job satisfaction. Additionally, there would be more space for other activities that make better use of the technicians' skills (not doing so is also a waste according to the lean framework). For the planning department, having a lower variability will make it easier to make a more effective schedule since different production steps and upcoming frames can be better aligned.

Reducing variability of concrete quality could be achieved by inspecting the mould more often, and repairing it if necessary, increasing the quality of the mould (e.g., better materials), replacing the mould more often, or choosing a different composition of concrete. These improvements would lead to a reduction in the time spent on phases 1 and 8. In the simulation model, we use this reduction in processing time as input in five experiments. Each experiment reduces the mode and maximum time spent on the parts of phases 1 and 8 that are impacted by the quality of the concrete by 7.5%. Ideally, the quality of concrete should be compared to the time spent in production to determine this relationship. Since this data does not exist and the impact of the potential solutions to reduce variability are unknown, this percentage is hypothetical. In Table 6 we display the input for Component B that we use in the simulation model.

Table 6: Used input of processing times per phase (in hours) for Component B (adjusted for confidentiality)

Phase	Type	Experiment 1 baseline	Experiment 2 -7.5%	Experiment 3 -15%	Experiment 4 -22.5%	Experiment 5 -30%
1	Minimum	100%	100%	100%	100%	100%
	Mode	100%	92.62%	85.36%	77.99%	70.61%
	Maximum	100%	92.56%	85.12%	77.68%	70.24%
8	Minimum	100%	100%	100%	100%	96.89%
	Mode	100%	94.84%	89.67%	84.44%	79.27%
	Maximum	100%	94.62%	89.28%	83.90%	78.52%

As a side note, the mode would become lower than the minimum in phase 8 of experiment 5, so in this case the minimum is adjusted to match the mode. Table 7 displays the average throughput time and its standard deviation of Component B for each experiment.

Table 7: Average throughput time in working days of Component B (adjusted for confidentiality)

	Experiment 1 baseline	Experiment 2 -7.5%	Experiment 3 -15%	Experiment 4 -22.5%	Experiment 5 -30%
Average	100%	97.91%	97.57%	92.91%	93.92%
Standard deviation	100% (baseline)	96.10%	90.31%	100.11%	92.29%

Given that only parts of the production process are affected by these measures, the total throughput time and standard deviation remain similar, although be it slightly decreasing. In general, reducing the width of this interval will cause frames to finish more often on the planned date. The benefit being that it makes capacity planning easier, translating in a reduced throughput time for other frames as well.

The fourth factor, the variability in scheduling the outsourced steps, would profit from these changes as well. With a reduced variability in required processing times, it becomes easier to plan the outsourced steps since the margin of error can be decreased. In practice, this would mean that the outsourced step might be able to be planned XXX earlier.

The first outsourced step for Component B happens in phase 4. In the following example we take a look at the required number of working days before the frame is ready for this outsourced step according to the simulation model. Table 8 displays the average throughput time and the standard deviation for phases 1-3 and the percentage of frames that are finished with phases 1-3 in the specified number of working days.

Table 8: Throughput time in working days up to phase 3

	Experiment 1 baseline	Experiment 2 -7.5%	Experiment 3 -15%	Experiment 4 -22.5%	Experiment 5 -30%
Average	100%	98.84%	96.91%	96.14%	91.89%
Standard deviation	100% (baseline)	94.18%	91.27%	91.27%	88.73%
Throughput time (working days)	Percentage of frames finished				
XXX	43.69%	44.66%	48.54%	50.98%	61.76%
XXX	53.40%	54.37%	51.46%	49.02%	38.24%
XXX	2.91%	0.97%	0.00%	0.00%	0.00%

If we look at the first outsourced step, which happens in phase 4, we can see in Table 8 that an increasing number of frames are finished earlier with phases 1-3. Starting from experiment 3, we see that no frame requires Y working days anymore to finish the first three phases. This would suggest that it would be safe for Mecal to schedule the outsourced step Y + 1 days after starting production. Following this suggestion would save XXX of waiting time in the production process.

Since these outsourced steps prove to be a bottleneck in the production process, the Theory of Constraints suggests that this step should be the control point in planning and control (see Section 3.2). To deal with the bottleneck, we should make as much use of the constraint as possible and subordinate everything else to the constraint (step 2 and 3). In practice this would mean planning appointments of outsourced steps first and the production start dates of the frames second. This should make sure that the constraint (outsourced steps) operates at maximum effectiveness and waiting times in between are minimised. Under the assumptions that the outsourced step can be booked, Mecal could confidently schedule the outsourced step Y + 1 days after starting production if the processing times become equal to the distribution of experiment 3, or lower.

If these changes are not enough, the fourth step suggests elevating the constraint. Bringing outsourced steps inhouse reduces the variability that comes with scheduling these appointments altogether. The drawback, of course, is that Mecal requires the equipment and knowledge to do these steps themselves. Given that frames sometimes need to wait for multiple days before the external party comes to Mecal, investigating this option might prove worthwhile in an attempt to reduce throughput time.

Improving the scheduling process is also an option to reduce mura. By improving the scheduling process, such as the deliveries of concrete, capacity planning of technicians, or the outsourced steps, Mecal can make a better use of the available resources and reduce throughput time. In other words, reducing mura can also be achieved by addressing muri, which we discuss next.

6.2. Muri

After discussing mura, we now proceed with addressing muri. In Chapter 4 we identified the main sources of muri to be:

- Inadequately tracking of throughput time of Components A and B
- Having three different, disconnected systems for planning and monitoring the production process
- The usage of materials with the potential to cause significant waiting times

These sources all lead to overloading waste, which can be prevented by proper planning and control.

The first factor is inadequately tracking throughput time. As discussed in Chapter 1, we consider the core problem to be: "*time spent on each production step is unknown*". In a more general sense, this relates to inadequately assessing operational performance.

To continuously improve production of the MSF-X, it makes sense to track current production performance; not only to monitor the current process, to make sure that products are finished in time and that processes are set up correctly on a daily schedule, but also to detect (structural) problems and potential improvement points in the production process. From a Lean perspective, identifying KPIs is crucial for leanness evaluation, of which the most significant measures are time related (Karim & Arif-Uz-Zaman, 2013). Some important metrics in Lean are throughput rate, process cycle efficiency, process cycle time, work-in-process (Montgomery, 2010) and also overall equipment effectiveness and on-time delivery (Chiarini, 2011b).

Throughput time, process cycle time and process cycle efficiency (%VAT) are shown in the value stream map of Section 4.1. Another potential measure that we consider is the overall equipment effectiveness (OEE), which is calculated as follows (Slack et al., 2016, p.361-362):

$$OEE = a * p * q$$

Equation 6: OEE calculation

Where *a* is the availability of the process, *p* is the speed of the process, and *q* is the quality of the product that the process creates. The OEE shows the percentage of planned production time that is truly productive. The total available operating time incurs capacity losses as a result of availability losses, speed losses, and quality losses, as shown in Table 9.

Table 9: Types of time losses in OEE

Type of loss	Meaning	Factors in Mecal
Availability	Time lost from total available operating time as a result of set-up losses, changeover losses and breakdown failures.	- Setting up concrete plates in the production lanes - Time spent on getting materials - Waiting for materials to cure/dry to start next activities (if applicable) - Waiting for outsourced steps - Equipment being defective - Technicians being trained or absent
Speed	Time lost from total operating time due to individuals not working at the optimum rate.	- Not enough WIP for all available technicians - Technicians still in training
Quality	Time lost from net operating time as a result of quality losses.	- Time spent on rework - Inspection activities

Accounting for these types of time losses gives the availability rate *a*, the performance rate *p*, and the quality rate *q*, as shown in Figure 14:

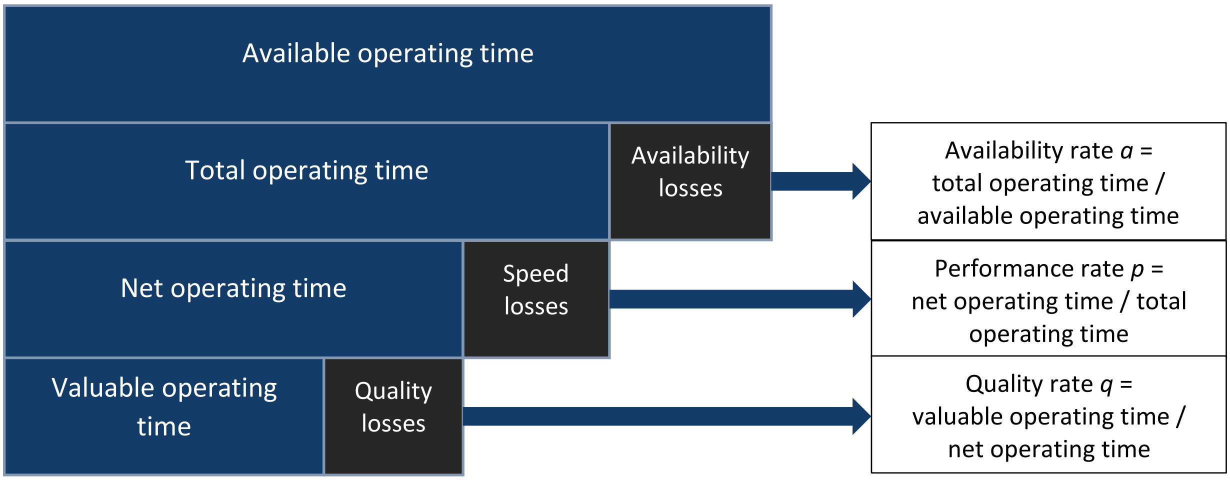


Figure 14: Dimensions of OEE, adapted from Slack et al. (2016)

Tracking OEE over time helps with monitoring the current state of the process and the impact of future improvements to it. While OEE can be useful to track the actual performance, the Theory of Constraints argues against the use of local performance measures, since doing so would make departments lose sight of the bigger picture (Mabin & Balderstone, 2003). Instead, TOC argues to measure:

- Throughput, defined as sales revenue less totally variable costs.
- Inventory, defined as total money invested in the business which is to be or could be sold.
- Operating expense, defined as all non-variable costs associated with turning inventory into throughput.

