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Improving the production process of shuttering slabs

at Company X

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Improving the production process of shuttering slabs at Company X

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Preface

We conducted this bachelor thesis to finish the bachelor Industrial Engineering and Management at the University of Twente. Furthermore, we executed the thesis at Company X with the supervision of the interim manager of Company X and the supervisor from the University. The aim of this thesis is to improve the production output of the main production process; the making of shuttering slabs.

First, I would like to thank all the employees of the company for feeling welcome and for the great working environment. The employees at the production process were always open for questions and a little chat and they were always enthusiastic to help with my research. Furthermore, the employees at the office were not included in my research, however in the lunch breaks we could laugh and talk about how it was going and they were always nice to me. Besides this I want to thank my supervisor from the company for the knowledge and expertise that he transferred to me. I really appreciate this, because it kept me very motivated to do good and to keep on going. It also gave me a good insight of what I might want to do in the future. Next to the academic perspective of this thesis I learned a lot about the practical perspective and that the combination is a lot of fun.

Second, I want to thank my first supervisor from the University, Marco Schutten. The feedback he gave me always helped me to make my work better and to understand how to write a good academic report. The cooperation with him was a very pleasant experience. I also want to thank Peter Schuur for being my second supervisor. The feedback he gave me helped me making the report more understanding for people that do not know much about the research.

Third, I would like to thank my buddies, Dennis Zuidema, Jimmy van Santen and Niels van Boxel, for providing me with feedback. I want to especially thank Niels, because he is also my housemate and in the corona period he really kept me motivated to keep on working. Besides this I also want to thank Maarten van Oosterom for helping me with some coding in Excel to process data.

Finally, I would like to say that this is the period of the bachelor's that I found the most fun and that I have learned the most from. It combines the theoretical and practical skills to really tackle real life problems. I would suggest such a company to all future students and advise them to make the most of such a thesis.

Mark de Goeij

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Management summary

We executed this research at Company X located in X. Company X produces shuttering slabs. These are concrete floors that are fully customized to the needs of the customer. In the near future the demand for shuttering slabs will increase, because more and more buildings, especially houses, need to be made. Because of this, it is desired to improve the production process to have higher production efficiency. With observation, interviews with employees and with data analysis, we identified the problems. The core problem is that the delivery of concrete mix, with the concrete mix truck, at workstation 17 is too late. A truck with concrete mix is continuously driving from the concrete mix plant towards the production hall and back to supply workstation 17 with concrete mix to pour it into the mould. Besides the main core problem, there are more problems at other workstations that cause the production process to not achieve the desired 8 “soft” production moulds per hour. A “soft” production mould is a mould with all the parts in it and with the concrete mix that is not hardened yet. The name “soft” production mould is used, because only at workstation 2 the products (shuttering slabs) are “hardened”. The shuttering slabs in the mould harden in the curing chamber and are then transported towards workstation 2 where they are lifted out of the mould. The goal of this research is to come up with solutions that improve the processes at the workstations that are underperforming (have a output lower than 8 “soft” production moulds per hour). The following question is this main research question:

“How can Company X achieve a higher production rate?”

In order to answer this question, we first need to know what the current production process looks like. By observing and analysing data we explained the production process. The current production process consists of 11 workstations and 9 stations. At the workstations something is done to the mould to in the end get a “soft” production mould and the other stations are buffers. The focus of this research is on workstations 2, 3, 5, 7, 17 and 18, because at these workstations time exceedings occur which limits the production process to achieve the 8 “soft” production moulds per hour.

A literature study on how to improve the workstations is done, with the knowledge of how all the processes work. From the literature study, we identified techniques and methods which can help improve the processes at the workstations. First some lean tools and techniques are identified. One of the lean tools that we used is Value Stream Mapping (VSM). With VSM a map is made to make a visual representation of the production process and to show where things have to be improved. Another thing that we used is the 5S Methodology. With this methodology the processes at the workstations is organized and standardized to make the work easier for the employees. Cellular Manufacturing is used to combine similar work at different workstations to for example reduce setup and flow times. Besides this, SMED lean manufacturing is used. This methodology is used to reduce the changeover / refill times and setup times at the workstations.

Besides Lean tools and techniques, Six Sigma is used to minimize the variation at the workstations. This will create a more balanced flow of work and will lead to reductions in waiting times at the workstations.

We also identified some methods to improve the bottlenecks. The Theory of Constraints (TOC) is used to get rid of a bottleneck in the production process. The five focussing steps (5FS) and the drum-buffer-rope (DBR) methodology is used to achieve this. The 5FS is a stepwise approach to get rid of a bottleneck. The DBR methodology is a methodology that is used to control the release of jobs with the information from the performance of the bottleneck. With DBR, buffers are used to have work or inventory ready for the constraint in order for the constraint to never be out of work. The buffer also absorbs variability.

In order to come up with solutions we first need to know the causes for the problems. The current performance of the workstations is measured and visualized with the help of a Value Stream Map. First the

bottleneck is identified and the performance indicators are measured to see what goes wrong at the workstations.

With the causes for the problems known we search for solutions. A lot of solutions options are generated and with a weighted decision matrix, which includes the criteria from Company X., the best solutions are chosen.

For workstation 17 and 18 the delivery of concrete is inconsistent. The best option would be to get an extra concrete mix truck to deliver concrete mix to create a bigger time buffer. The extra truck can already be filled with concrete mix when the other is still at the production hall to deliver the mix to workstation 17 and 18. Besides this, a communication device would be good to implement as it is a quick and inexpensive option and this would lead to a smaller travel and filling time. The implementation of a new machine however, is expensive and hard to implement. On the other hand, It will most likely lead to a lower lead time because it would be more accurate and faster in pouring the concrete and it will lead to better quality.

For workstation 7 the button to transport the mould from 7 to 8 is not pressed at workstation 8 and the refill times of steel coils are too high. The work that is done at workstation 8 should be moved to workstation 10. This is possible because the work will add up to an average lead time that would be lower than 7.5 minutes. Furthermore, because nothing is done at workstation 8 in that situation the mould can go automatically from 7 to 8. Because of this solution the button does not have to be pressed, which removes the problem. Besides this, the inventory of lattice girders (reinforcement for into the mould) at workstation 7 must be made bigger to create a bigger buffer during the refill of steel coils. The machine stops producing lattice girders when a refill happens and thus when there are enough lattice girders in inventory to place into the mould then the placement of lattice girders at workstation 7 does not have to stop. Another thing that must be done is to prepare for a steel coil refill before it is empty and not when it is empty.

For workstation 2 the amount of work that needs to be done for two people is too much and thus the amount of shuttering slabs in the mould must not be bigger than 2 to stay under the desired lead time (more than 2 shuttering slabs leads to a output lower than 8 "soft" moulds per hour). Besides this, during a break an employee from another workstation must take over the work from the employee that is taking a break. To prevent product damages a new machine is needed and organisational measures must be taken at the other workstations to make sure the quality increases.

For workstation 3 the work is not done in the right order. The work needs to be done according to the standardized work description. This will lead to a lower lead time and makes it easier for the employees.

For workstation 5 the preparation of the work is done at the wrong time and the transportation takes too long. The work for the upcoming moulds needs to be prepared in the time they have left from the current mould. Also, a laser system needs to be made to make the transport faster, but also safe. When someone steps into the laser the mould stops with transporting and with the laser the mould can thus be transported automatically without leading to an unsafe situation.

The potential impact of these solutions is varying per workstation from an increase in individual output of 2% to 33% and a decrease in variation of 26% to 53%. With this it is still hard to say if the overall output will become 8 "soft" moulds per hour. However, it will be a lot higher than the output of the whole process, which is 6.4 "soft" moulds per hour. This is because workstations 17 and 18 (the bottleneck) will improve a lot and the variation of the other workstations will go down, which creates a more balanced flow of work.

Based on the research, we make the following important recommendations:

- The first recommendation is to evaluate whether and to what extent the solutions have improved the production process and thus to see where further improvements have to be made. The whole process of analyzing the processes and getting to solutions can be done over and over again to achieve continuous improvement.

- Another recommendation is to listen to the employees more often and to really involve them in the process of decision making. They are the eyes and ears of the process and know way more than often is thought. This will also lead to more motivated employees that think about process improvement. This recommendation can be strengthened with a saying from the Lean methodology: Tell me, I forget. Show me, I remember. Involve me, I understand.

- Furthermore, with regards to data gathering a recommendation would be to have more sensors or other data gathering methods to get more information about the performance of the production process. Currently no information is available about how long it actually takes to do the work (this is only measured by hand in this research) and thus also how long a mould is waiting to be transported to the next (work)station. Another recommendation would be to document all the failures and variations in production in some documentation system. With this, causes for underperformance are easier to trace back.

- The last recommendation is for the employees that are not working at the production process, but do make decisions regarding the production process. They should go into the production hall more often to see what happens. You cannot see everything on a screen and from data.

Overall, Company X can improve their production process of shuttering slabs. Some solutions can already be implemented and some need more research.

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List of abbreviations

Abbreviation	Full name	First introduced
5FS	5 Focussing Steps	Page 26
BV	Besloten Vennootschap	Page 1
DBR	Drum-Buffer-Rope	Page 24
DMAIC	Define Measure Analyze Improve Control	Page 23
EPS	Expanded Polystyrene	Page 8
LT	Lead Time	Page 70
NVA	Non-Value Adding	Page 19
OPT	Optimized Production Technology	Page 24
RT	Refill Time	Page 80
SMED	Single Minute Exchange of Dies	Page 21
STD	Standard Deviation	Page 81
T-Bs	Time Buffers	Page 26
TOC	Theory of Constraints	Page 26
TPS	Toyota Production System	Page 19
TT	Transport Time	Page 79
PT	Process Time	Page 72
UT	Utilization Rate	Page 82
VGA	Is a machine type	Page 5
VSM	Value Stream Map	Page 20
WT	Waiting Time	Page 79

List of technical terms

Technical term	Dutch translation	First introduced
Carousel system	Carrousel systeem	Page 1
Curing chamber	Hardingskamer	Page 2
Demoulding	Ontkisten	Page 8
“Hardened” production mould	Harde productie mal	Page 2
Lattice girder	Tralieligger	Page 5
Metal shutterings	Metalen scheidings balken	Page 4
Mould	Mal	Page 1
Plotter	Automatische tekenmachine	Page 4
Reinforcement	Wapening	Page 1
Roller system	Rol systeem	Page 1
Shuttering slab	Breedplaatvloer	Page 1
“Soft” production mould	Zachte productie mal	Page 2
Supplementary parts	Extra onderdelen	Page 4

1. Introduction

We executed this bachelor thesis at Company X. The thesis focuses on analysing the production process and improving the bottlenecks to get a higher output. Section 1.1 gives an introduction to the company. Furthermore, Section 1.2 explains the problem that occurs at the production process, Section 1.3 gives a short overview of the research design, Section 1.4 the intended deliverables and Section 1.5 gives the conclusion of the introduction.

1.1 Company description

Company X is located in censored and they make 5 types of concrete related products. The most important one is the traditional shuttering slab (type of concrete floor), which is made in the first production hall together with special reinforcement. The traditional shuttering slab is made on an advanced carousel system, which is a roller system that allows the moulds to travel from station to station. The system is powered with small motors. A mould is a sort of big table that can be filled with different parts and in the end a shuttering slab is made. The process of making these shuttering slabs can be seen in Figure 1.1.

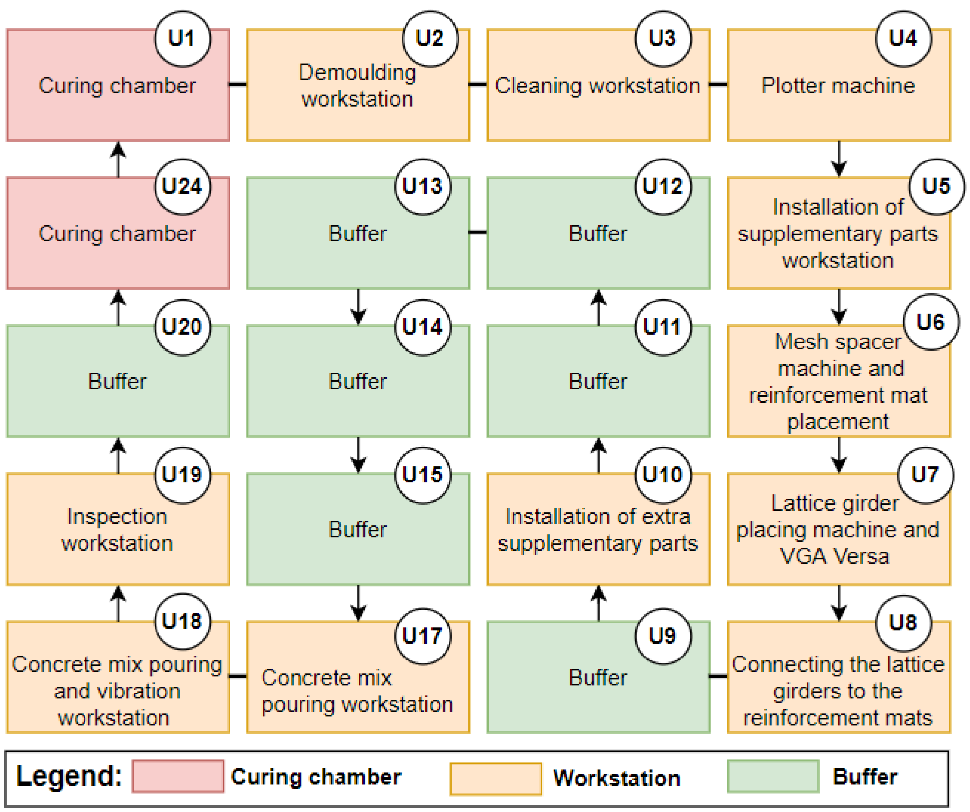

Figure 1.1: The production process of shuttering slabs.