Arguably, although these measures provide a better fit with financial performance on a strategic level, they are less suitable to identify underlying issues in operations compared to typical production KPIs such as the OEE, process cycle efficiency, throughput rate etc. Therefore, a combination of these kinds of systems, local KPIs, as well as global KPIs, would likely be best for the operations department.

To get a better overview of the current throughput times in the production process, we need to consider the second factor that we mentioned at the start of this section: having three different, disconnected systems for planning and monitoring the production process. In Section 4.2.2.1 we discussed the different types of monitoring and control systems that are currently in place. We concluded that the observed throughput time of both components is not explicitly measured, and that the closest estimates are given by the hour registration form.

In order to assess current and future performance it is vital that these operational KPIs are tracked. Short-term the most obvious solution would be revising the hour registration form. This form currently does not align with the production process of any of the two components. A potential solution would be to align these three types of monitoring and control (i.e., terms used by planning department, production phases according to hours registration forms, production phases according to production quality checklist).

Having overlap between these systems would give more insight into what the actual time spent is on different types of activities and gives the planning department better estimates to work with. In addition, it might become easier to communicate the current progress of a frame and aid with planning technicians. We would consider using the production phases as defined on the production quality checklist to be the best solution. The hour registration form would need to be revised to include these phases. After a while, these same phases could be used to communicate the current progress and make a better planning for the upcoming frames.

The third factor is the usage of materials with curing time. Once production times are clearer, it could be beneficial to revise the planned tasks that should be done on a given day if necessary. It might become apparent that certain parts of production require more time, and other parts require less time. This way, it would become easier to make sets of activities that end with applying materials with curing time, making sure that production steps are planned around it.

To prevent overloading waste, a sufficient number of technicians need to be present to handle all upcoming frames. Therefore, we investigated the impact of additional workers in the simulation model by defining four experiments:

- Experiment 1: two senior technicians and three junior technicians (baseline)
- Experiment 2: one additional junior technician
- Experiment 3: one additional senior technician
- Experiment 4: one junior technician becomes a senior technician

Experiment 1 represents the current situation. In consultation with the planning department, we have assessed this situation to be, on average, the best estimate of the current workforce. In reality, the workforce can be different over time. For example, technicians go on holiday, technicians go abroad for installing frames, technicians could change from production location, new people are hired etc.

Figure 15 shows the 95% confidence interval for the average throughput time of all frames for each experiment.

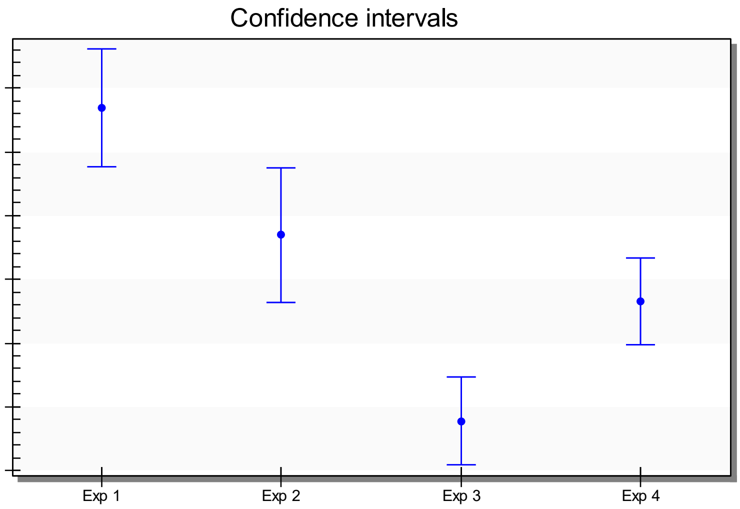


Figure 15: 95% confidence interval of the average throughput time of all frames (adjusted for confidentiality)

This figure shows that an additional senior technician would reduce the average throughput time of all frames the most. Regarding throughput time, the second-best option would be training a junior technician to a senior technician.

This option gives a higher reduction in throughput time compared to hiring an additional junior technician. Figure 16 displays the average throughput time per experiment for Components A and B specifically.

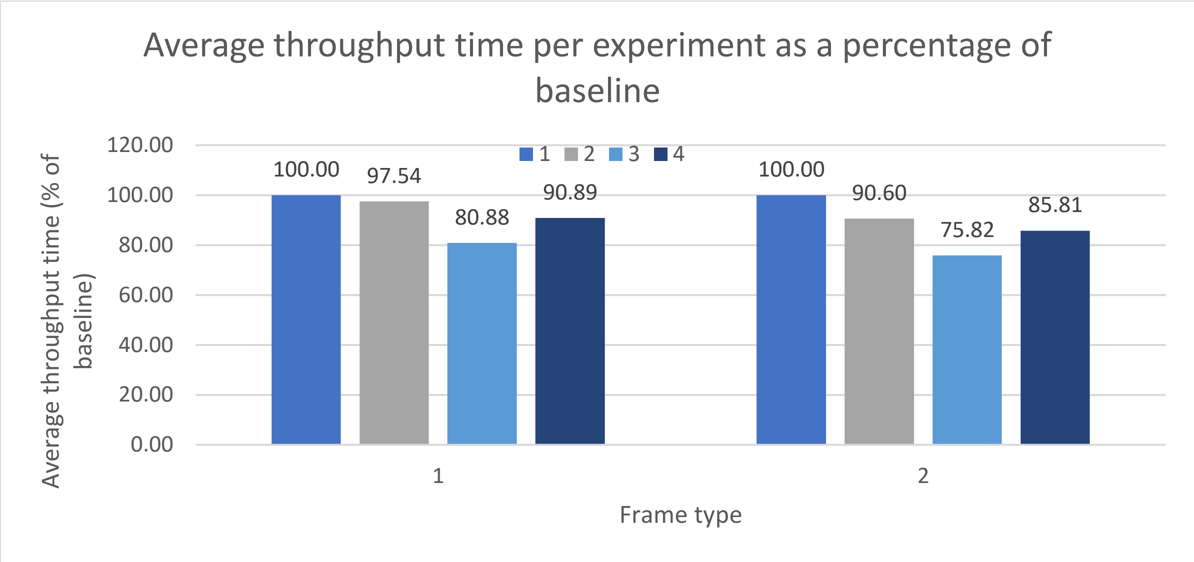


Figure 16: Average throughput time of the components of the MSF-X per experiment (adjusted for confidentiality)

We draw the same conclusion from this figure as before: hiring an additional senior technician reduces throughput time the most and training a junior technician to a senior technician is the second-best option. Of course, hiring additional technicians results in lower waiting times that occur when frames are waiting for a technician, as can be seen in Figure 17.

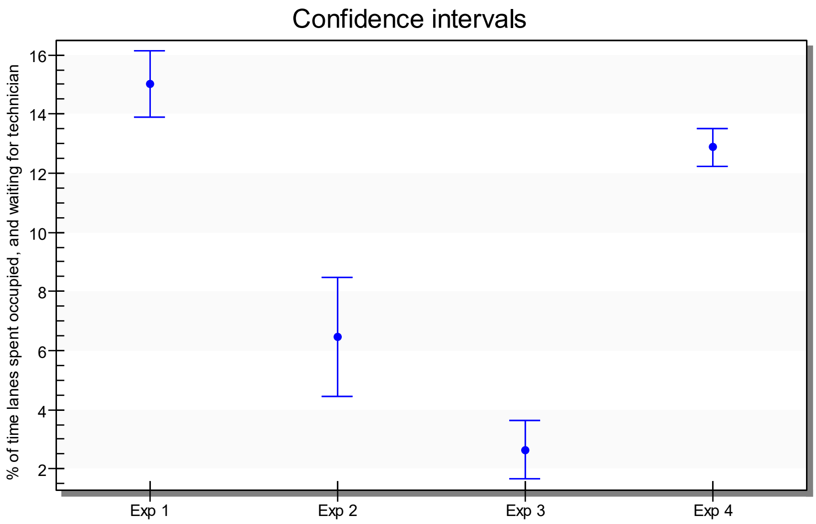


Figure 17: 95% confidence interval of percentage of working time that production lanes spent waiting for technicians

In this figure we see that experiment 4 (junior technician trained to senior technician) has a lower waiting time compared to the base case with the same number of technicians. This difference can be explained by frames that can only be done by senior technicians. If these technicians are not available, the frame needs to wait. As expected, we observe that experiments 2 and 3 lead to significantly lower waiting times. Table 10 shows the average utilisation of the production lanes for each experiment.