The production process

There are 20 stations in total. At 11 of these 20 stations something is done (see U2, U3, U4, U5, U6, U7, U8, U10, U17, U18 and U19 in Figure 2). The stations where something is done are workstations. At the other stations nothing is done (see U9, U11, U12, U13, U14, U15, U20, U24, U1 in Figure 2). These are buffers or stations at the curing chamber (see U24 and U1 in Figure 2), which are also sort of buffers. The stations at the curing chamber are there to transport a production mould in or out of the curing chamber.

The process starts at U4 where an empty clean mould is coming from U3. Starting at U4 and ending at U19 the empty mould is filled with different parts. A mould with all the different parts and with the unhardened concrete mix in it is called a “soft” production mould. This “soft” production mould is transported into the curing chamber to harden and will then become a “hardened” production mould. The “hardened” production mould is transported from U1 to U2 when the product(s) in the mould is/are hardened (see Figure 1.2). The product is a shuttering slab. A “hardened” production mould can contain more than 1 shuttering slab. The number of shuttering slabs in a “hardened” production mould depends on the sizes of the shuttering slabs. An empty mould is 12.5 meters long and 3 meters wide. A shuttering slab can have all kinds of sizes in this range and thus more shuttering slabs can be made in a mould. At U2 the shuttering slab(s) is (are) taken out of the mould and put on a stack to be transported to the outside “tas” field. This is a big field that is located outside to store all the stacks before being transported to the construction site. At U3 the empty mould is cleaned to be used again. The empty mould is then transported to U4 where the whole process starts again.

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Figure 1.2: Hardened production mould.

1.2 Problem description

This section explains the problems that the company is facing. Section 1.2.1 describes the action problem the company has and Section 1.2.2 explains the problems in the production process. Furthermore, Section 1.2.3 explains the core problems.

1.2.1 The action problem

According to Company X, the current production process is not working efficiently. The main production is the production of shuttering slabs. Company X, which is the problem owner, indicates that the production output should be 8 “soft” production moulds per hour. To achieve a production output of 8 “soft” moulds per hour the work at the workstations should be done in 7.5 minutes including the transport time (60/8 = 7.5 minutes).

However, currently there is no production output of 8 “soft” production moulds per hour. This means that there is a gap between the norm and the reality. The action problem is defined as follows:

“The production rate of “soft” production moulds, at Company X, is currently 6.4 “soft” production moulds per hour and the production needs to go to 8 “soft” production moulds per hour”

1.2.2 Problem identification

There are a lot of problems that cause the production process to not achieve the production output of 8 “soft” production moulds per hour. The problem cluster in Figure 1.3 shows the problems at the production process. The problems that lead to the box “machine problems” are problems at the machines. Besides this, the problems that lead to the box “human problems” are problems that are occurring due to human actions.

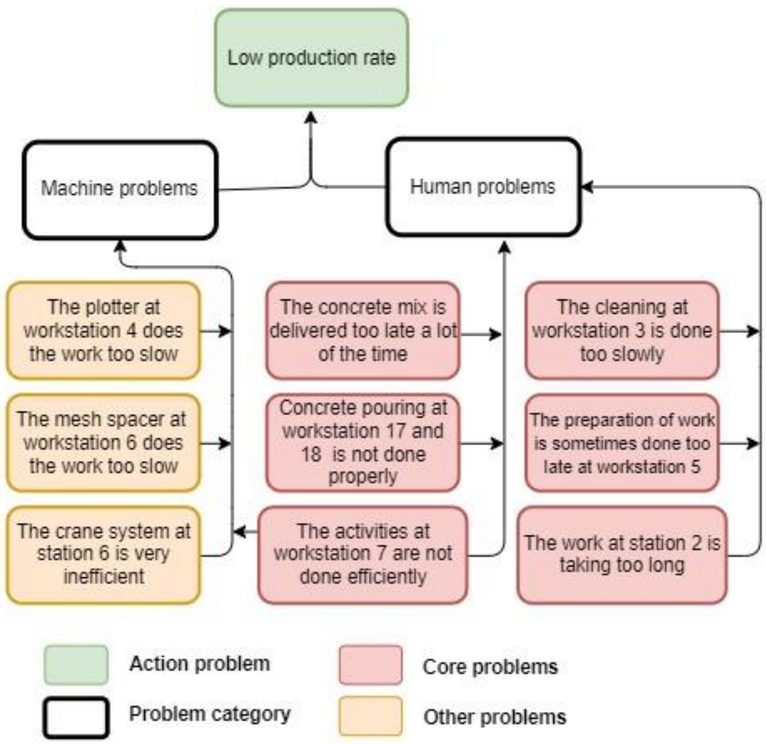

Figure 1.3: The problem cluster.

Problem at workstation 2

At workstation 2 the shuttering slab(s) are taken out of the mould and are put on a stack with a crane. This process takes too much time.

Problem at workstation 3

At workstation 3 the mould from workstation 2 is cleaned. This process is done too slowly, because it can be done in 7.5 minutes (including transport time), but it does not always happen.

Problem at workstation 4

The plotter machine draws lines on the mould to give an indication where certain parts have to be placed or glued at workstation 5. The plotter does not always take the optimal path when plotting contours on the bottom of the empty mould. This is a problem in the software of the machine, but it is not a very big problem. Most of the time the plotter is fast enough to plot the contours within 7.5 minutes (which gives an output of 8 "soft" production moulds per hour). However, optimizing the machine can improve the speed of the work that is done at this workstation.

Problem at workstation 5

The installation of metal shutterings (see Figure 1.4) on the mould and the installation of certain supplementary parts is done at workstation 5. The biggest problem here is that the preparation of the work is done inefficiently. The preparation of the work consists of cutting supplementary parts in the right sizes. Sometimes the people have some time left from working on placing the supplementary parts on the previous mould and in that time they could have prepared for the upcoming mould. However, they start to work on the supplementary parts only when the next mould arrives.

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Figure 1.4: Metal shutterings.

Problem at workstation 6

The mesh spacer machine is a machine that places plastic rings on the bottom of the mould to elevate the reinforcement. The mesh spacer at workstation 6 has the same kind of problem as the plotter machine at workstation 4. It does not always take the optimal paths and the optimal options (the best option of type of distance holder) when it comes to choosing the type of distance holders (see Figure 1.5). Thus here there is also an optimization problem.

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Figure 1.5: Distance holders.

Problems at workstation 7

At workstation 7 the lattice girders are placed on the mould by a crane. The machine making the lattice girders, called the VGA Versa lattice girder welding machine, sometimes has a failure. Furthermore, activities around the machine are not done efficiently. One of the problems is that the refill of steel coils is done very inefficiently and this takes a lot of time which can lead to a standstill in the production process.

Problems at workstation 17 and 18

At workstations 17 and 18 the pouring of concrete is sometimes done too fast. The employees have enough time to pour the concrete mix into the mould, but they think they have to do it as fast as possible. Because of this the quality of the shuttering slab is sometimes very bad and the slab has to be repaired at workstation 2, which takes extra time. Besides this, the slab can become too thick and this is a waste of concrete mix. However, the bigger problem is concerning the delivery of concrete mix. Often the work at workstation 17 and 18 is at a standstill, because there is no concrete mix. Concrete mix is delivered by a concrete mix truck that continuously drives from the concrete mix plant towards the production hall and back. The problem is that this takes too long and that the production is at a standstill.

1.2.3 Motivation of core problems

From the book “Solving Managerial Problems Systematically” (Heerkens & Winden, 2017), a core problem has the following characteristics:

- There should be a clear relationship with other problems
- The problem should not have a direct cause itself
- The problem should be able to be influenced
- If there are more core problems, then choose the most important one

The core problems based on the problem cluster in Figure 1.3 at Company X are:

1. The concrete mix is delivered too late by the concrete mix truck a lot of the time at workstation 17 and 18.

2. The pouring of concrete is not done properly at workstation 17 and 18.
3. The activities at workstations 7 are not done efficiently.
4. The work at station 2 is taking too long.
5. The cleaning at workstation 3 is done too slowly.
6. The preparation of work is sometimes done too late at workstation 5.

The measurable variable is the production output. The production output is divided into two types: The production output of the whole process and the production output of an individual workstation. The production output of the whole process includes the outputs of all the (work)stations and also includes the time the (work)stations are empty. Furthermore, the production output of an individual workstation includes the times a mould is at the workstation and excludes the times the workstation is empty. This is because the performance of the individual workstations is relevant in order to know what the output is and how much it should increase. The overall production output is relevant for the complete performance of the process.

1.3 Research design

We solved the core problems to achieve the desired production rate of 8 “soft” production moulds per hour. The main research question of this research is:

- *How can Company X achieve a higher production rate?*

By answering the following knowledge questions during the research we are able to answer the main research question:

- *What does the current production process look like?*

To answer this knowledge question we did a descriptive study to see what the current situation looks like. We gathered information about the production process by interviewing the head of production, the foremen and some employees that work at the production process. Besides this with the use of the guideline book from the company we made a good description of the activities at certain workstations. With this information we used Value Stream Mapping to make an overview of all the value streams of the process. We also used observation to see what happens at the different workstations.

- *What theories and methods, based on scientific literature and case studies, can be used to improve the process at the workstations 2, 3, 5, 7, 17 and 18?*

To answer this knowledge question we did an explanatory study in the form of a literature study. We conducted an systematic literature review to gather theories and methods that can be used to improve the process at the workstations. We described the theories and methods in further detail. Furthermore, the information helps with choosing a solution approach.

- *What problems are occurring at and around workstations 2, 3, 5, 7, 17 and 18?*

To answer this knowledge question we conducted an explanatory study. Again with the help of interviews with the stakeholders mentioned before, we gathered problems at the workstations. Besides this we analysed the data from the software system with Excel to see when things go wrong and together with the information from the teams channel (here the failures are documented) we identified the causes and relationships.

- *What are the solution options to tackle the problem(s) at workstations 2, 3, 5, 7, 17 and 18?*

To answer this knowledge question we did an explanatory study. We discussed the theories and methods that are found with the previous knowledge question. Furthermore we used the relevant methods and or theories to come up with a solution approach and eventually to come up with solutions options.

- *Which solution options can be implemented by Company X, taking into account the criteria from the company?*

To answer this knowledge question we conducted an explanatory study. With the help of criteria from the company, we selected possible solutions and an implementation plan is made for these solutions. We discussed the criteria that is used with the supervisor at the company. The plan must be understandable for the employees that work directly at the production process and gives a base for further research.

1.4 Deliverables

We made the following deliverables during the assignment:

- Description and a current-state Value Stream Map of the production process.
- List of the problems occurring at the workstations and solution approach on how to solve these problems.
- The best solutions based on criteria and an implementation plan on how to implement the best solution(s) for the problems that are found.
- Advice on how to proceed further with especially advice on how to approach the workstations in the future to eliminate the next bottleneck and so on.

2 Overview of the production process

This chapter describes and explains the current situation of the production process at Company X. Furthermore, this chapter answers the following research question:

"What does the current production process of making shuttering slabs look like?"

Section 2.1 describes the relevant workstations to get a good understanding of what activities take place. In the end Section 2.2 gives the conclusion.

2.1 The workstations

We see the complete production process layout in Figure 2.1. The Us with a number indicate the different (work)stations. The production starts with U4 and ends with U3 and it operates in a circular manner. This means that the moulds from U3 (end of the process) starts again at U4 (begin of the process). U16 is used as a repair station. The focus is on workstations 2, 3, 5, 7, 17 and 18 because the core problems occur at these stations. This section explains these workstations in more detail. Appendix A explains the other (work)stations.

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Figure 2.1: Production process layout.

U2 (demoulding station)

At this workstation the shuttering slab(s) are lifted out of the mould (see Figure 2.2) and placed at a stacking place with a small crane. Figure 2.3 shows an empty mould. The crane is operated by one person. Before lifting, the person that operates the crane has to manually place the hooks of the crane under the lattice girders. Some waste is cleared from the shuttering slab by a second person. This waste can be EPS circles (foam circles to make holes in the shuttering slab for electricity etcetera), cardboard corners or the EPS beams (to separate different shuttering slabs). The shuttering slabs can be stacked at 2 different stacking places and if needed a 3rd place can be made available. Wooden beams have to be placed at the bottom of a stack to support the shuttering slabs. The amount of wooden beams is depending on the weight of the complete stack. Besides the wooden beams, some smaller wooden blocks or special bricks are put between the different shuttering slabs. These are there to separate the shuttering slab(s), because otherwise the bottom would be damaged by the lattice girders of another shuttering slab. They also operate as pressure points and this ensures the shuttering slabs stay in place during transport. Furthermore, on each stack a sticker is stuck to the side with information and the number of the stack is painted on top of the stack to show the crane outside which stack it is. We see the timeline of the work, with the time it takes on average at this workstation, in Figure 2.4. The green part is the process time that the employees have, to do the work, to still be under the 7.5 minutes including transport time.

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Figure 2.2: Hardened production mould towed out of the mould.

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Figure 2.3: Demoulded mould.

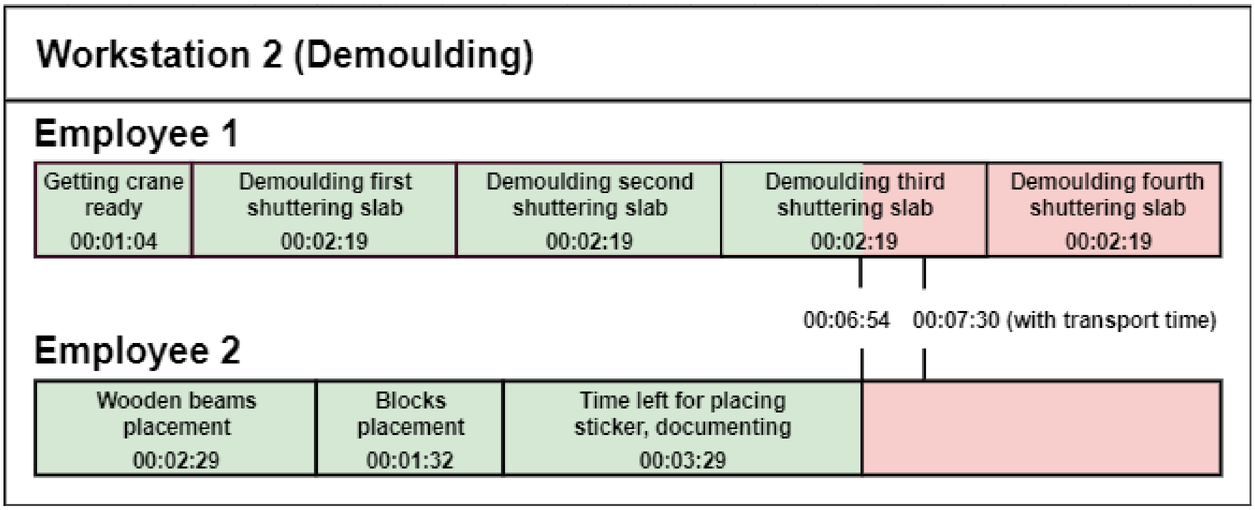

Figure 2.4: Timeline of the work at workstation 2.

U3 (cleaning station)

The metal shutterings are taken out of the mould and are placed at the end of the mould by one employee. Then they are towed by a magnetic crane onto a roller bar system. The crane is operated by the same employee. The metal shutterings can be pushed onto an automatic conveyor belt via a roller bar system. This conveyor belt transports the metal shutterings to workstation 5. Furthermore, parts of waste, like cardboard, concrete and EPS that stick to the bottom of the mould, are scraped off the mould with a special tool. The sides of the mould are also wiped clean with a broom. This is done by the same employee that operates the crane. The other small parts of waste are wiped off the bottom of the mould by the cleaning machine and afterwards the machine cleans the surface of the mould. If the mould is still not clean the process of scraping and cleaning is done again until the mould is clean (see Figure 2.5 for a clean mould). We see the timeline of the work at this workstation in Figure 2.6.

[redacted]

Figure 2.5: Clean mould.

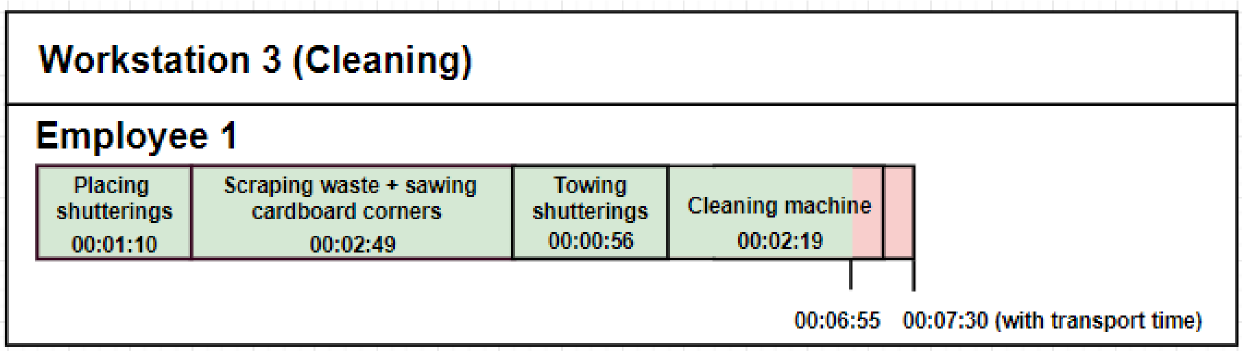

Figure 2.6: Timeline of the work at workstation 3.

U5 (installation)

The people at this station put the metal shutterings (these beams separate different shuttering slabs in the mould). We see this in Figure 2.7. On the right places that were plotted by the plotter at U4. In the moulds 2 or 3 of these metal shutterings are placed. The supplementary parts (see Table 2.1) are glued on the bottom of the mould on the plotted places by two employees (see Figure 2.8). These are added to the mould, because these are places where electricity, ventilation, sewer systems, etcetera will be located. The material of the supplementary parts can be removed or drilled away easier than the concrete of the shuttering slab itself. EPS, gypsum and tempex are a lot less hard than concrete. Some of the supplementary parts need to be made into the right dimension at the workstation and some already have the right dimension. After this, the sides of the mould are sprayed with a special liquid to prevent the concrete mix from sticking to the mould. Two employees are working here to get the work done. We see the timeline of the work at this workstation in Figure 2.9.

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Figure 2.7: Metal shutterings.

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Figure 2.8: Mould with supplementary parts.

Table 2.1: List of supplementary parts.

Part name	Explanation	Picture
1. Tempex beams	These are styrofoam beams. They are glued onto the bottom of the mould to separate different shuttering slabs from each other. They are smaller than the metal shutterings.	Censored

2. Gypsum blocks	These are glued onto the bottom of the mould to create places where someone later on can drill out parts of the slab more easily. It is a lot softer than the concrete. It is used because ventilation or other types of pipe systems need to go through the slab.	Censored
3. EPS cylinders	These are glued onto the bottom of the mould to also be able to make openings in the slab more easily.	Censored
4. Cardboard corners	These are glued onto the mould to keep the metal shutterings in place and to make small adjustments for the shape of the shuttering slab.	Censored

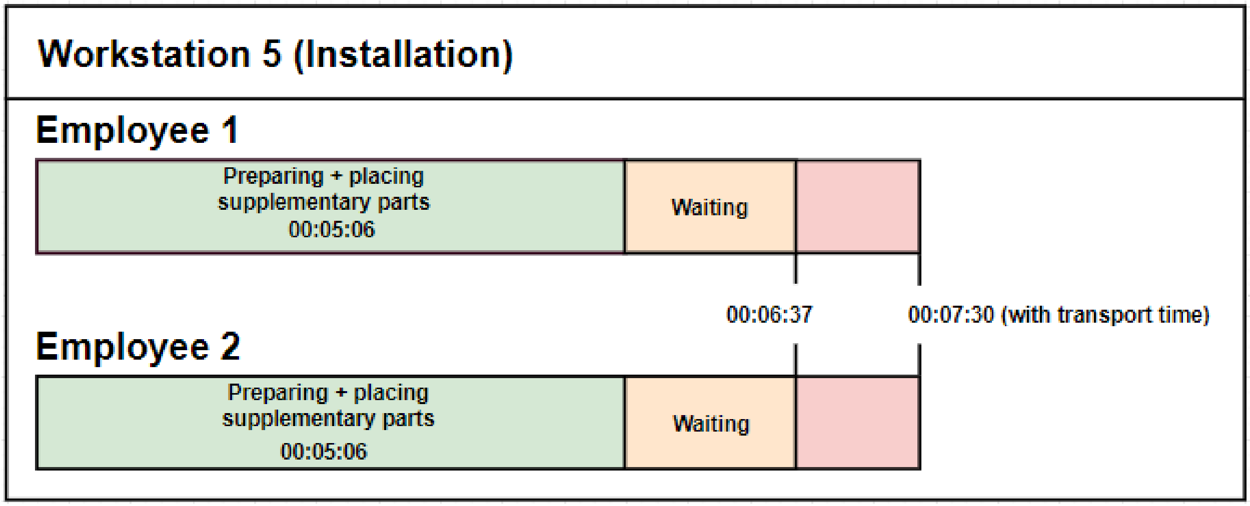

Figure 2.9: Timeline of the work at workstation 5.

U7 (lattice girder placement)
The first process at workstation 7 is the production of lattice girders with the VGA Versa welding machine. Steel wires are needed to make the lattice girders and because of that some steel coils are standing near the machine to feed the machine with steel wires. 6 steel coils are standing on 6 reels to each feed the machine with a steel wire for certain parts of the lattice girder. There are 2 coils to feed 8mm wire to A and B, 2 to feed 6mm wire to C and D, 1 to feed 8mm to E or 1 to feed 10 mm wire to E (see Figure 2.10). If these coils are empty, they need to be filled again with new steel coils.

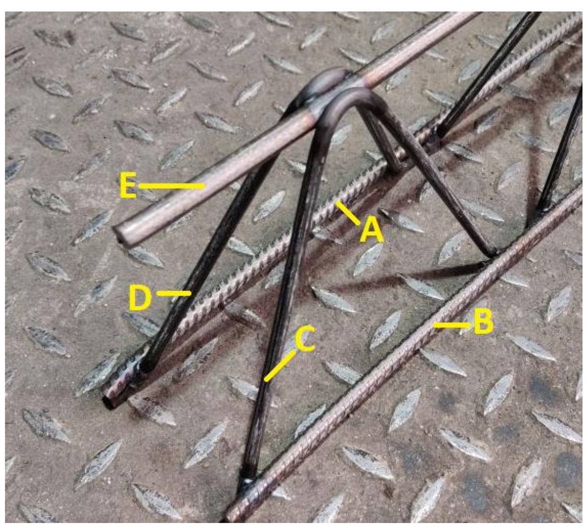

Figure 2.10: Steel wire layout.

The machine can make lattice girders of different heights and lengths. The minimum height that can be made is 80mm and can go up to 360mm in steps of 10mm. Besides this the minimum length the machine can make is 800mm and the maximum length is 11500mm. The machine first bends the diagonal wires (see C and D in

Figure 2.10) and then welds the different wires together to make a lattice girder with the layout. When the lattice girder has the right length, it will be cut by the machine, and it will start to make the next one. The finished lattice girders are transported by a small lift and put on to a belt as inventory for the automatic crane.

The second process at workstation 7 is the process of placing the lattice girders on the reinforcement mat (see the orange arrow in Figure 2.11) in the mould by an automatic crane. The automatic crane can pick up 1 to 4 lattice girders at once from the inventory and place it into the mould. The crane has two grappling devices that do this. The lattice girders must be of the same height and somewhat of the same length to be picked together. The inventory is located one level above the mould and because of this the crane has to transport the grappling devices horizontally to pick the lattice girders from the inventory and vertically to go down and place them into the mould. We see the end result in Figure 2.11. Furthermore, we see the timeline of the work at this workstation in Figure 2.12. The refill scenario happens when a steel coil is empty.

Censored

Figure 2.11: Lattice girders placed on the reinforcement mats.

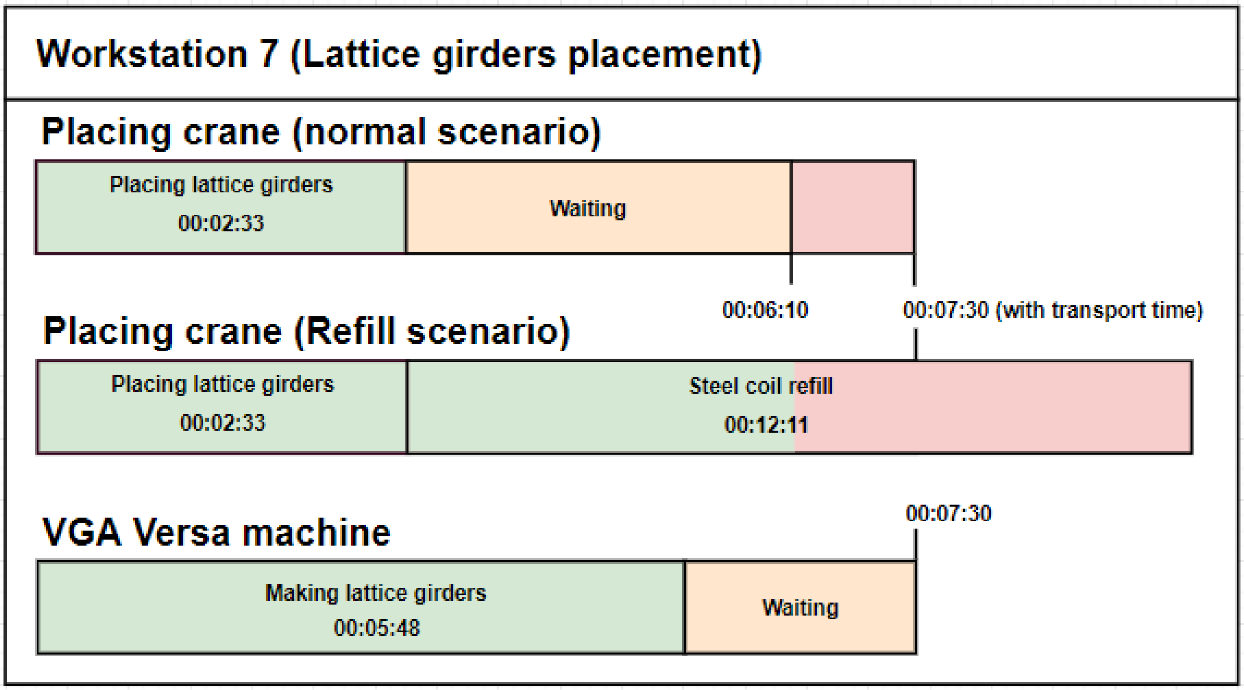

Figure 2.12: Timeline of the work at workstation 7.