Table 10: Capacity utilisation of production lanes in percentages

		Experiment			
		1 (baseline)	2 (+ 1 junior)	3 (+ 1 senior)	4 (junior -> senior)
Waiting empty	Average (%)	7.79	8.59	8.93	8.12
	Standard deviation	0.68	1.34	0.86	1.65
Waiting occupied	Average (%)	15.02	6.46	2.64	12.87
	Standard deviation	1.57	2.82	1.37	0.91
Working	Average (%)	77.19	84.95	88.43	79.01
	Standard deviation	1.53	3.58	1.56	1.67

Since all simulation runs have a fixed number of frames to produce, the simulation runtime varies under a different workforce. Figure 18 displays the 95% confidence interval of the average number of working days per experiment.

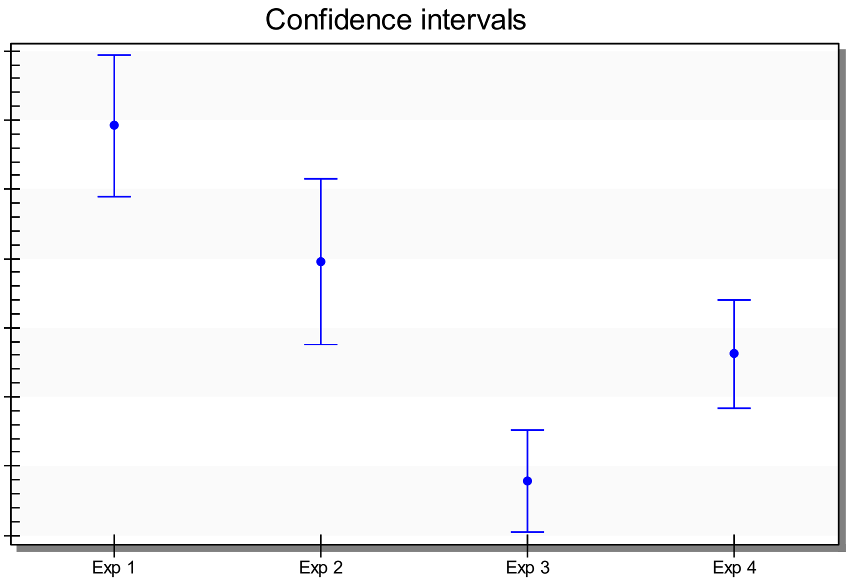


Figure 18: 95% confidence interval of number of working days during simulation run per experiment (adjusted for confidentiality)

The production lanes in the base case have an average working state 77% of the time. We see that this percentages increases to 85% with an additional junior technician, to 88% with an additional senior technician, and to 79% in the case where a junior technician becomes a senior technician. Notably, the standard deviation in the case of an additional junior technician is a lot higher compared to the other experiments. This is because an additional junior technician cannot work on all types of frames, making the utilisation of the production lanes more reliant on the types of frames that come in. In the same way we see that experiment 4, where one junior technician is trained to become a senior technician, has a lower standard deviation for the waiting occupied state compared to the other experiments.

Having an additional senior technician gives the best results in terms of utilisation and reduction in throughput time. However, this option is also the most difficult to achieve. Given the desired quality at Mecal, it will require quite some time before someone is found and trained to be a junior technician, let alone a senior technician. Therefore, we conclude that properly training existing technicians to handle the more difficult frames is a better and more viable option than hiring and training additional technicians if only one option can be chosen. According to the simulation model, training one junior technician to a senior technician would reduce the average throughput time of Component A by XXX and the average throughput time of Component B by XXX (see Figure 16).

As part of a long-term strategy, it would be sensible to gradually hire more technicians to deal with increasing demand, while at the same time training existing technicians to make sure that there is enough capacity for the more difficult frames.

6.3. Muda

In this section, we give some potential solutions/improvements in Table 11 for the previously identified muda. These suggestions have not been further investigated using quantitative data.

Table 11: Potential solutions for muda

Non-value adding activity	Applicable to Component		Potential solution / improvement
	A	B	
Measuring and ensuring flatness and slope values of concrete.		X	Promote Leica usage Levelled platforms for frames Labour dedication (assigning technicians who are good in using the Leica) Increasing the quality of concrete by repairing or replacing the mould more often, or changing the composition of concrete
Setting up the concrete plates	X	X	Levelled platforms for frames
Filling holes/irregularities in concrete.	X	X	Increasing the quality of concrete by repairing or replacing the mould more often, or changing the composition of concrete
Placing interface plates on concrete, lifting them, and placing them again.	X		Requires further research
Fitting plugs		X	This step could potentially be skipped. To be sure, tolerances should be checked to investigate if it possible that these plugs do not fit.
Marking centre lines before gluing.	X	X	Requires further research
Waiting for drying/curing time of used materials.		X	Improvements in scheduling (making sure that these materials are applied at the end of the day) / reduce process variability
Waiting for outsourced steps.	X	X	Improvements in scheduling (start of production and date of appointment) / reduce process variability
Removing glue residues.	X		Highlight that glue residues should be removed immediately after applying glue
Checking and removing burrs from threads	X		Procuring higher quality parts

6.4. Conclusion

In this Chapter, we provided multiple solutions to address the previously identified waste. We mainly discussed some options for addressing the wide range of processing times for some production phases. This is caused by a lack of consistency (mura), and overburdening waste (muri) as a result of not fully knowing the required time and resources. By repairing or replacing the concrete mould more often, or choosing for a different composition of concrete, the variability in the quality of concrete can be addressed. In turn, less time is spent on phases that are affected by the quality of concrete. The simulation model suggests that if the time spent on activities having a strong link to the quality of concrete can be reduced ~15% or more, no frame will take more than Y days to be ready for the first outsourced step. By using the appointments of the outsourced steps as control points for planning and control, and scheduling them before starting production, XXX of waiting time can be reduced for Component B.

To address muri, Mecal should revise the hour registration form such that it overlaps with the production phases. By revising the hour registration form, data on throughput times in different parts of the production process can be gathered. Additionally, a combination of local KPIs and global KPIs need to be tracked in order to assess financial performance on a strategic level, as well as more specific improvement points in the operations department.

Regarding the impact of having additional technicians to reduce throughput time, we would recommend training existing junior technicians to senior technicians. Based on the simulation model, the estimated reduction in average throughput time is XXX for Component A and XXX for Component B.

7. Conclusions and recommendations

In this chapter, we provide the main findings of the thesis. More specifically, we state our conclusion of this research in Section 7.1. In Section 7.2, we provide the recommendations to reduce the throughput time of the MSF-X. In Section 7.3, we discuss some of the limitations of this research. We end this chapter by discussing some opportunities for future research in Section 7.4.

7.1. Conclusions

In Chapter 1, we introduced the research question of this thesis as:

What are some of the actions Mecal can take to contribute to the goal of reducing the time needed for production and installation of the Machine Support Frame by at least 19% to achieve the set production KPIs?

We started this research by investigating the current production process of the MSF-X in Chapter 2. Based on the gathered information we constructed the process flows of Component A and Component B in Appendix A and Appendix B, respectively.

In Chapter 3, we performed a literature review to find suitable theories to improve throughput time. We concluded that we use Lean as our main framework to identify different types of waste and the Theory of Constraints to guide us in dealing with bottlenecks. Since mura and muri are closely related to variability and uncertainty, we used a framework that provided strategies to deal with these kinds of issues in particular.

In Chapter 4, we aimed to identify how much time is spent at each stage of the production process, as well as existing issues and bottlenecks. We estimated the required time by providing technicians with the production quality checklist of both components and asking them for their estimations of the minimum, mode, and maximum required time for different sets of production steps. Based on this data, we created two value stream maps as depicted in Figure 7 and Figure 8. Existing issues and bottlenecks were identified using the three types of waste as defined by the Lean framework: *mura, muri,* and *muda*.

In Chapter 5, we used the previously gathered data to construct a simulation model to aid us with analysing the impact of potential solutions.

In Chapter 6, we gave an overview of potential solutions for addressing these types of waste and existing bottlenecks. We found several actions that Mecal can take in order to reduce the throughput time of the MSF-X.

To address muri, Mecal should revise the hour registration form such that it overlaps with the production phases. By revising the hour registration form, data on throughput times in different parts of the production process can be gathered. Additionally, a combination of local KPIs and global KPIs need to be tracked in order to assess financial performance on a strategic level, as well as more specific improvement points in the operations department.

Another recommendation to prevent overloading waste and cope with increasing demand is to continue training and hiring new technicians. The experiment in the simulation model suggests that training a junior technician to a senior technician would reduce the average throughput time of Component A by XXX and Component B by XXX. This experiment also shows that having an additional senior technician (compared to baseline) has an even larger impact of XXX and XXX working days respectively.

We concluded that training a junior technician to a senior technician is more viable, since acquiring a new senior technician is difficult due to the extensive training that is required.

Next to muri, we provide solutions to address mura. To spend less time on activities that are related to the quality of the concrete, and to address the variability in concrete quality, Mecal could repair or replace the mould more often, and/or choose a different composition of concrete. Spending less time on these tasks if the quality of concrete increases is also beneficial for job satisfaction since these tasks can be rather tedious. Additionally, it would create more space for other activities that make better use of the technicians' specific skills.

The simulation model suggests that if the time spent on production steps affected by the quality of the concrete can be reduced by ~15% or more, no frame will take more than Y days to be ready for the first outsourced step. If we follow the Theory of Constraints methodology, Mecal should use the appointments of the outsourced steps as control points for planning and control, and schedule them before starting production. If this 15% is achieved, Mecal could schedule the first appointment on day Y + 1, potentially saving XXX of waiting time for Component B.