U17 (concrete pouring)

At this station the concrete mix is poured into the mould with all the parts in it (see Figure 2.13). This is done by a machine that is operated by 1 person. The machine is also filled at this station with a gutter that is connected to the outside of the building. A concrete mix truck can connect itself to this gutter and then the concrete mix can be poured into the machine. We see the timeline of the work at this workstation in Figure 2.14. The refill scenario happens when the machine does not have any concrete mix anymore. The machine will then be filled up again with concrete mix from the truck.

Censored

Figure 2.13: Concrete mix poured into mould.

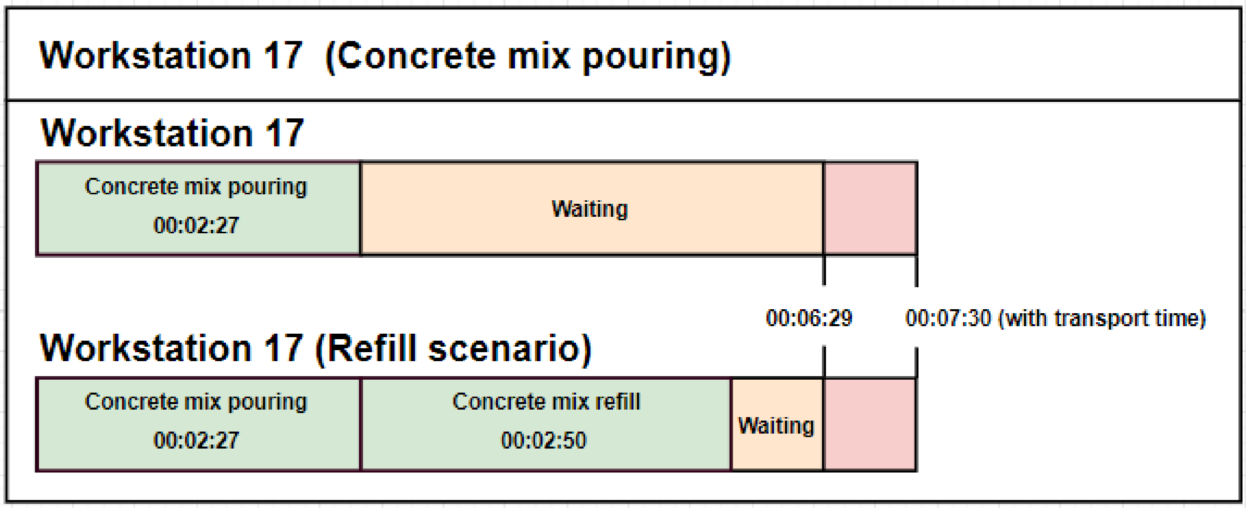

Figure 2.14: Timeline of the work at workstation 17.

U18 (concrete pouring and vibrating)

The pouring machine can also get to this station. However, this station can also be used as a shaking or vibration platform to equally distribute the concrete mix. Furthermore, the person at this station will distribute the concrete equally if necessary with a rake and he will take away concrete mix from the supplementary parts. Before shaking or vibrating the mould, some clamps are placed at the metal shutterings to prevent them from moving. Shaking is always done and vibrating is sometimes done. Vibrating is only needed when the concrete mix is a bit too dry or when too much concrete mix is poured at a certain place. Figure 2.15 shows how the "soft" production mould looks when everything is done. Furthermore, we see the timeline of the work at this workstation in Figure 2.16.

Censored

Figure 2.15: Mould with concrete mix vibrated/shaked.

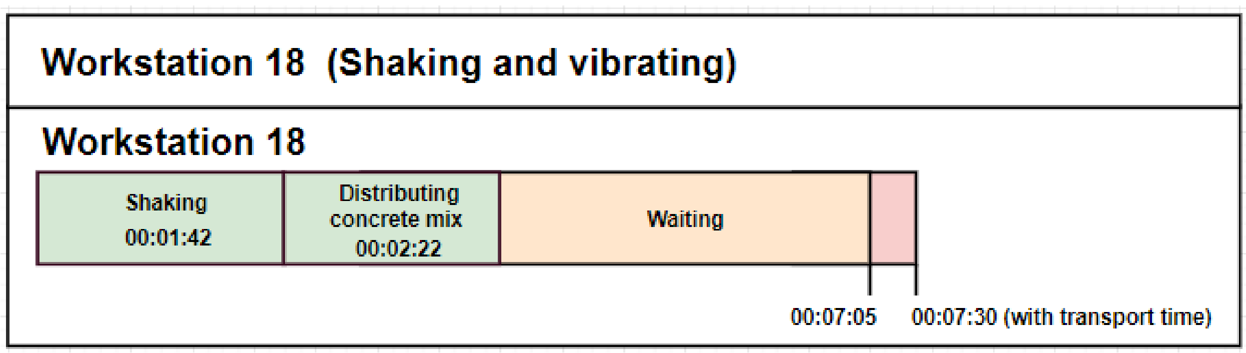

Figure 2.16: Timeline of the work at workstation 18.

2.2 Conclusion

We explained the production process in this chapter, by answering the following research question:

"What does the current production process look like?"

The current production process consists of 11 workstations and 9 stations. At the workstations something is done in the mould to in the end get a "soft" production mould and the other stations are buffers. Workstations 2, 3, 5, 7, 17 and 18 are explained in more detail, because the focus is on these workstations.

At workstation 2 the "hardened" production mould comes out of the curing chamber and the shuttering slabs are lifted out of the mould. Furthermore, at workstation 3 the empty mould is cleaned. At workstation 5 some supplementary parts are placed into the mould to make holes for electricity etc. and to separate the different shutterings slabs in the mould. At workstation 7 the lattice girders are made and are placed on the reinforcement mats. In the end at workstation 17 and 18 the concrete mix is poured into the mould and the mould is vibrated to equally distribute the concrete mix. Stations 1, 9, 11, 12, 13, 14, 15, 20 and 24 are buffers and station 16 is a repair station.

3 Improving the production process: Literature review

This chapter describes the methods and theories to improve the production process at Company X. Furthermore, this chapter answers the following research question:

"What theories and methods, based on scientific literature and case studies, can be used to improve the process at the workstations 2, 3, 5, 7, 17 and 18?"

Section 3.1 gives background information on the production process at Company X and what has to be done to achieve a higher production output. Section 3.2 explains the Lean methodology and gives some tools and techniques. Furthermore, Section 3.3 explains Six Sigma. Moreover, Section 3.4 explains the Theory of Constraints and the methods and theories that are derived from this methodology. In the end Section 3.5 gives the conclusion.

3.1 Prefabrication processes

Construction on-site has been criticized for a long time, because it has a low productivity, it has poor safety records and it is environmentally unfriendly due to large waste production (Deffense et al., 2011). Prefabrication on the other hand, can offer some advantages when compared with traditional on-site construction methods. It reduces costs, construction time, waste production and it increases quality and safety on-site (Deffense et al., 2011).

Company X has a prefabrication production process that makes shuttering slabs. The production process does not achieve the performance that the company desires. This underperformance leads to a lower production output. By searching for methods and theories that can improve the production process, a higher production output and thus a better working prefabrication production process can be achieved.

The main goal of this literature study is to gather methods and theories that can reduce the lead time of the different workstations and especially the workstations that are underperforming. Underperformance occurs when a workstation has lead times higher than 7.5 minutes.

3.2 Lean methodology

Lean is a method that can be used to minimize unnecessary waste or minimize non-value adding (NVA) activities. The Lean method comes from the Toyota Production System (TPS) from the early 1950s in Japan (Antony et al., 2011). The NVA activities can be split up into 2 types. Type 1is the waste that is generated during the process, but cannot be avoided and type 2 is waste that occurs during the process, but can and must be avoided/reduced. Furthermore, these 2 types can be split into 8 sub-categories (Khairunnisa et al., 2020 & Ahmad et al., 2019):

- Transportation: Movement of people or parts between workstations that is unnecessary.
- Inventory: Materials and products that are in inventory do not have any value added to them. Cash is reduced and is tied to the inventory. Besides this, storage is needed which costs money. Some materials and or products need to be preserved in inventory and might become obsolete or damaged, which will also cost money.

- **Motion:** Movement of people or parts within a process that is unnecessary.
- **Waiting:** People or parts waiting for a work cycle to finish.
- **Overproduction:** Products that are produced too much, too early and/or too fast.
- **Over/Excess-processing:** Making something extra to the product that the customer does not need, want or care about.
- **Defects:** All defects must be repaired or reworked. This is extra unnecessary time.
- **People and unexploited knowledge:** People are not always working in an optimal way and the knowledge of employees is not used or not used enough.

Several Lean tools and methods can be used to improve a production process. Sections 3.2.1, 3.2.2, 3.2.3 and 3.2.4 give an overview and an explanation of Value Stream Mapping, the 5S Methodology, Cellular Manufacturing and Single Minute Exchange of Dies Methodology respectively.

3.2.1 Value Stream Mapping (VSM)

VSM can be used to map the complete process with visual icons (Deffense et al., 2011). It is useful, because it can give a better and clear understanding of the process. The method breaks the process down into smaller, more detailed steps. Furthermore, it shows the information about process times and the amount of materials together with the production rate of the product and a lot more. A current-state value stream map visualises the current situation of the production process (Deffense et al., 2011). Kaizen bursts in the value stream map show where things have to be made better (Deffense et al., 2011). “Kai” literally means change and “zen” literally means good and together it means good change or more logical continual improvement (Deffense et al., 2011). The next step is to make a future state map. This shows how the process should perform in the future. After this a plan must be created to get to this future state map.

Some advantages of VSM can be listed as follows:

1. The process can be seen visually as a whole and not only as individual processes (Fawaz et al., 2006).
2. It creates a good basis of what the production process looks like and from there good decisions can be made (Fawaz et al., 2006).
3. Next to the production flows the communication and information flows can be seen (Manjunath et al., 2014).
4. The ability to collect, analyze and present information in a short period of time (Manjunath et al., 2014).

Possible downsides of VSM can be that it is basic and that sometimes not all information is needed from the Value Stream Map and thus some excess work is done.

3.2.2 5S Methodology

The 5S Methodology aims at organization and standardization of work (Deffense et al., 2011). Organization is important, because a structure of how the production should go is needed to have a fluent process. This structure should be managed to ensure continuation. Standardization is important, because it ensures that steps are the same each time and that the worker can easily do this without having to think every time a product has to be made. The 5S’s are (Deffense et al., 2011):

- **Seiri (Sorting):** Only keep the essential tools and materials and get rid of all the others.

- **Seiton (Stabilize):** All items that are used at the workplaces should have a specific place and clearly marked/labeled. The items must be placed in such a way that the workflow can be efficient.
- **Seiso (Systematic Cleaning):** Maintaining and cleaning the machines should be a continuous job. All workplaces should be clean and organized to improve workflow.
- **Seiketsu (Standardizing):** The work that is done at workplaces should be consistent and standardized, following the previous rules established.
- **Shitsuke (Sustaining):** Once the previous rules have been established, they

  will be the standard for future work. The focus now is to maintain these new rules and continuously seek improvement, repeating the steps all over again.

Some of the advantages of 5S are the following (Dominquez et al., 2015):

1. When implemented it establishes and maintains quality.
2. When implemented it increases productivity.
3. When implemented it increases safety.

A big disadvantage of 5S is that the implementation can be hard. The organization needs to have full commitment to achieve quality, to motivate the staff in order to achieve competitiveness (Dominquez et al., 2015).

3.2.3 Cellular Manufacturing

Cellular Manufacturing is a Lean method (E.P.A., 2021). The method combines similar equipment and work cells joined by their similarities (Deffense et al., 2011). A cell is a cluster of dissimilar processes or machines that are close together (Hyer et al., 1989). In a production process there can be a combination of cells.

Some advantages of Cellular Manufacturing are that setup times (by using the same equipment) and flow times can be reduced (by reducing setup and move time, waiting time for movement of work, and by using small transfer batches (a transfer batch is explained in Section 3.4)) (Hyer et al., 1989). This will lead to less inventory and a lower market response time. A disadvantage is that the employees have to be trained to fully understand and perform well within the cells.

3.2.4 Single Minute Exchange of Dies (SMED) Methodology

Single Minute Exchange of Dies is a methodology that can be used to reduce setup and or changeover times (Ferradás and Salonitis, 2013). Ferradás and Salonitis also state that changeover time is the period between the last good product from the previous production order leaving the machine and the first good product coming out from the following production order.