Following the recommendations of increasing the quality of concrete and training one junior technician to become a senior technician, we conclude that an estimated XXX could be saved in the throughput time of the components of the MSF-X. This represents a reduction of 2.85% in total throughput time (up to and including installation). The other recommendations have not been quantified and are therefore not included in this percentage. We conclude that the research objective of reducing the time needed for production and installation of the Machine Support Frame by at least 19% cannot be achieved by these quantified recommendations alone, and further measures need to be taken to achieve this reduction.

7.2. Recommendations

To improve throughput time, we would recommend Mecal to take the following actions:

- Investigate options for reducing the number of glued parts or find different techniques of assembling these parts to the frame.

- Train technicians to use the Leica and continue making the working instructions clearer.

- Reduce variability of the quality of concrete by repairing or replacing the mould more often, and/or choosing for a different composition of concrete. Reducing the time spent on activities that are the result of lower concrete quality will improve job satisfaction and make better use of technicians' skills. According to the simulation model, this could reduce the waiting time for the first outsourced step by XXX. Also, it might be beneficial to investigate bringing some of the outsourced steps inhouse if the required resources and knowledge are available.

- Define a number of local and global KPIs to assess financial performance on a strategic level as well as operations performance on the operational level. Revise the working hours form to match the production quality checklist so throughput can be measured more accurately. Use the gathered data to detect potential improvements points and use it to improve scheduling and the production process in the future.

- To further increase capacity, new technicians should be hired over time. Given the fact that it may take a while before these technicians have enough experience, Mecal should also focus on training existing technicians to make sure that there is enough capacity to deal with the more difficult frames. We recommend training a junior technician to become a senior technician. According to the simulation model, this would reduce the average throughput time of Component A by XXX and Component B by XXX.

7.3. Discussion

In this section we highlight some of the limitations of this research and the contribution to theory and practice.

The main limitation is the validity of the used data for both the value stream map and the simulation model. Since there is no historical data available for the processing times, we resorted to estimating it. Of course, this approach has a much lower validity than using actual observed data. As a result of a lack of historical data, it is also difficult to have strong quantitative arguments for proposed solutions.

The provided estimates that we used throughout the thesis are educated guesses, so there is a risk of them not representing reality and being incorrect. In the same manner, we generalise these estimates to be correct for all technicians. Since technicians may have more or less experience with working on certain kinds of frames, have different working procedures etc., this is very unlikely to be the case. Additionally, estimates for throughput time, or the number of days required in the production schedule, are likely to ignore a number of unforeseen factors that change over time. Examples would be that working speed is not constant, the quality of concrete varies, Mecal may receive late deliveries, technicians are absent etc. These factors are also not included in the simulation model.

This thesis contributes as a case study to the lean framework, therefore showing the value and affirming existing theory. The simulation model relates more to practice, showing some of the potential that simulation studies might offer. This would be especially interesting in the future if there is more data with higher validity.

7.4. Future research

Next to some of the recommendations suggested in Section 7.2, Mecal might want to look into expanding the simulation model once more data about processing times is gathered. Once that data is available, Mecal should check the validity of the used data and adjust the input in the simulation model if necessary. It would be interesting to make the simulation model more accurate and use it for capacity planning or future changes to the system. In the same way, Mecal could use some of the proposed KPIs to set goals for future improvements to the production process of the MSF-X.

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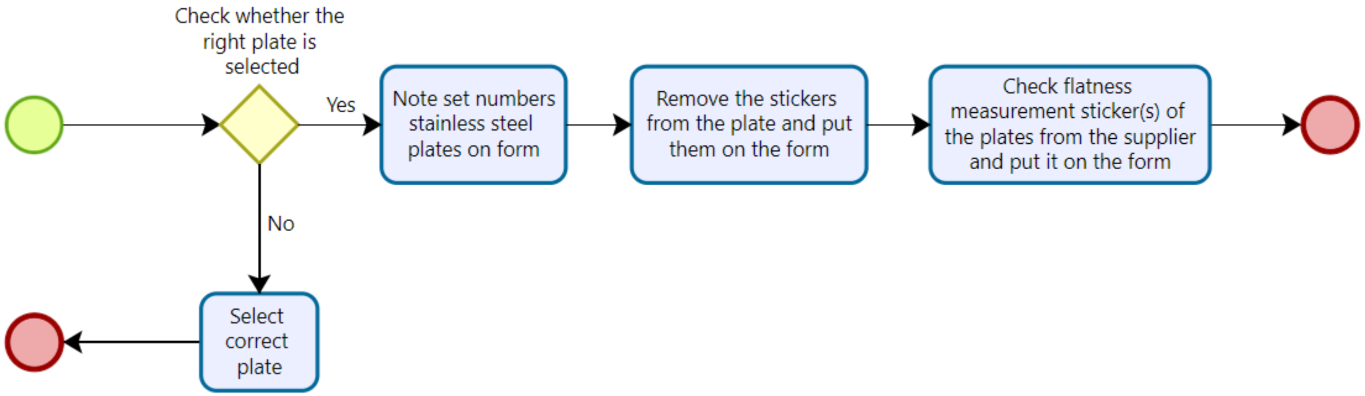
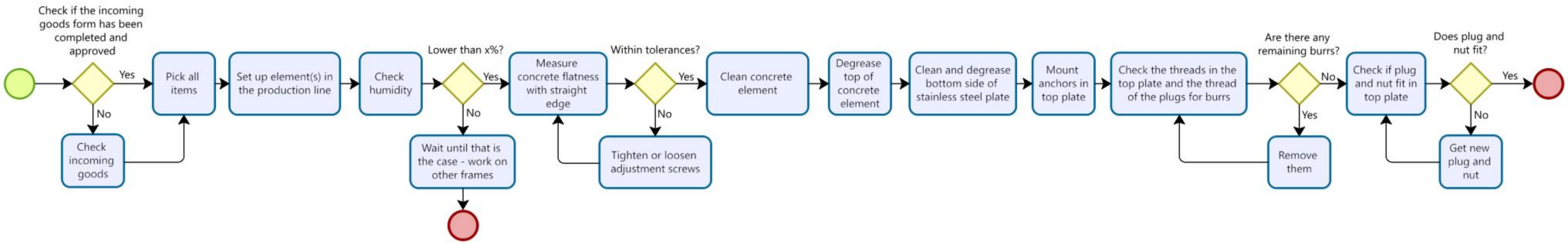
Appendix A: Process flows of Component A

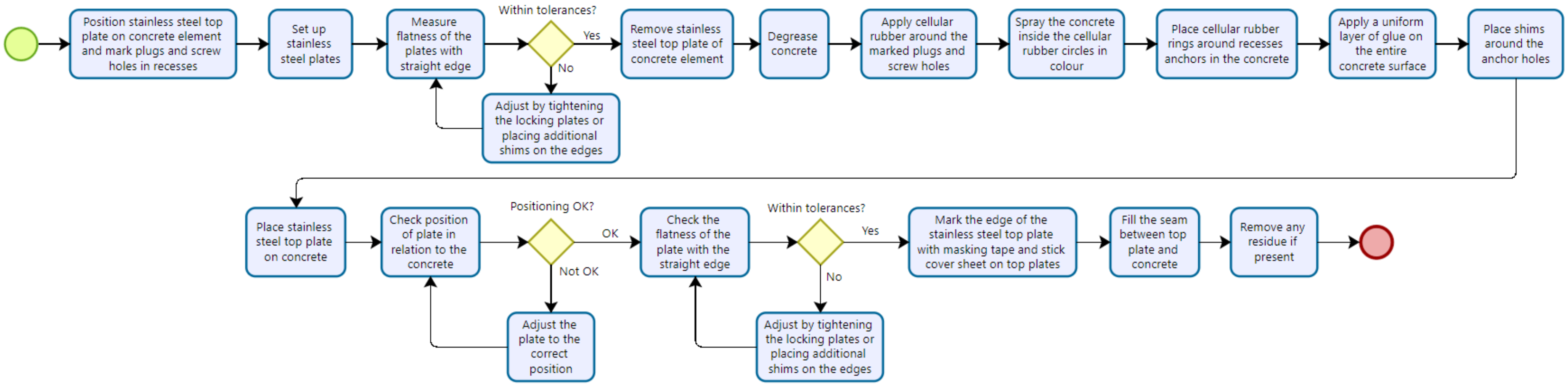
Appendix A.1: Phase 1



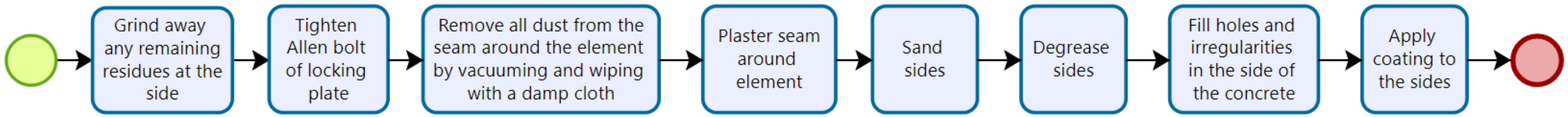
Appendix A.2: Phase 2



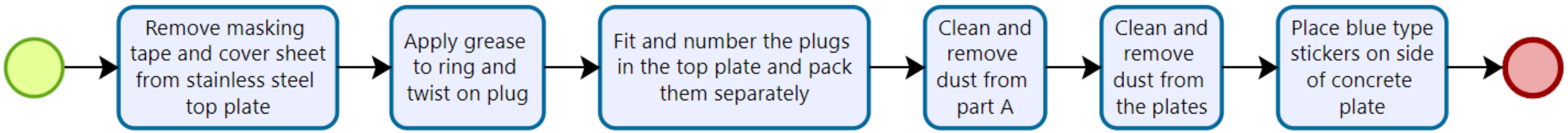
Appendix A.3: Phase 3



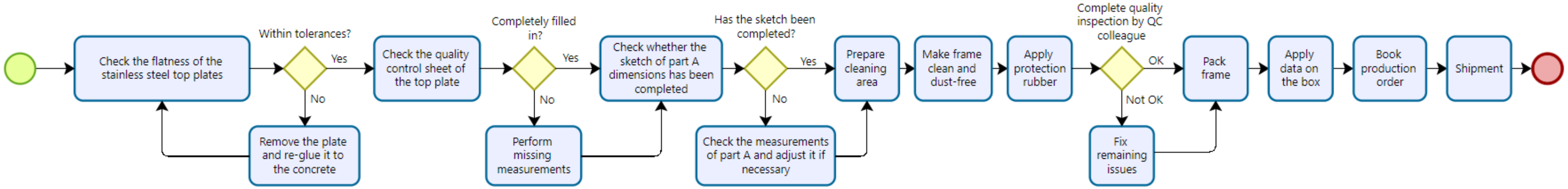
Appendix A.4: Phase 4



Appendix A.5: Phase 5

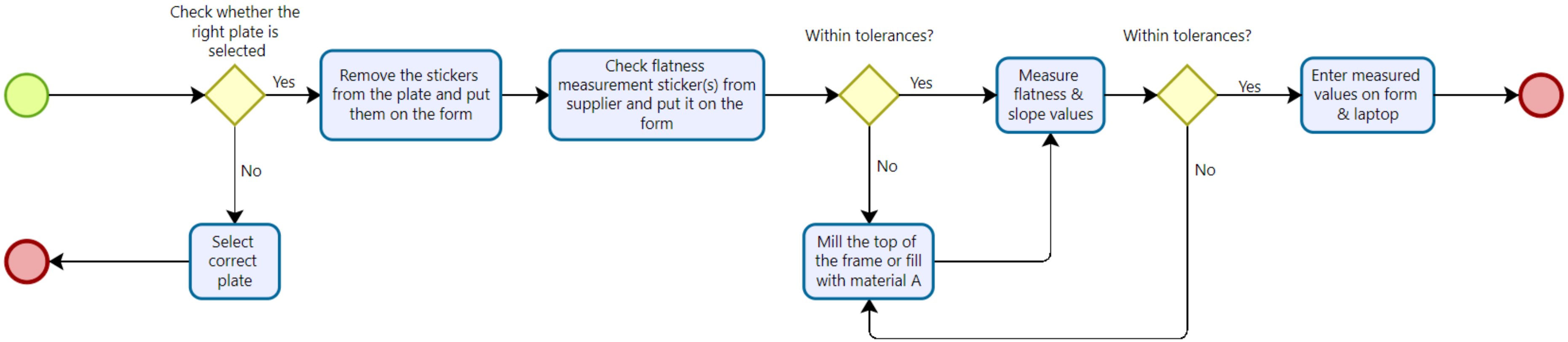


Appendix A.6: Phase 6

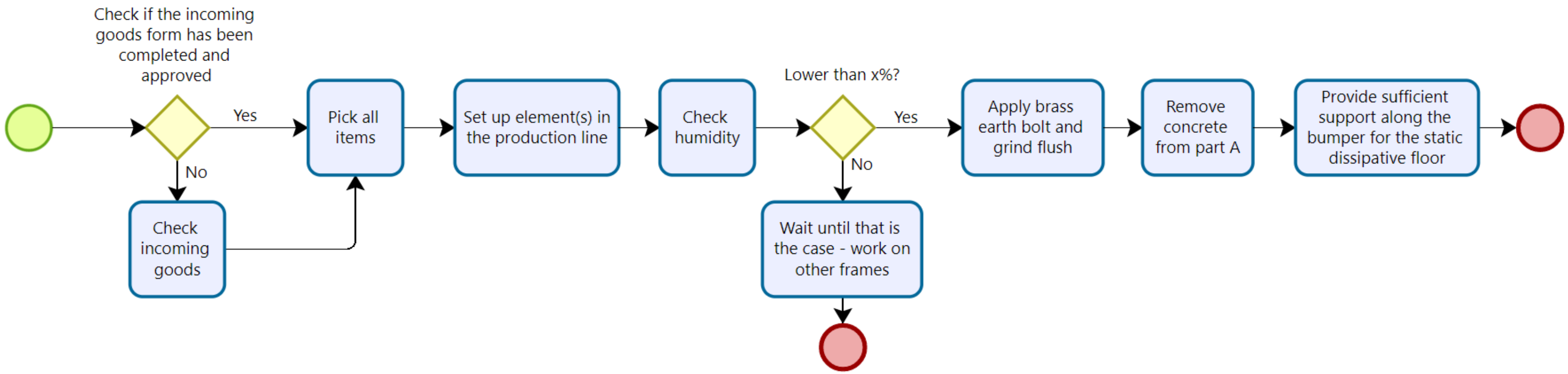


Appendix B: Process flows of Component B

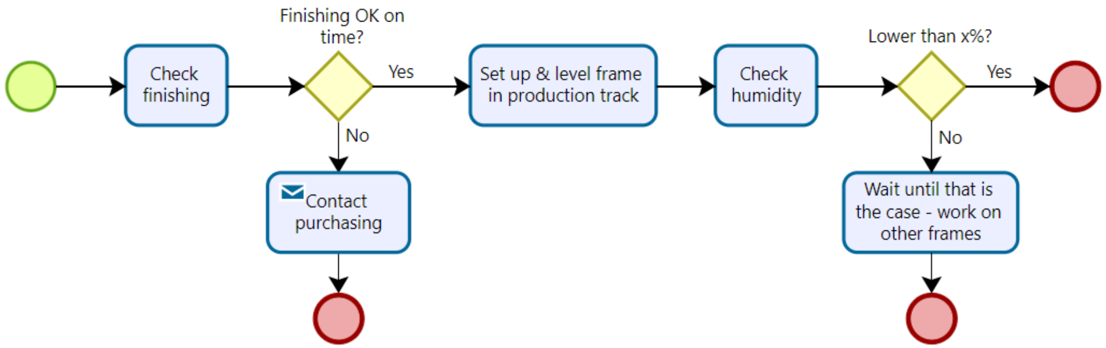
Appendix B.1: Phase 1



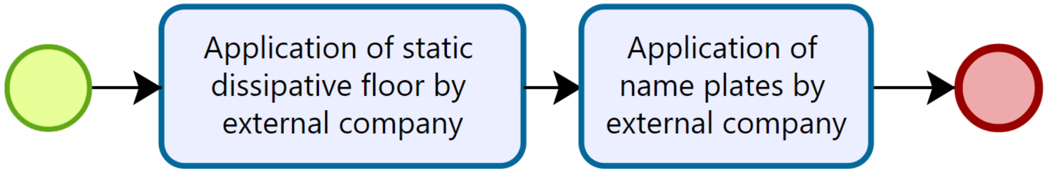
Appendix B.2: Phase 2



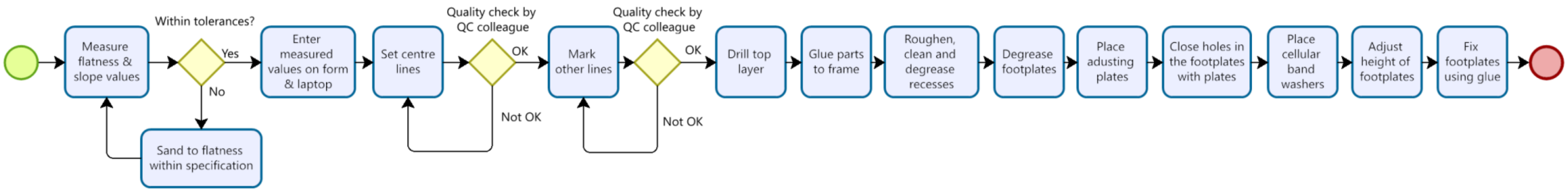
Appendix B.3: Phase 3



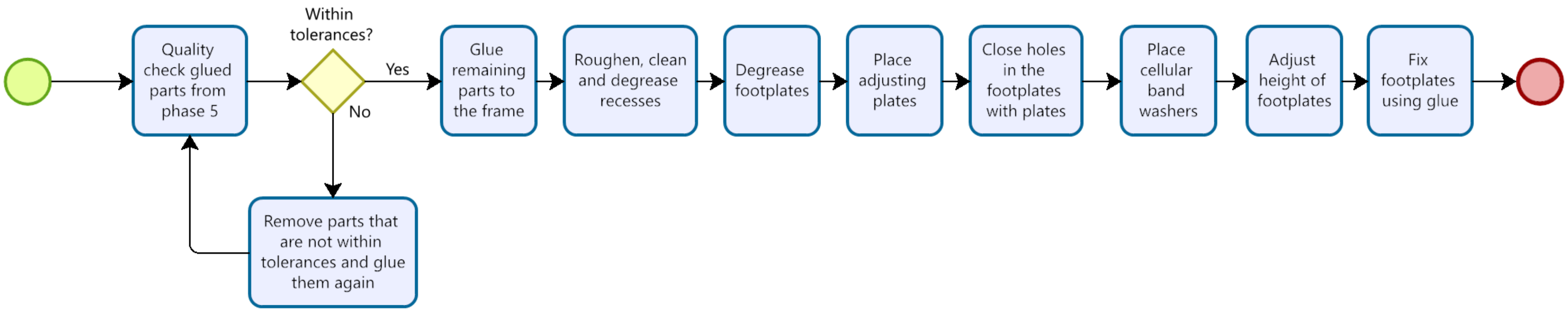
Appendix B.4: Phase 4



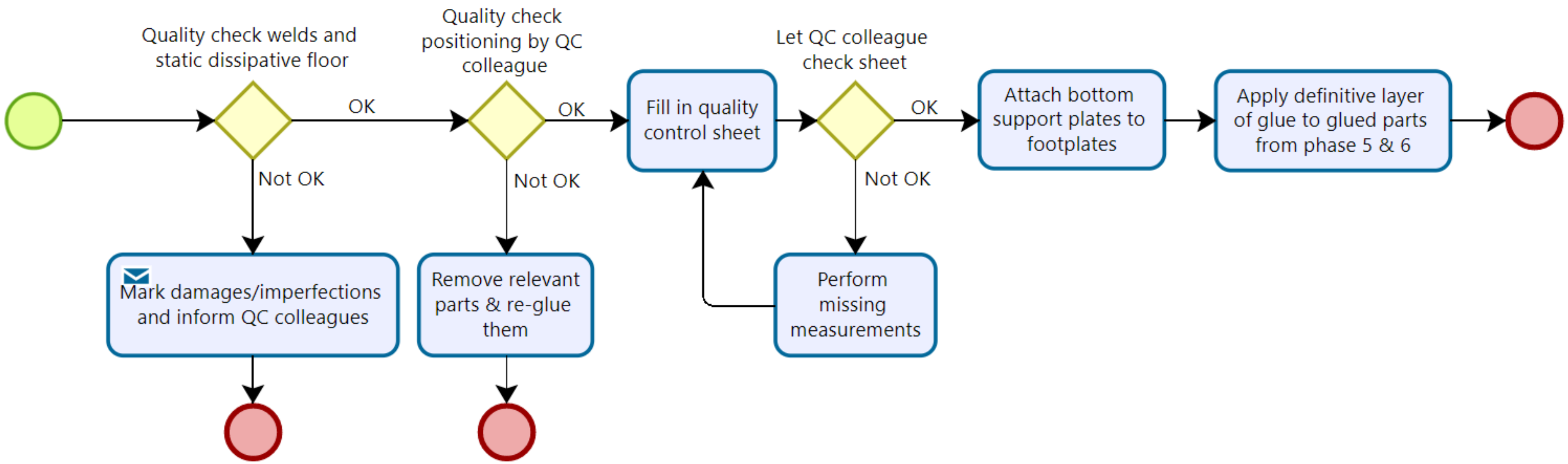
Appendix B.5: Phase 5



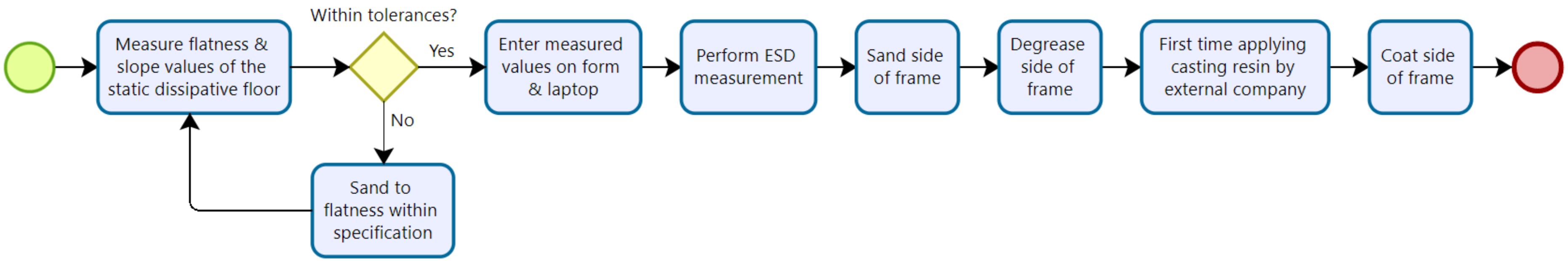
Appendix B.6: Phase 6



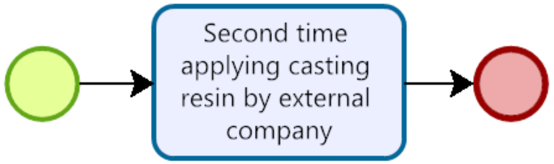
Appendix B.7: Phase 7



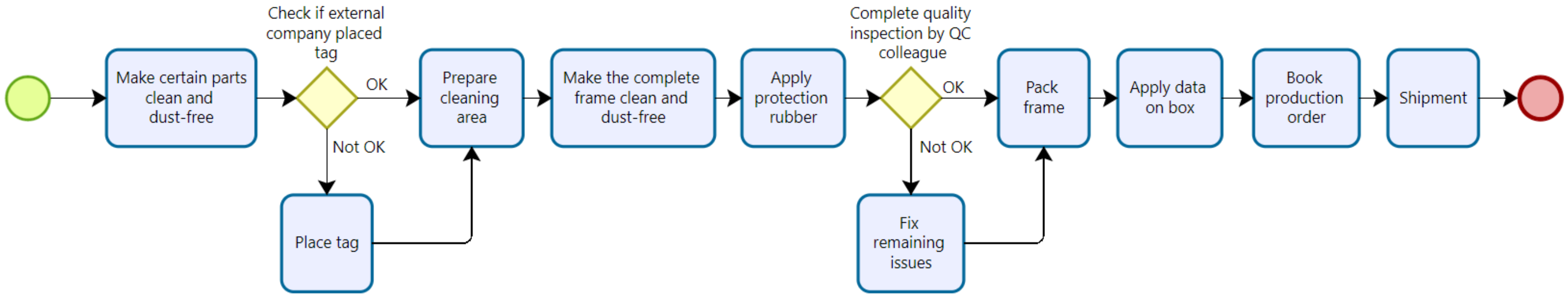
Appendix B.8: Phase 8



Appendix B.9: Phase 9



Appendix B.10: Phase 10



Appendix C: Systematic literature review

The aim of the bachelor thesis is to reduce the throughput time of a product. To achieve this, we first need to identify possible theories that exist in literature. The relevant research question for the systematic literature review is research question B (as discussed in Section 1.3):

What are some of the available theories in academic literature to improve throughput time and which one could be used given the context at the company?

The main concepts in this research question are theories, academic literature, and throughput time. A theory is defined as "a set of systematically interrelated concepts, definitions, and propositions that are advanced to explain and predict phenomena (facts)" (Cooper & Schindler, 2013, p. 62).

The second concept, *academic literature*, is related to the sources from which we want to acquire this knowledge. These theories should come from peer-reviewed articles, scientific journals, research reports or study books.

The third concept is throughput time, which is the average elapsed time taken for inputs to move through the process and become outputs (Slack et al., 2016, p. 186).

Appendix C.1: Selection criteria

To produce relevant selection criteria, we use Cooper's (1988) taxonomy of systematic literature reviews' scope. This consist of five parts: research focus, goal, perspective, coverage, organisation, audience. Based on this taxonomy, we define several criteria that should help in finding relevant sources.

Inclusion criteria	Reason
Suited for production environments in SMEs (<250 employees)	Depending on the size of the company someone might use different methods to improve the efficiency of the production process. Therefore, we decide to put a limit on the number of employees to make sure that the companies do not differ too much in terms of size compared to the company of this thesis.