There are two types of activities when conducting a changeover (Ferradás and Salonitis, 2013). There are internal and external activities. The internal activities can only be done when the machine is shut down and the external activities can be done when the machine is running. Furthermore, three steps have to be done to reduce the changeover time:

- **Step 1:** The internal and external activities must be identified and separated.
- **Step 2:** The internal activities must be converted to external activities as much as possible.
- **Step 3:** The activities, internal and external, must be streamlined to have an efficient and quick changeover/refill.

The benefits of SMED are the following (Al-Akel et al., 2017 & Ferradás and Salonitis, 2013):

1. It reduces batch sizes, which leads to more flexibility and improved product flow in the production process.
2. The downtime between two batches and of the equipment can be shortened and standardized.
3. Leads to an increase in production output.
4. Better teamwork and better workload are expected.

However, there are also some downsides. Sometimes for complex manufacturing systems the simple use of the SMED methodology is not enough (Faccio, 2013). Furthermore, because of the strict application the methodology is not a very efficient way to reduce setup times in every situation (Ferradás and Salonitis, 2013). The example that is give is for an automotive supplier and this can thus maybe not be as successful for a different kind of manufacturer.

3.3 Six Sigma

Six Sigma is a method that can be used to reduce waste and remove variability in production (Oguz et al., 2012). In a Six Sigma process there are only 3.4 defects per million opportunities (Council For Six Sigma Certification, 2018). This means that 99.99966 percent of the time products are made without defects. In a lot of cases this is not possible, but the goal is to always improve to get closer to that number.

Variation

One of the ways to continuously improve is to remove variation. Variation is unwanted, because it causes inconsistency in processes and this will lead to inconsistency in the quality of the product. Furthermore, inconsistency in the quality of the product will lead to lower customer satisfaction (Council For Six Sigma Certification, 2018). The causes for variation can be categorized in several classes (Oguz et al., 2012):

- Late delivery of material and equipment
- Design errors
- Change orders (work is added or deleted from the original order)
- Equipment breakdowns
- Tool malfunctions
- Improper crew utilization
- Labor strikes

- Environmental breakdowns (weather problems)
- Poorly designed production system
- Accidents
- Work that is too hard, because of the physical aspect

The production process can operate in a more balanced flow when the variation is reduced. Variation can be reduced by following the DMAIC approach with the following steps (Aziz and Ketabforoush, 2021 and Farhad et al, 2009):

- Step 1: Define

  Define the requirements and expectations of the customer, define the project boundaries and define the process by mapping the business flow.

- Step 2: Measure

  In this step the process is measured and especially the manufacturing parameters to see what goes wrong. This is done by measuring and observing the process, waiting and transport times of the workstations.

- Step 3: Analyze

  In this step the data from the previous step is analyzed. The causes are analyzed by looking at the variation. The causes with the highest variation should be taken care of.

- Step 4: Improve

  In this step the problems that cause the most variation are improved. This is done by finding solutions for the causes and implementing these.

- Step 5: Control

  In this step the solutions for the causes are controlled.

The benefits of Six Sigma are the following (Aziz and Ketabforoush, 2021):

1. Tthe return of investment can be increased significantly.
2. Structural and stepwise method to control and solve the variations.
3. The defect roots can be found easier with the DMAIC cycle.

However, Six Sigma could also lead to undesired results (Aziz and Ketabforoush, 2021). This is due to the incorrect use of statistics. Besides this, a lot of companies hesitate to implement Six Sigma, because in a lot of cases the process could not improve with Six Sigma (Aziz and Ketabforoush, 2021). This is because the method did not comply with the sources of the defects. Furthermore, with the industries and technology rapidly developing the need for more than one quality improvement method may be desirable (Aziz and Ketabforoush, 2021).

3.4 Theory Of Constraints (TOC)

The concept of TOC is that every system has at least one constraint (Naik and Pandit, n.a.). If this would not be the case, then all companies would make unlimited profit. Because of this, a constraint is anything that limits a system to achieve higher performance. Naik and Pandit (n.a.) conclude that TOC has two big components. The first one is philosophy, which is the backbone of the principle of TOC. The Five Focusing Steps (5FS) and the Drum-Buffer-Rope (DBR) scheduling methodology are the theories and methods that cover the philosophy. The second component is a generic approach to analyse and solve problems with the Thinking Process (TP). TOC has developed from Optimized Production Technology (OPT), which is based on the following 9 scheduling rules:

1. **Balance flow, not capacity.** This means that the work should be done in the lead time of the bottleneck or a little bit faster (to fill the buffer and always have work ready for the bottleneck). This leads to less work-in-progress and less waiting time of employees not doing anything.
2. **The utilization level of a non-constraint (non-bottleneck) is determined by some other constraint in the system and not by its own.** The bottleneck decides the pace of the process (when all other stations can do things faster).
3. **Activation and utilization of a resource are not synonymous.** ExpertsMind (n.a.) conclude that for example when the inventory for workstation 5 is 100 parts and it can process 100 parts per hour, but workstation 17 can only process 60 parts per hour. Then the utilization can be 100% for both, however because workstation 17 can only process 60 parts per hour (100% activation, because it gets 60 from other workstations), workstation 5 will also process 60 parts per hour (pace of the bottleneck) and then the activation of workstation 5 is only 60%.
4. **Any time lost at the bottleneck is lost time for the whole system.**
5. **Any time saved at the bottleneck is just a mirage.**
6. **Bottlenecks decide both throughput and inventories.**
7. **The transfer batch may not, and many times should not, be equal to the process batch.** ExpertsMind (n.a.) conclude that the transfer batch is the batch of products or parts that are finished and go to the next process and the process batch is the batch of products that will be processed. The statement means that a process batch of 50 parts should not be first completely finished before going to the next phase, but it should already transfer some of the finished parts. This will lead to a shorter lead time. We see this in Figure 3.1 below.

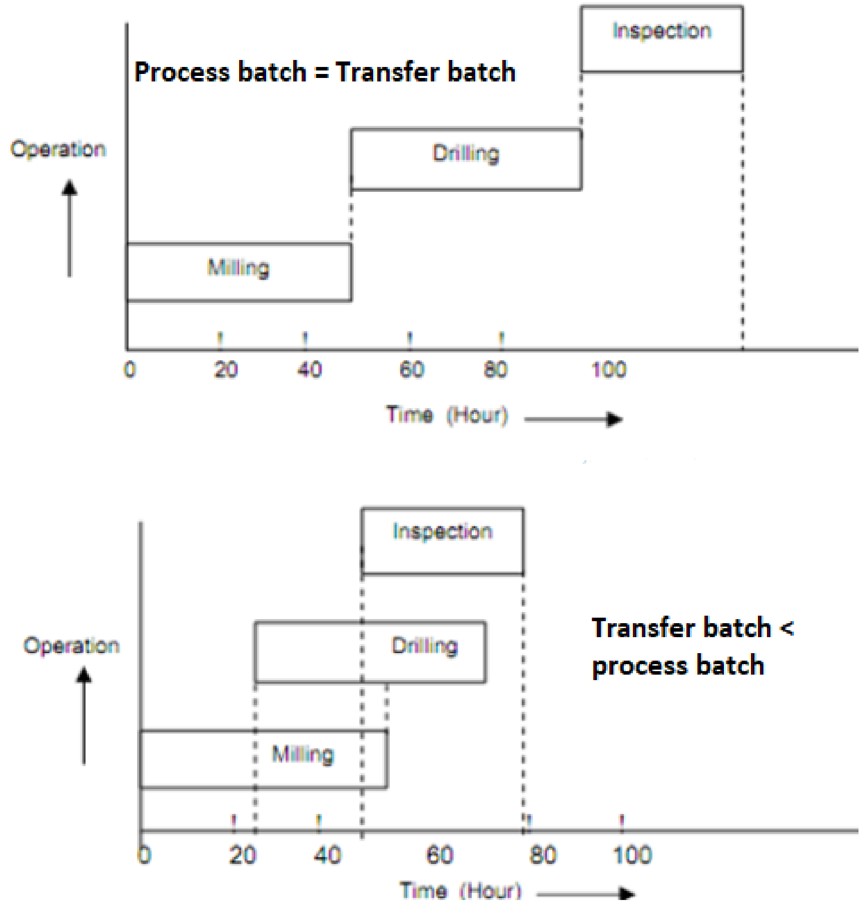

Figure 3.1: Transfer batch versus process batch.

Note. The image was created to give an insight on batch types. From "Transfer Batch and Process Batch Assignment Help", by ExpertsMind.com, 2021.

8. **The process batch should be variable, not fixed.** At some points in time the process batch can and should be larger or smaller depending on the pace of the bottleneck. When the buffers in front of the bottleneck become empty then the process batch should maybe be bigger towards the bottleneck. The other way around also applies.
9. **Schedules should be established by looking at all the constraints simultaneously. Lead times are the result of a schedule and cannot be predetermined.**

The benefits of TOC are the following (Naik and Pandit, n.a.):

1. It improves the annual sales.
2. It reduces late orders.
3. It reduces finished product inventory.

3.4.1 Five Focusing Steps (5FS)

The principle of TOC consists of five focusing steps 5FS (Naik and Pandit, n.a.). The following steps are needed to identity and get rid of the bottleneck:

- **Step 1:** Identify the constraint of the system also called the bottleneck of the system.
- **Step 2:** Decide how to exploit the bottlenecks. This can be done by removing limitations that reduce the flow and non-productive time.
- **Step 3:** Make all other non-constraints (non-bottlenecks) operate to the likes of the constraint (bottleneck).
- **Step 4:** Increase the output of the bottleneck.
- **Step 5:** Find the new bottleneck and begin again at step 1.

3.4.2 Drum Buffer Rope (DBR) scheduling methodology

Drum Buffer Rope (DBR) is a theory that was developed by Eliyahu M. Goldratt, and it is used to control the release of jobs with the information from the performance of the bottleneck (Qu et al., 2017). The two main issues that can be addressed with DBR is the ability of the system to execute the wanted product flow and the impact of deviations on the product flow (Naik and Pandit, n.a.).

The drum of the system is the constraint of the system (Qu et al., 2017). This is the (work)station that decides the pace of the process. This means that the (work)station that has the lowest output is the drum of the process and this (work)station decides the production output of the whole production process. There are three types of bottlenecks (Qu et al., 2017):

- **Type 1:** This is a moderate bottleneck, where process times at all non-bottlenecks are reduced by 5%.
- **Type 2:** This is a severe bottleneck, where process times at all non-bottlenecks are reduced by 20%.
- **Type 3:** This is a very severe bottleneck, where process times at all non-bottlenecks are reduced by 35%.

Furthermore, if there are more bottlenecks in the system then they should be directly next to each other or separated by 4 non-bottlenecks (Qu et al., 2017).

The buffer is the amount of work measured in terms of time in front of the constraint (Qu et al., 2017). These buffers are also called Time-Buffers (T-Bs) (Naik and Pandit, n.a.). The idea of a buffer is to have work or inventory ready for the constraint in order for the constraint to never be out of work. Another characteristic of the buffer is to absorb variability.

T-Bs can be divided into 3 types (Naik and Pandit, n.a.):

- **Constraint buffers:** These are the buffers that contain parts that are waiting in front of a constraint.
- **Assembly buffers:** These are the buffers that contain parts which are not processed by a constraint but need to be made with constraint parts.
- **Shipping buffers:** These buffers contain the finished products that are ready to be shipped.

Qu et al. (2017) conclude that the rope is the communication for providing feedback on how the release of work is controlled. The rope is a sort of mechanism that warns the stations in front of the buffer to release more work when needed (when the buffer is becoming empty) or to slow down work when needed (when the buffer is becoming full). There are two ropes (Qu et al., 2017):

- Rope 1: This rope exploits the constraint by determining the schedule at the bottleneck.
- Rope 2: This rope makes sure that the system operates to the performance of the constraint.

3.5 Conclusion

We explained the theories and methods that can be used to improve the production process in this chapter, by answering the following research question:

"What theories and methods, based on scientific literature and case studies, can be used to improve the process at the workstations 2, 3, 5, 7, 17 and 18?"

We will use Lean to minimize unnecessary waste or minimize non-value adding activities at the workstations. The following lean tools and methodologies are used:

- One of the lean tools that we will use is Value Stream Mapping (VSM). With VSM a map can be made to make a visual representation of the production process and to show where things have to be improved.
- Another thing that we will use is the 5S Methodology. With this methodology the processes at the workstations can be organized and standardized to make the work easier for the employees.
- We will use Cellular Manufacturing to combine similar work at different workstations to for example reduce setup and flow times.
- Besides this, we will also use SMED lean manufacturing. This methodology can be used to reduce the changeover and setup times at the workstations.

We will use Six Sigma to minimize the variation at the workstations. This will create a more balanced flow of work and will lead to reductions in waiting times at the workstations.

We will use the Theory of Constraints (TOC) to get rid of a bottleneck in the production process. The Five Focusing Steps (5FS) and the Drum-Buffer-Rope (DBR) methodology are used to achieve this. The 5FS is a stepwise approach to get rid of a bottleneck. The DBR methodology is a methodology that we will use to control the release of jobs with the information from the performance of the bottleneck (Qu et al., 2017). With DBR, buffers are used to have work or inventory ready for the constraint in order for the constraint to never be out of work. The buffer also absorbs variability.

4 Problem analysis

The aim of this chapter is to give an approach on how the problems at the workstations are analysed. This chapter answers the following research question:

"What problems are occurring at and around workstations 2, 3, 5, 7, 17 and 18?"