Includes a specific methodology or theory (methodological in nature)	The sources need to follow a certain methodology or theory. If a company increases throughput time by replacing their machines with newer versions, we need to know how they figured out that the machines were the bottleneck in the process.
Is related to the fields of production, operations management, or operations research	To make sure that the sources are relevant, they need to be based on these fields, just like this thesis is.
Is applicable to products that have a low variety	Given the context at the company, we need to make sure that the discussed theories can be applied effectively to products with a lower variety.
Written for operations managers or academics	The intended audience should be other academics or operations managers looking to improve the production process. This is to make sure that it is useful for the thesis and the company.

Exclusion criteria	Reason
Sources published before 1990	Technology evolves at a fast pace. Therefore, we do not consider the methodologies used in sources from before 1990, since they are probably not that applicable anymore to today's production environments.
Sources in languages other than Dutch or English	To make sure that the sources can be sufficiently understood, they need be written in English or Dutch.
Case studies in companies relying heavily on machinery and barely on production staff	It could be the case that we find sources that are about automated production processes, meaning that they rely heavily on machinery & robots and barely on production staff. Given the product that is considered, this is not something that can be applied in this thesis.

Appendix C.2: Databases

Relevant databases should include peer-reviewed articles about industrial engineering and management and specifically about production systems. The databases that will be used are Scopus, Web of Science, and Emerald Insight. We decide to include Scopus and Web of Science because of their multidisciplinary focus and large scope. Additionally, we decide to include Emerald Subject Collections because of their collections of "operations, logistics and quality" and "business, management & strategy", which should give some more specific results that are harder to find in Scopus or Web of Science.

Appendix C.3: Search terms & strategy

Based on the defined concepts, we looked for similar terms. These related search terms are found by using thesauruses and previously found articles or study books, such as the book by Slack et al., (2016). Using these concepts and related terms, the initial search matrix is created.