Section 4.1 gives an analysis of the production process to see how the workstations perform. Furthermore, Section 4.2 gives a more detailed overview of the activities or events that cause these problems at the workstations. In the end Section 4.3 gives the conclusion.

4.1 Performance analysis

Section 4.1.1 gives an analysis of the bottleneck by looking at the output per workstation. Furthermore, Section 4.1.2 gives an analysis of the whole process with the help of a Value Stream Map.

We do the bottleneck analysis to identify the worst performing workstation and we do the workstation analysis to see how all workstations are performing in more detail to see what the problems are. Besides this we define the order of importance to fix the workstations by looking at the performances of the different workstations.

4.1.1 Bottleneck analysis

We use the 5FS method to improve the bottleneck (worst performing workstation). This method uses a stepwise approach to get rid of a bottleneck. The first step of 5FS is to identify the bottleneck. The lowest production output decides which workstation is the bottleneck. We see the production output of the individual workstations in Table 4.1. We use all the outputs per workstation individually in the months March and April. With this we are able to calculate the performance per station and thus we can see which workstation is the worst performing station (the bottleneck). We conclude that workstation 17 is the bottleneck, because it has the lowest production output. Appendix B.1 shows how the output is calculated in more detail.

Table 4.1: Production output of the workstations.

Workstation	2	3	5	7	17	18
"soft" moulds per hour	8.99	9.86	9.90	11.23	7.47	8.41

4.1.2 Workstation performances

We use step 2 and 3 from the DMAIC approach from Six Sigma to analyze the workstation's performances by looking at the amount of time exceedings (lead time of a mould at a workstation is larger than 7.5 minutes) and by looking at the performance indicators in the VSM (see Figure 4.3). With this information we are able to identify the order of importance to fix the workstations and the problems per workstation.

In Figure 4.1 we see the number of time exceedings per workstation (this is calculated with the analysis in Appendix B.1). A time exceeding is a time period of a mould standing at a workstation that takes longer than 7.5 minutes including transport time, that is caused at the workstation itself (this can be 00:07:31, but also 00:09:45). This means that for example time exceedings at workstation 3 that are caused by workstation 4 are not included in the number of time exceedings at workstation 3. With this we can see how the workstations perform individually. Furthermore, we do not take into account the size of the time exceeding for this analysis. We will take the size into account at the problem analysis to see what causes the most exceeded time.

March and April	total number time exceedings	total number of time periods
workstation 2	467	4078
workstation 3	472	4081
workstation 5	498	4086
workstation 7	507	4089
workstation 17	1324	4036
workstation 18	1088	4076

Figure 4.1: Number of time exceedings per workstation.

We see that besides the output of workstation 17 (from Table 4.1) also the number of time exceedings is the highest for this workstation. This means that workstation 17 is the worst performing workstation. At workstations 2, 3, 5, 7 and 18 also a lot of time exceedings occur, which also lead to a lower production output of the whole process. We do not only need to fix the bottleneck, but we also need to take care of the causes for the time exceedings at the non-bottlenecks in order to achieve a higher production output.

A part of the first step of the DMAIC approach from Six Sigma is to map the process. Making a Value Stream Map (VSM) helps visualizing the whole performance of the production process. We do not only include workstations 2, 3, 5, 7, 17 and 18, but also the other (work)stations to get a full overview. The second step of the DMAIC approach from Six Sigma is to measure the performance parameters. We make a current-state VSM to see how the current production process performs. We see this VSM in Figure 4.3 and Figure 4.2 shows the legend. The measurements and explanation of the data in the VSM are explained in Appendix B.2.

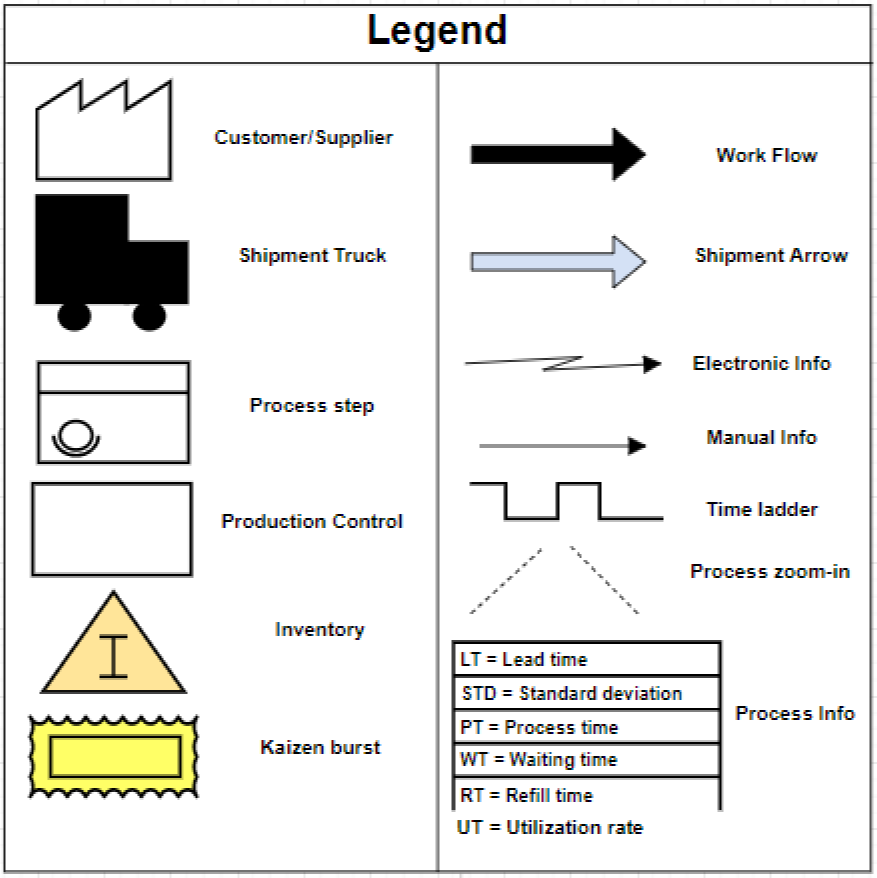

Figure 4.2: Legend VSM.

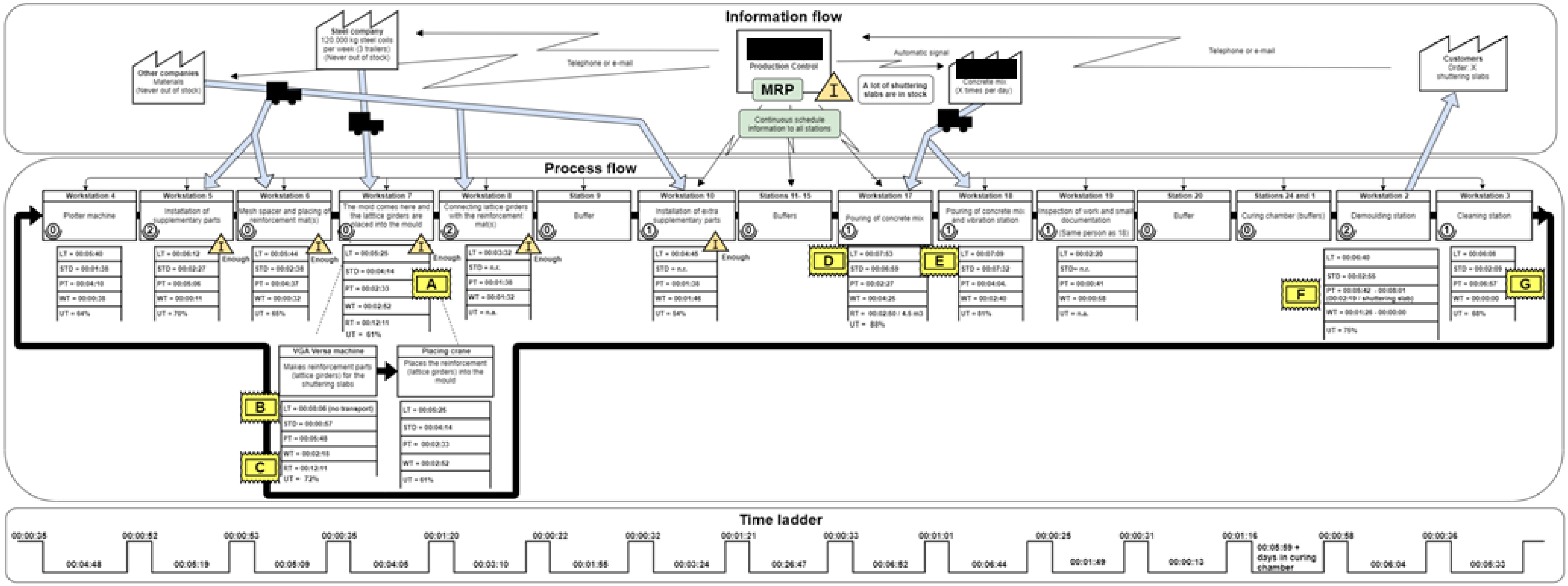

Figure 4.3: Current-state VSM.

Workstation 18 has the most time exceedings after workstation 17 (see Figure 4.1), which leads to a high variability in lead times (see Kaizen burst E). Workstation 7 is next because it also has a high variability in lead times and it has the next highest amount of time exceedings (see Figure 4.3 and Kaizen burst A). Workstations 2 and 3 both have high process times (see Kaizen burst F and G), but workstation 2 has the lowest output (see Table 4.1). Furthermore, workstation 5 also has a lot of time exceedings (see Figure 4.1), but it still performs well according to the VSM (see Figure 4.3). The order to fix the workstations is 17, 18, 7, 2, 3 and 5.

4.2 Problems at the workstations

Getting the causes for the problems at the workstations is the next step of the DMAIC approach from Six Sigma. Analysing the time exceedings of the workstations will provide more information about the causes for the problems. Section 4.2.1 gives the analysis for the problems at workstation 17 and 18. Furthermore Section 4.2.2 for workstation 7, Section 4.2.3 for workstation 2, Section 4.2.4 for workstation 3 and Section 4.2.5 for workstation 5.

4.2.1 Workstations 17 and 18

These workstations currently work simultaneously and that is why the analysis includes both. The second step of 5FS is to decide how to exploit the bottleneck. This can be done by removing limitations that reduce the flow and non-productive time. We must first identify the limitations (causes for the high lead times and the high variability in lead times). With the first, second and third step of the DMAIC approach from Six Sigma we identify and analyze the root cause for the variation in lead times and the high lead times. This is done by analysing the time exceedings at the workstations from the month March and April (Appendix C.3 explains the full analysis in more detail). The analysis works as follows:

1. Put all the time periods of the moulds from the software program of the workstations 17 and 18 in Excel (only 30 production days in the month March and April could be analysed, because the data from the other production days was missing). The software program collects all the time periods that a mould is standing at a certain (work)station.
2. Mark all the time exceedings (time periods over 7.5 minutes) to see when the process is underperforming.
3. Collect information about why a time exceeding can occur. At these workstations this can be a break, a shift change, a late delivery of concrete or unknown. This information is from the Microsoft Teams channel of Company X (here all failures and refill times are documented) and from the company (times the truck delivers concrete).
4. Assign the causes to the time exceedings.
5. Calculate the time that is lost (time the mould is standing at the workstation for longer than 7.5 minutes) due to a certain cause to see what the biggest problems are.

From the analysis the following things causes workstations 17 and 18 to underperform:

- **Late delivery of concrete mix:** We see in Table 4.2 that the late delivery of concrete mix is the main cause for time exceedings at workstations 17 and 18. The concrete mix is delivered by one truck from "Company Z", which is located close-by. One truck is completely dedicated to deliver concrete mix to Company X. However, the problem is that the truck is almost always too late. The late delivery is the main reason why there is a high variation at workstations 17 and 18 and why there are so many time exceedings.

- **Breaks:** We see in Table 4.2 that not many breaks cause a time exceeding and that little time is lost.
- **Shift changes:** We see in Table 4.2 that not many shift changes cause a time exceeding and that little time is lost.
- **Unknown:** We see in Table 4.2 that a lot of time is lost due to unknown reasons. These reasons cannot be traced back.

Table 4.2: Causes and time information for workstations 17 and 18.

cause	number of time exceedings	average exceeded time per cause	total time lost in days	moulds lost
late delivery of concrete mix	623	00:10:23	4.49	861.8
breaks	22	00:05:00	0.08	14.7
shift changes	8	00:02:31	0.01	2.7
unknown	374	00:04:26	1.15	221.1
Total production time	-	-	**11.09**	-
			total moulds lost:	**1100.3**

There is another reason besides the time exceedings why workstations 17 and 18 are not performing optimally. From the 9 scheduling rules from the TOC methodology, any time lost at the bottleneck is lost time for the whole process. This means that if the bottleneck is not working all the time then that time is lost in the whole process. The utilization rates of workstations 17 and 18 are not 100% and because of that the bottleneck is not used optimally. We see the current utilization rates in Table 4.3. A utilization rate of 100% is most likely not possible, but it is desired to have an as high as possible utilization rate for the bottleneck. The full utilization calculation is in Appendix B.2.7.

Table 4.3: Current utilization rate workstation 17 and 18.