Key concept	**Related terms**	**Broader terms**	**Narrower terms**
Theory	Methodology, philosophy	Model, technique, system	
Throughput time	Production time, cycle time, throughput rate	Duration, time, schedule	Process time

Appendix C.4: Search log

Using this search matrix, we created the foundation of a search string, which will be refined along the way. The column "retrieved articles" contains the number of found articles using the search string and also the number as found in the concept matrix of results. The concept matrix is limited to the most important theories and does not include variations of them. This is done to keep an overview of what we consider to be the most relevant theories, which are those that can be applied to the bachelor thesis.

Database	Query	#hits	Retrieved articles	Comments
Scopus	TITLE-ABS-KEY((theory OR methodology OR philosophy OR model OR technique OR system) AND (“throughput time” OR “production time” OR “cycle time” OR “throughput rate” OR duration OR time OR schedule OR “process time”))	7,765,969	0	Search string too broad.
Scopus	TITLE-ABS-KEY ((theory OR methodology OR technique) AND ("throughput time" OR "production time" OR "cycle time" OR "throughput rate" OR "process time"))	12,967	0	Removed philosophy, model, system, duration, time, schedule. Number of hits drastically reduced, but still very broad.
Scopus	TITLE-ABS-KEY ((theory OR methodology OR technique) AND ("throughput time" OR "production time" OR "cycle time" OR "throughput rate" OR "process time")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "BUSI") OR LIMIT-TO (SUBJAREA , "DECI"))	8,025	3 (articles used as references in a result)	Excluded subject areas other than “Engineering”, “Business, Management and Accounting” and “Decision Sciences” Results are becoming more relevant, but a lot of results are really specific and not generally applicable.
Scopus	TITLE-ABS-KEY ((theory OR methodology OR technique) AND ("throughput time" OR "production time" OR "cycle time" OR "throughput rate" OR "process time")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "BUSI") OR LIMIT-TO (SUBJAREA , "DECI")) AND (LIMIT-TO (DOCTYPE , "re"))	122	1 (#4)	Selected document type “review” Most articles are too specific
Web of Science	ALL=((theory OR methodology OR technique) AND ("throughput time" OR "production time" OR "cycle time" OR "throughput rate" OR "process time"))	6,726	1 (#5)	Results seem more relevant and more related to Industrial Engineering and Management topics
Web of Science	ALL=((theory OR methodology OR technique) AND ("throughput time" OR "production time" OR "cycle time" OR "throughput rate" OR "process time")) Web of Science Categories: Engineering Industrial or Engineering Manufacturing or Operations Research Management Science or Management or Mathematics Applied or Business or Mathematics Interdisciplinary Applications Document Types: Review Articles	29	2 (#6 and #7)	Refined the results to only include the categories Engineering Industrial, Engineering Manufacturing, Operations Research Management Science, Management, Business, Mathematics Applied, Mathematics Interdisciplinary Applications. Set document type to review.
Emerald Insight	(content-type:article) AND (theory OR methodology OR technique) AND ("throughput time" OR "production time" OR "cycle time" OR "throughput rate" OR "process time")	10,547	2 (#8 and #9)	Emerald Insight does not provide many options for filters. Sorted by relevance. Found a useful article relating to optimized production technology / theory of constraints, which is worth looking into.

Emerald Insight	(content-type:article) AND (theory OR methodology OR technique) AND ("theory of constraints" OR "TOC" OR "optimized production technology" OR "OPT") AND ("operations management" OR "production") AND review	8,986	2 (#10 and #11)	Changed some search terms to include optimized production technology / theory of constraints. Sorted by relevance. Many results were found, which seem to be relevant.
Scopus	TITLE-ABS-KEY ((theory OR methodology OR technique) AND ("theory of constraints" OR "TOC" OR "optimized production technology" OR "OPT") AND ("operations management" OR "production") AND review)	75	1 (#12)	We decided to check Scopus to see if there are other relevant articles regarding this topic.

Appendix C.5: Concept matrix of results

#	Article	Title	Variability	Lean	Six Sigma	Lean (Six) Sigma	Total Quality Management (TQM)	Business process re-engineering	Value stream mapping	Optimized production technology / Theory of Constraints
1	Näslund (2008)	Lean, six sigma and lean sigma: Fads or real process improvement methods?		X	X	X				
2	Snee (2010)	Lean Six Sigma – getting better all the time				X				
3	Chiarini (2011)	Japanese total quality control, TQM, deming's system of profound knowledge, BPR, lean and six sigma: Comparison and discussion		X	X		X	X		
4	Singh et al. (2011)	Value stream mapping: Literature review and implications for Indian industry							X	
5	Zheng et al. (2008)	Cycle time reduction in assembly and test manufacturing factories: A KPI driven methodology	X						X	
6	Raval et al. (2018)	Revealing research trends and themes in Lean Six Sigma: from 2000 to 2016				X				
7	Yadav et al. (2017)	Analysis of research trends and constructs in context to lean six sigma frameworks				X				
8	Harrison (1995)	Themes for facilitating material flow in manufacturing systems	X							X

9	Karim & Arif-Uz-Zaman (2013)	A methodology for effective implementation of lean strategies and its performance evaluation in manufacturing organizations		X						
10	Mabin & Balderstone (2003)	The performance of the theory of constraints methodology: Analysis and discussion of successful TOC applications								X
11	Gupta & Boyd (2008)	Theory of constraints: A theory for operations management								X
12	Stevenson et al. (2005)	A review of production planning and control: The applicability of key concepts to the make-to-order industry								X

Appendix D: Profile of the sources of uncertainty (Simangunsong et al., 2012)

Source of uncertainty	Dimension	Literature	Literature with empirical evidence
U1. Product characteristics	The product specification, e.g. colour, length, size, and packaging, can lead to uncertainty in processing times, e.g. when a product is new and the specification is not yet fully clarified	van Donk and van der Vaart (2005)	NA
	The packaging characteristics, e.g. uncertainty about how a new product is to be packaged can lead to uncertainty in product handling times	van der Vorst and Beulens (2002)	van der Vorst and Beulens (2002): Food
	The product life cycle, e.g. shorter life cycles lead to uncertain output volumes, as there are more frequent new product introductions, leading to more frequent quality and engineering problems	Miller (1992), Fisher (1997), Sawhney (2006)	Sawhney (2006): Electronics
	The perishability of products leads to uncertainty in output volumes, etc.	van der Vorst and Beulens (2002)	van der Vorst and Beulens (2002): Food
	The product variety offered: this leads to uncertainties in the quantities of product to stock, etc.	Fisher (1997)	NA
U2. Manufacturing process	Machine breakdowns lead to uncertain output volumes	Miller (1992), Davis (1993), Koh *et al.* (2002), Towill *et al.* (2002), Sawhney (2006)	Towill *et al.* (2002): Automotive Sawhney (2006): Electronic
	Variable process yield and scrap-rates lead to uncertain output volumes	Miller (1992), van der Vorst *et al.* (1998), Towill *et al.* (2002), van der Vorst and Beulens (2002)	Towill *et al.* (2002): Automotive van der Vorst and Beulens (2002): Food
	Changes in employee productivity due, for example, to labour absence, turn-over, labour unrest or strikes	Miller (1992), Sawhney (2006)	Sawhney (2006): Electronics
	Accidents, that disturb the production process	Miller (1992)	NA
	General: authors who do not specify a dimension	Mason-Jones and Towill (1998), Geary *et al.* (2002), Christopher and Peck (2004)	NA
U3. Control/chaos uncertainty	Difficulties in production planning when the sales order is small compared with the production-batching system	Wilding (1998), Geary *et al.* (2002), Towill *et al.* (2002)	Towill *et al.* (2002): Automotive
	Chaos resulting from supply-chain control systems, e.g. wrong control rules, mismatch in the ICT system	Geary *et al.* (2002), Towill *et al.* (2002), van der Vorst and Beulens (2002), Prater (2005)	Towill *et al.* (2002): Automotive, van der Vorst and Beulens (2002): Food (limited evidence)
	Errors caused by inaccuracies or poor reports from supply-chain partners which are beyond the control of the organisation	Geary *et al.* (2002)	NA
U4. Decision complexity	Different goals across functional departments, which may or may not be mutually supportive, that disrupt supply-chain processes, e.g. in terms	Prater (2005)	NA

Source of uncertainty	Dimension	Literature	Literature with empirical evidence
	of delayed decisions that slow down the whole process		
U4. Decision complexity (contd)	Capacity constraints, e.g. maximum production output, machine utilisation, warehouse and truckload capacity including availability of rental options, etc., that leads to the uncertainty of the delivery of an order to the customer	Prater (2005)	NA
	Uncertainty inherent in long range traditional strategic planning, e.g. technology innovations or price/cost changes	Prater (2005)	NA
	Administrative issues and decision policies that lead to uncertainty in the supply-chain caused by unresponsive decision processes	van der Vorst *et al.* (1998)	van der Vorst *et al.* (1998): Food (limited evidence)
U5. Organisation/ behavioural	General behavioural issue, e.g. risk taker vs. risk averse behaviour, that leads to disruption in supply-chain processes	van der Vorst *et al.* (1998), Wilding (1998)	van der Vorst *et al.* (1998): Food (limited evidence)
	Political influence in an organisation that leads to the uncertainty of the execution of a supply-chain decision, e.g. senior versus junior employees/ managers	van der Vorst and Beulens (2002)	van der Vorst and Beulens (2002): Food (limited evidence)
U6. IT/IS complexity	IT/IS system unavailability that may stop all supply-chain activities	Bandyopadhyay *et al.* (1999), Finch (2004), Smith *et al.* (2007), and Savic (2008)	NA
	Data/information security issues that lead to uncertainty, e.g. in terms of information integrity and trust in the system	Bandyopadhyay *et al.* (1999), Finch (2004), Smith *et al.* (2007), and Savic (2008)	NA
	IT/IS system performance that leads to uncertainty, e.g. in terms of productivity of processes	Bandyopadhyay *et al.* (1999), Finch (2004), van der Vorst and Beulens (2002), Prater (2005), Smith *et al.* (2007), and Savic (2008)	van der Vorst and Beulens (2002) Food (limited evidence)
U7. End-customer demand	Seasonal demand variability, e.g. Christmas, Eid al-Fitr, Chinese New Year, school holidays, dry or rainy seasons.	Lee (2002), van der Vorst and Beulens (2002), Sun *et al.* (2009)	Lee (2002): fashion (limited evidence) van der Vorst and Beulens (2002) Food (limited evidence), Sun *et al.* (2009)
	Changes in consumer tastes that lead to unexpected changes in demand for a company's product	Miller (1992), van der Vorst *et al.* (1998)	van der Vorst *et al.* (1998): Food (limited evidence)
	Irregular or sporadic events that lead to uncertainty, e.g. sports events	Bartezzaghi and Verganti (1995)	Bartezzaghi and Verganti (1995) Telecommunications (limited evidence)
U8. Demand amplification	Demand signal processing that leads to unusually high stock levels in the upper regions of the supply chain	Lee *et al.* (1997), Wilding (1998), Dejonckheere *et al.* (2003), Blecker	Lee *et al.* (1997): Computer, consumer goods and retail, Dejonckheere *et al.*

Source of uncertainty	Dimension	Literature	Literature with empirical evidence
		et al. (2005), Prater (2005)	(2003):Consumer goods and retail
	Rationing game that stimulates customers to order more units than they need, this lead to uncertainty of actual end-customer demand patterns.	Lee *et al.* (1997), Wilding (1998)	Lee *et al.* (1997): Computer and automotive
U8. Demand amplification (contd)	Order batching policy, which obscures actual demand.	Lee *et al.* (1997), Wilding (1998), Geary *et al.* (2002)	Lee *et al.* (1997): Consumer goods and retail
	Price variations, e.g. discounts or promotions, that lead to unexpectedly high demand	Lee *et al.* (1997), van der Vorst *et al.* (1998), Wilding (1998)	Lee *et al.* (1997): Food and consumer goods, Wilding (1998): Retail industry
U9. Supplier	The timing of supply may be uncertain if the supplier is regularly unable to meet promised due dates	Davis (1993), Towill *et al.* (2002), van der Vorst and Beulens (2002), Sawhney (2006)	van der Vorst and Beulens (2002): Food Sawhney (2006): Electronics
	The quality of supplied product may vary, e.g. this may depend on the quality of the variable crop quality	Towill *et al.* (2002), van der Vorst and Beulens (2002), Sawhney (2006)	van der Vorst and Beulens (2002): Food Sawhney (2006): Electronics
	The availability of supply may be uncertain	Miller (1992), van der Vorst and Beulens (2002)	NA
U10. Parallel interaction	General parallel interaction issue among suppliers that supply different products to a company, e.g. cross-docking issues	Wilding (1998), van der Vorst and Beulens (2002), Prater (2005), Manuj and Mentzer (2008)	van der Vorst and Beulens (2002): Food
U11. Order forecast horizon	General order forecast horizon issue, i.e. the longer the horizon, the larger the forecast errors, and hence there is a greater demand uncertainty	Muckstadt *et al.* (2001), van der Vorst and Beulens (2002), van Donk and van der Vaart (2005)	van der Vorst and Beulens (2002) Food (limited evidence)
U12. Chain configuration, infrastructure and facilities	The geographic areas covered by the supply chain, such as difficult terrain or long distances.	Prater *et al.* (2001), van der Vorst and Beulens (2002), Manuj and Mentzer (2008)	Prater *et al.* (2001): Electronics
	Uncertainty in network relationships caused, for example, by differences in culture, processes and strategy	van der Vorst and Beulens (2002)	van der Vorst and Beulens (2002): Food (limited evidence)
	The availability of dependable communication that leads to delayed processes and reduced flexibility	Miller (1992), Prater *et al.* (2001),	Prater *et al.* (2001): Electronics
	The availability of dependable transportation infrastructure that leads to delivery process disruptions	Miller (1992), Prater *et al.* (2001), Rodrigues *et al.* (2008)	Prater *et al.* (2001): Electronics
U13. Environment	Political stability, i.e. political instability in a country that has a serious impact on supply-chain processes	Miller (1992), Andreas and Ulf (2004)	NA
	Government regulation, when it is often changed, it may disrupt company plans, e.g. a new trade barrier for imported raw material	Miller (1992), van der Vorst and Beulens (2002), Christopher and Peck (2004)	NA

Source of uncertainty	Dimension	Literature	Literature with empirical evidence
	Macroeconomic issues, e.g. price inflation, fluctuations in exchange and interest rates, may press a company to change its plan, e.g. switch to local suppliers in case of an unfavourable exchange rate	Miller (1992), Christopher and Peck (2004)	NA
	Issues in a society, for, e.g. social unrest, may lead to violence, causing inability to run normal supply-chain operations in the affected area	Miller (1992), Andreas and Ulf (2004)	NA
U13. Environment (contd)	Competitor behaviour, e.g. a competitor may unexpectedly launch a new product to the market that forces a company to revise its supply-chain plans	Miller (1992), van der Vorst and Beulens (2002), Andreas and Ulf (2004)	NA
U14. Disaster	Natural disaster, e.g. earthquakes, hurricanes, and storms, that has a great impact on the supply-chain processes	Miller (1992), Zsidisin *et al.* (2000), Christopher and Peck (2004), Kleindorfer and Saad (2005)	Kleindorfer and Saad (2005) identified the supply-chain issues caused by Hurricane Andrew in 1992, the Kobe earthquake in 1995, and the Taiwan earthquake in 1999

Appendix E: Explanation of production phase lead time equation

As stated in Section 4.1, the lead time between production phases due to material use with a fixed lead time on a given working day is:

$$L = \begin{cases} MIN\big(c - b, MAX(7.5 - a - b, 0)\big), & if\ b \leq c \\ 0, & otherwise \end{cases}$$

Where:

- **7.5** is the number of working hours on a working day, accounting for breaks in between.
- **L** is the observed lead time as a result of waiting for the material to be cured to the extent that the next production phase can start, and no other activities can be done in the meantime.
- **a** is the required time to apply the material to the frame.
- **b** is the time that can be spent on other production steps on the frame after application, for which the material does not need to be fully cured. With fully cured we mean cured to a degree that is acceptable for the next production phase to start (see Table 2).
- **c** is the required curing time for the next production phase of the material in question.

We distinguish between two cases: *b* > c and *c* ≤ *b*:

If *b* > *c* then the lead time will be equal to zero. This is because the material is fully cured before all activities in the meantime are finished, meaning that the next production phase can start as soon as these activities are finished.

If *b* ≤ *c* then the lead time is equal to:

- *c – b,* if *b* = *c*, or if the technicians need to wait for the material to cure because there are still some hours left on a working day. This happens after both *a* and *b* are completely finished in less than 7.5 hours, but the material is not fully cured after *b* is finished. In this case the remaining curing time does not exceed the current working day, meaning that it is possible to start some of the activities from the next production phase on the same day.

- *7.5 – a – b*, if the curing time exceeds the remaining working hours after both *a* and *b* are finished. For example, if *a* takes two hours, *b* takes four hours, and *c* takes twelve hours, then *a* and *b* are finished after six hours, there are two hours remaining on the working day, but the material takes longer than these two hours before it is properly cured. This means that in this case, the lead time is *7.5 – a – b* = 1.5 working hours.

  The expression *7.5 – a – b* is put in a maximum operator together with zero in the event that *a + b* takes more than 7.5 hours. If that is the case, then the lead time will be zero since the technicians can continue working for the full working day and any applied material will be fully cured the next day regardless.

These two options (*c – b* and *7.5 – a – b*) are put in a minimum operator to ensure that the right value is picked depending on <u>when</u> the curing takes place. To illustrate this, we show two examples:

For the first example we use the example of *a* = 2, *b* = 4 and *c* = 12 again. The first expression *c – b* results in 12 – 4 = 8 hours of lead time, but most of these hours take place after the working day. This is irrelevant since the technicians would not be working at these times in the first place. The second expression *7.5 – a – b* gives 7.5 – 2 – 4 = 1.5 and we find L = MIN(8,1.5) = 2. Since the remaining curing time exceeds the remaining working hours, any remaining hours after *a* and *b* are finished is the lead time. We see that the second option is the correct amount of lead time to start the next production phase.

For the second example we take a = 2, b = 3 and c = 4 and see that the curing time does not exceed the current working day. In this case the expression *7.5 – a – b* = 2.5, but since the curing time does not exceed the full working day, this is incorrect. The equation gives us:

$$L = MIN\big(c - b, MAX(7.5 - a - b, 0)\big) = MIN\big(c - b, MAX(2.5,0)\big) = MIN(1,2.5) = 1$$

From the equation we find that in this case the lead time is indeed equal to *c – b*. The technicians need to wait for one hour after finishing *b* for the material to be properly cured, which is the prerequisite for starting the next production phase.

Appendix F: Simulation model code

Removed due to confidentiality