	Utilization rate workstation 17	Utilization rate workstation 18
With breaks included	88%	85%
With breaks excluded	93%	91%

4.2.2 Workstation 7

The first problem is that the variation of lead times is very high, which sometimes leads to time exceedings. We use the same approach for getting the root causes as at workstations 17 and 18 (Appendix C.2 explains the full analysis in more detail). From the analysis the following things causes workstation 7 to get time exceedings:

- **Steel coil refill:** A steel coil has to be refilled when the reel is empty. We see in Table 4.4 column "time exceeded on average" that at steel coil refills where a time exceeding occurs, a lot of time is lost.
- **Not pressing the button at workstation 8 to transport the mould from workstation 7:** A button must be pressed in order for the mould to be transported from workstation 7 to workstation 8. This is not done quickly enough and because of that a lot of time is lost (see Table 4.4).

- **Machine failures:** A machine failure is something that happens at or in the machine that causes the machine to stop. This can be for example that the wire is not going straight into the machine or that a bold breaks in the machine. This does not happen too often, but it is a cause for some of the time exceedings at this workstation. However, when it happens a lot of time is lost per occurrence (see Table 4.4).
- **Welding blocks changeovers:** There is little data registered about when this refill happens. However, a changeover of welding blocks happens more often than documented (failures and changeovers are documented in the Teams channel of Company X). Most likely these time exceedings are also included in the unknown causes.
- **Unknown:** It is not possible to get the causes for these time exceedings.

Table 4.4: Causes and time information for workstation 7.

cause	number of time exceedings	average exceeded time per cause	total time lost	moulds lost
steel coil refill	129	00:04:14	09:06:11	72.8
not pressing button	101	00:10:46	18:07:22	145.0
machine failures	16	00:11:36	03:05:37	24.7
welding changeover	4	00:11:04	00:44:14	5.9
unknown	254	00:04:11	17:42:08	141.6
Total production time	-	-	25.33 days	-
			total moulds lost:	390.1

Another reason why workstation 7 is not performing optimally is that the VGA Versa welding machine has a high lead time (time it takes between the beginning of making the lattice girder and finishing it). We can see this in the VSM (Figure 4.3) at Kaizen burst B. This is due to the process and waiting time at the machine. The process time is 00:05:48 and the waiting time is 00:02:18 and together this exceeds the 7.5 minutes. This is not measured by the GPA software (software that measures when a mould is at a certain workstation), but it is measured by observing the machine making lattice girders.

4.2.3 Workstation 2

The problem at workstation 2 is that the work is not always done in or under 7.5 minutes (including transport time), which leads to a time exceeding. We use the same approach for getting the root causes as at workstations 17 and 18 (Appendix C.1 explains the full analysis in more detail). From the analysis the following things causes workstation 7 to get time exceedings:

- **Breaks:** Breaks happen at 9:00, 12:00, 18:00 and 21:00 and they are 15 minutes long. We see in Table 4.5 column "time exceeded on average" that, at breaks where a time exceeding occurs, a lot of time is lost. Furthermore, the total amount of moulds that could have been produced in that time is also very high.
- **Shift changes:** A shift change happens at 14:30, however the time lost in total is not that much and it also does not happen that often (see Table 4.5).

- **The number of shuttering slabs in the mould:** When there are 3 or more shuttering slabs in a mould, it is very likely that there will be a time exceeding, because the time it takes to lift out 3 slabs will exceed the 7.5 minutes. All in all the work can often not be done in time with two people when there are more than 3 shuttering slabs in the mould. We see in Table 4.5 that a lot of time is lost and that it happens often.
- **The shuttering slab is damaged:** Repairs have to be done when a shuttering slab is damaged. We see in Table 4.5 that a lot of time is lost and that it happens often.
- **Unknown:** A lot of time is lost due to these unknown causes (see Table 4.5). However, these causes cannot be traced back. An assumption (observed at workstation 2) for one of the unknown causes is that a lot of the time the mould at workstation 2 can go to workstation 3, but the employee from workstation 3 is doing things at workstation 2 and that is why the mould cannot move on.

Table 4.5: Causes and time information for workstation 2.

cause	number of time exceedings	time exceeded on average	total time lost	moulds lost
Breaks	49	00:13:01	10:37:36	85.0
Shift changes	5	00:04:11	00:20:57	2.8
3 shuttering slabs	104	00:02:21	04:04:24	32.6
4 shuttering slabs	12	00:02:28	00:29:41	4.0
5 shuttering slabs	1	00:00:25	00:00:25	0.1
product damages	36	00:05:34	03:20:13	26.7
unknown	259	00:03:03	13:08:53	105.2
Total production time	-	-	**24.98 days**	-
			total moulds lost:	**256.3**

4.2.4 Workstation 3

The main problem at this workstation is that the work is not done in or under 7.5 minutes (including transport time) at some moulds. We use a different approach for finding the causes for the time exceedings. Due to time constraints the time exceedings are not analysed, but the process is observed to see how long certain activities take and thus to see what causes the moulds to be longer than 7.5 minutes at the workstation. The following things cause workstations 3 to get time exceedings:

- **Wrong priority decisions:** The employee at this workstation sometimes does a job that has less priority than another job. A job that has less priority is a job that does not have to be done in order for the mould to move on from workstation 3 to workstation 4. The jobs with less priority are: The transport of the metal shutterings to workstation 5 and sawing the cardboard corners in half and putting them in the containers.
- **Not pressing the button for transport:** A button needs to be pressed at workstation 3 in order to transport the mould to workstation 4. This is done too late sometimes.
- **Very dirty mould:** Sometimes the mould is very dirty and then it takes a lot of time to clean it. Furthermore, sometimes the cleaning machine needs to go over the mould a second time and this takes too long.

- **Mould from workstation 2 could have gone to workstation 3:** The employee at workstation 3 is laying the metal shutterings at the front of the mould at workstation 2, while the mould could have already gone to workstation 3.

4.2.5 Workstation 5

This section discusses the problem at workstation 5. There is not a very clear cause at workstation 5 for why the work is sometimes not done in or under 7.5 minutes. It is difficult if not impossible to trace back the cause(s) for the time exceedings at workstation 5. However, we see in Table 4.6 that the time it takes to place the supplementary parts onto the bottom of the mould is very doable. We see the work that has to be done in Figure 4.5 and 4.6. The electricity boxes are done at workstation 10 and the other things at workstation 5.

Table 4.6: Process times with certain moulds.

Process times	Explanation
00:05:54	In Figure 32 it can be seen that a lot of supplementary parts have to be placed and this can still be done in the given time.
00:04:20	In Figure 33 a mould can be seen with less work.

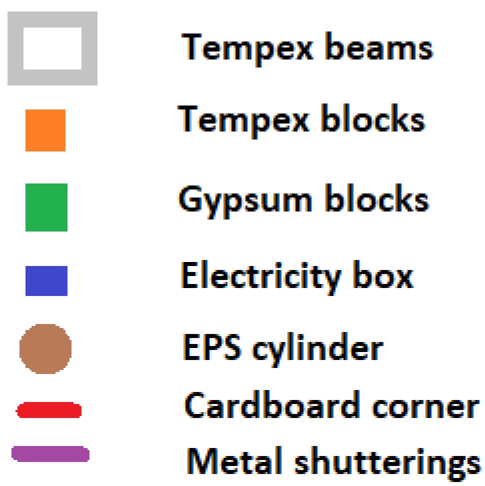

Figure 4.4: Legend mould examples.

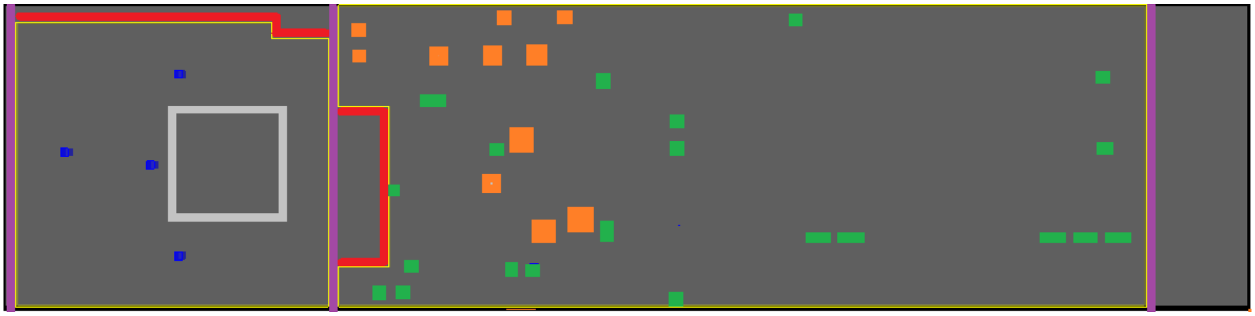

Figure 4.5: Example 1 of a mould where supplementary parts have to be placed.

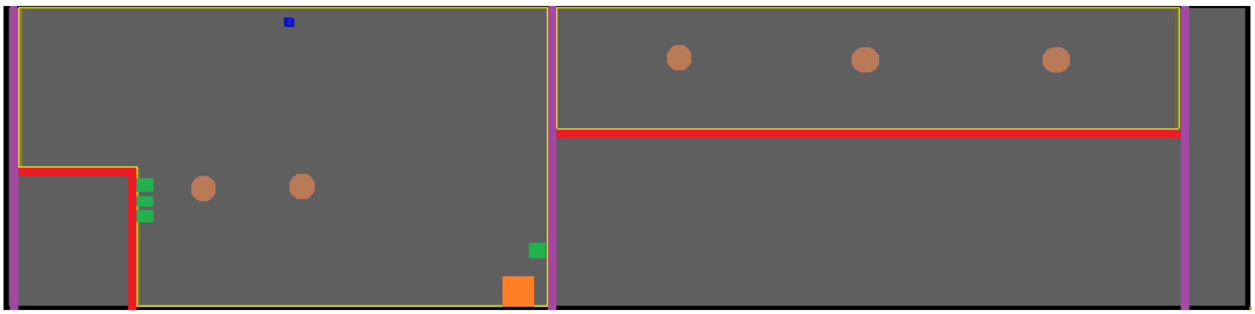

Figure 4.6: Example 2 of a mould where supplementary parts have to be placed.

The work can be done in the time they have (within 00:06:55). The main cause of a time exceeding can only be that the preparation of work is not done at the right time. Furthermore, sometimes the button is not pressed quick enough to transport the mould from workstation 5 to workstation 6.

4.3 Conclusion

In this chapter the performance of the workstations and the problems at these workstations are analysed, by answering the following research question:

"What problems are occurring at and around workstations 2, 3, 5, 7, 17 and 18?"

We measured and visualized the current performance of the workstations with the help of a Value Stream Map. First, we identified the bottleneck and we measured the other performance indicators to see what goes wrong at the workstations. At workstation 17 the lead time is too high, which leads to a lower production output than 8 "soft" production moulds per hour. Also, the variation in lead times is very high and this leads to an unbalanced production flow. This is also the case at workstation 18 and 7. Next to the high variation in lead times at workstation 7, the VGA Versa machine has a high lead time and there are high refill times of steel coils. Furthermore, at workstation 2 and 3 the process times are very high, which leads to time exceedings.

The causes for these problems at the workstations are the following:

- At workstation 17 and 18 the delivery of concrete mix is late a lot of the time. Besides this, some time is lost due to some of the breaks and some of the shift changes. However, the time lost is very low. Furthermore, workstation 17 is not fully utilized.

- At workstation 7 the biggest problem is that the button at workstation 8 is not pressed quickly enough and due to this the mould waits at workstation 7. Besides this, the steel coil refills take too much time, and this leads to a high lead time. Furthermore, machine failures also cause the workstation to get time exceedings and thus a higher lead time. Next to these problems the VGA Versa welding machine is not always producing when it could have. This is due to the inventory being full. This is a problem, because when there is a steel coil refill more inventory is needed, and this could have been there if the inventory was bigger and if the machine could produce. Another problem is that the automatic crane cannot operate when the machine is stopped.
- At workstation 2 the main problem is that at breaks the lead times are too high. This is due to the employees taking too long breaks or because only one employee is working at that time because the other one is taking a break. Besides this, when the number of shuttering slabs is 3 or more then the work can become too much and then time exceedings can occur. Furthermore, product damages also lead to a lot of time exceedings.
- At workstation 3 the work is not done in or under 7.5 minutes at some moulds. This is due to a wrong working method and wrong priority decisions.
- At workstation 5 the preparation of work is not done at the right moment. When there is time left from a mould then the employees just wait for the next mould and then prepare this mould. Besides this the time it takes for transport takes too long because the employees do not always press the button quickly enough.

5 Solution approach

The aim of this chapter is to give an approach on how to get solutions for the problems at the workstations. This chapter answers the following research question:

"What are the solution options to tackle the problem(s) at workstations 2, 3, 5, 7, 17 and 18?

Section 5.1 explains the solution approach for the different workstations. Lastly, Section 5.2 gives the conclusion.

5.1 Solution options

This section explains the approach to get solution options. We use Step 2 and 3 from 5FS and step 4 of the DMAIC approach from Six Sigma. Step 2 and 3 from 5FS are: exploit the bottleneck (workstations 17 and 18) and to make all other non-bottlenecks (workstations 7, 2, 3 and 5) operate to the likes of the bottleneck. Step 4 from DMAIC is: the problems that cause the variation must be improved by finding solutions. Besides this we use some Lean methods to improve the workstations.

Section 5.1.1 explains the approach for workstations 17 and 18, Section 5.1.2 for workstation 7, Section 5.1.3 for workstation 2, Section 5.1.4 for workstation 3 and Section 5.1.5 for workstation 5.

5.1.1 Workstations 17 and 18

The variation in lead times and the high lead times are caused by the late delivery of concrete mix, breaks, shift changes and unknown causes. However, breaks and shift changes only account for 2% of the times lost and unknown causes cannot be investigated and thus these will not be taken into account. With a brainstorm session with the supervisor of the company and talking with employees the ideas for solutions are made. The following things can be done to reduce the lost time when concrete mix is delivered late:

1. Making a communication device that can show how long it takes for the truck to be back at the concrete mix plant. The concrete mix plant could then start earlier with making the concrete mix. From the DBR methodology (Section 3.4.2) this forms a sort of rope of the system for the bottleneck to communicate with the concrete mix plant.
2. Having a bigger truck with more concrete mix. This creates less movement of resources, thus less waste, and fewer chances of late delivery of resources. However, the problem that will occur is that the machine can still only take 4.5 m3 of concrete mix and then the problem of not having concrete will only be decreased by a ratio of 1.5 on average for example when the new truck can have 12 m3 of concrete mix. This is because the truck has 12 m3 and not 9 m3 of concrete mix (current truck capacity) and can thus stay 1.5 times longer at Company X. This leads to 1.5 times less trips to the concrete plant and thus 1.5 times less times it can be delivered too late.
3. Adding another truck to this system then it would perform even better, because the truck can leave right away or even already be at Company X when the other truck leaves.
4. Having a bigger machine which is able to have 9 m3 instead of 4.5 m3 concrete mix. This creates a larger time buffer for the truck to get concrete mix.
5. Making a buffer container where concrete mix can be stored. When the truck arrives, it would be able to pour all the concrete in the container and then immediately drive back to get new concrete mix.

The machine can then fill up from the container. This creates a larger time buffer for the truck to get concrete mix.

6. A complete new concrete mixer at the concrete mix plant completely dedicated to Company X. With this there will never be a case where the truck has to wait for another truck.

We can see the results of the solutions in Table 5.1. Appendix D.1 gives a more detailed explanation. With solutions 1, 2 and 3 it is crucial that the truck from Company X can always be directly filled at the concrete mix plant. Otherwise the travel + filling time would increase and would may become bigger than the time to bridge. If the travel + filling time is bigger than the time to bridge than time exceedings occur and thus time is lost. The following calculations show how to get to the results:

- Moulds per full machine = concrete mix in machine / concrete mix in a mould on average (1,9 m3)
- Moulds per full truck = concrete mix in truck / concrete mix in a mould on average (1,9 m3)
- Travel + filling time truck:
    - Current situation = 00:19:02 when the truck can be filled directly at the concrete mix plant (measured by travelling with the truck) and 00:31:48 when there is a different truck first.
    - Solution 1, 3, 4 and 5 = outward journey + filling truck ((weighing second batch + blending first batch) + (weighing third batch + blending second batch) + blending third batch + filling the truck 3x) + return journey = 00:02:57 + 00:03:00*3 + 00:00:15*3 + 00:03:19 = 00:16:01
    - Solution 2 = solution 1 + extra batch + filling = 00:16:01 + 00:03:00 + 00:00:15 = 00:19:16
    - Solution 6 = 00:00:30 when the truck is already at Company X (needs some time to attach to the machine) or 00:03:19 (return journey)
- Time to bridge = 00:07:30 (desired lead time per mould) * moulds per full machine (either 2.36 or 4.73)

Table 5.1: New travel + filling times with the several solutions.

	concrete mix in machine (m3)	moulds per full machine	concrete mix in truck (m3)	moulds per full truck	Travel + filling time truck	Time to bridge
current situation	4.5	2.36	9	4.73	00:19:02 - 00:31:48	00:17:42
solution 1	4.5	2.36	9	4.73	00:16:01	00:17:42
solution 2	4.5	2.36	12	6.31	00:19:16	00:17:42
Solution 3	4.5	2.36	9	4.73	00:00:30 - 00:03:19	00:17:42
solution 4	9	4.73	9	4.73	00:16:01	00:35:29
solution 5	4.5	2.36	9	4.73	00:16:01	00:35:29
solution 6	4.5	2.36	9	4.73	00:16:01	00:17:42

The utilization rate at workstations 17 and 18 (Section 4.2.1) are 85-88% (breaks included) and this is high, but it can be increased by making sure that the buffers before workstation 17 are full enough to always have a mould ready for workstation 17 when needed. This can be done with the following two approaches:

- From the TOC methodology the pace of the other workstations must be balanced to the pace of workstation 17. From the DBR methodology the rope of the system, which should be located from 17 to the other workstations, must give signals to the workstations how fast they should operate. When the buffers get empty, the workstations should process the mould faster and when the buffer is full, the workstations should process the moulds a bit slower. The pace of the process must be balanced to the pace of the bottleneck. The solutions for making the other workstations more balanced is described in Sections 5.1.2, 5.1.3, 5.1.4 and 5.1.5.

- Workstation 17 needs to work at a balanced pace. When workstation 17 has concrete mix, it should not process the moulds to fast. This is because when workstation 17 does the work in 3 minutes and the (work)stations before 17 cannot do the work this fast, then the buffer becomes empty and then workstation 17 cannot do anything. This leads to a lower utilization rate. It would not be bad to process the moulds at workstation 17 faster, because it will not lead to a lower output, but when the employees pour the concrete mix too fast then this can lead to quality issues. This will lead to a lower output in the future. Organisation measures are needed to keep the quality high. These measures can be implemented at all the workstations and are discussed in Section 5.1.3.

5.1.2 Workstation 7

The variation in lead times is caused by high refilling times of steel coils at the VGA Versa welding machine, by not pressing the button to transport the mould from workstation 7 to 8, by machine failures, by welding blocks changeovers and by unknown causes. For the welding blocks changeovers little data is known and thus we did not take it into account. We could not investigate the unknown causes. We inspired the solution options mostly from the theory at Chapter 3 and by talking with employees and the supervisor at the company. The following things can be done to deal with the causes:

1. Having more lattice girders at the automatic crane to create a bigger buffer (DBR) to deal with variation (Six Sigma). When there are enough lattice girders in the inventory to cover the steel coil refill time and the machine can make the lattice girders faster than that they are processed by the automatic crane then this can decrease the variation in lead times. This is because, when a steel coil refill is happening the automatic crane has enough lattice girders to place on the reinforcement mats and the machine can fill up the inventory again when the steel coil refill is finished. The amount of lattice girders that need to be in the inventory for this solution can be seen in Table 5.2 in the last column. The second column represents the amount of lattice girders that have to be placed in a mould (first the average of 9 and then the maximum of 16). The third column represents the extra time that needs to be covered with a buffer due to the refill time (this is the refill time – the lead time of the mould). The fourth column represents the time that is available for making extra lattice girders and placing these in the mould. The fifth column represents the number of lattice girders that need to be in inventory extra because the time to make and place is not enough to finish the mould in 7.5 minutes. The last column represents the total amount of inventory that needs to be in inventory to cover the lead time of two moulds. Appendix D.2.1 shows a more detailed calculation.

   Besides this, the automatic crane must operate separately from the VGA Versa welding machine. This means that when the machine is shut down, the crane must be able to place the lattice girders. Otherwise this solution will not work. Furthermore, the waiting time can be decreases when the automatic crane operates separately. This is because when the crane picks up lattice girders there will be space again for the machine to make lattice girders and thus the waiting time will be less and the lead time of the machine will decrease. With even more inventory space the waiting time will be decreased even more.

Table 5.2: Refill times with inventory levels needed.

Refill time	Number of lattice girders per mould on average (desired lead time of 00:07:30)	Extra time to cover due to refill time	Time to make up to 9 / 16 girders and place them	Needed extra inventory because not possible to make up to 9 /16	Total inventory / buffer places needed
00:12:11	9	00:12:11 - 00:07:30 = 00:04:41	00:07:30 - 00:04:41 = 00:02:49	6	9 + 6 = 15
00:09:11	9	00:09:11 - 00:07:30 = 00:01:41	00:07:30 - 00:01:41 = 00:05:49	2	9 + 2 = 11
00:04:12	9	00:04:12 - 00:07:30 = - 00:03:18	00:07:30 + 00:03:18 = 00:10:48	0	9 - 5 = 4
00:12:11	16	00:12:11 - 00:07:30 = 00:04:41	00:07:30 - 00:04:41 = 00:02:49	13	16 + 13 = 29
00:09:11	16	00:09:11 - 00:07:30 = 00:01:41	00:07:30 - 00:01:41 = 00:05:49	9	16 + 9 = 25
00:04:12	16	00:04:12 - 00:07:30 = - 00:03:18	00:07:30 + 00:03:18 = 00:10:48	2	16 + 2 = 18

2. Preparing for a steel coil refill before the steel coil is empty. This can be done by having an employee standing at the machine all the time (from solution 4 the employee from workstation 8 can be placed at workstation 7) to anticipate the refill and doing some activities before the refill with the SMED Manufacturing methodology. First identify the internal and external activities. The internal activities can only be done when the machine is shut down and the external activities can be done when the machine is running. Currently all activities are performed when the machine is shut down, because the steel coil becomes empty. However, some of the internal activities can be done when the steel coil is not empty yet. An internal activity that can be converted to an external activity is the placement of the crane near the steel coils. This will save a lot of time. The amount of time a refill will take with this solution can be seen in Table 5.3. at solution 2 Appendix D.2.2 shows more detailed calculations.
3. Having extra steel coil reels at the machine. With this only the time needed to weld the old steel wire to the new steel wire is needed, because now all the types of steel coils have a duplicate reel. The internal activity of placing the steel coil is now converted to an external activity. The amount of time a refill will take with this solution can be seen in Table 5.3 at solution 3. Appendix D.2.2 shows more detailed calculations.

Table 5.3: Time a refill takes.

Situation	Refill time
Currently	00:12:11
Solution 2	00:09:11
Solution 3	00:04:12

4. With the inspiration from the Cellular Manufacturing method work can be combined to make a more steady flow of production and in this case to also create an extra buffer after workstation 7. Moving the work from workstation 8 to a (work)station further in the line in order for the mould at workstation 7 to move automatically to workstation 8. This solution can be implemented, because when the work from workstation 8 and workstation 10 are combined, it will not exceed 7.5 minutes (see Figure 5.1). A big benefit from this solution is that the employee from workstation 8 can be used to stand permanently at the VGA Versa welding machine. In Table 5.4 we can see that all the time lost due to not pressing the button would be gone.

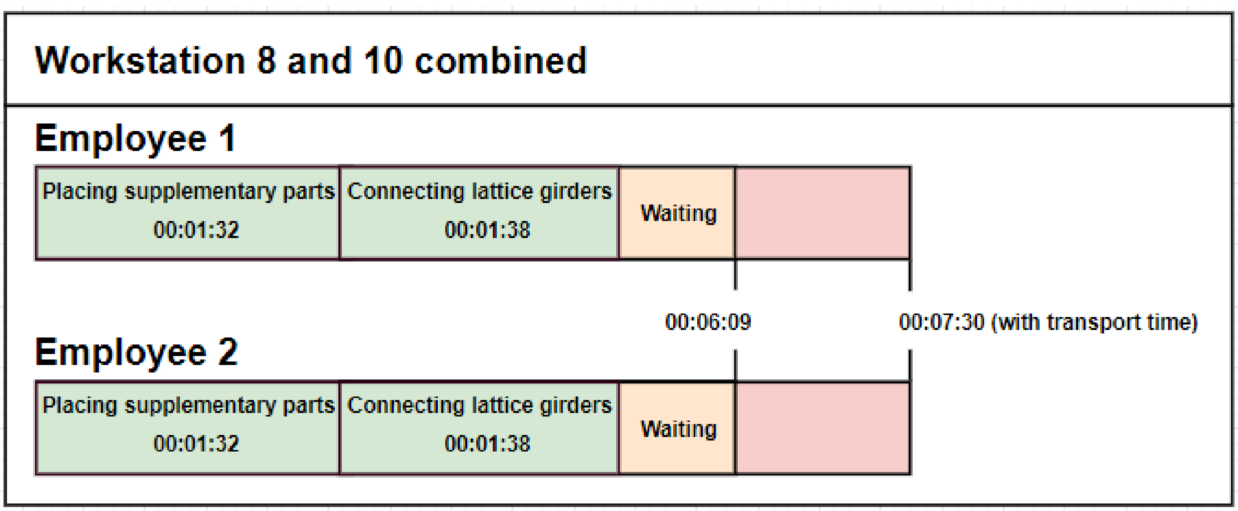

Figure 5.1: Work from workstation 8 and workstation 10 combined.

5. Making an alert system that alerts the employees that the button has to be pushed in order for the mould to go to the next (work)station. We see in Table 5.4 that the solution would get rid of 95-98% of the lost time.

Table 5.4: Time improvements per solution.

	time it takes currently without solution	time it would take with solution	possible time improvement (%)
solution 4	00:10:46 lost per mould	00:00:00	100
solution 5	00:10:46 lost per mould	00:00:10 - 00:00:30 depends on the speed of the employee	Most likely 95-98

5.1.3 Workstation 2

The problems at this workstation are that at some breaks, when more than two shuttering slabs are in the mould and when the shuttering slab is damaged. We could not investigate the unknown causes. At the time of a break one of the two employees is most of the time taking a break which leads to more work for one employee and this cannot be done in the desired process time. The solution for this problem is the following:

1. Get an employee from another workstation (workstation where less work has to be done at that moment) to work at workstation 2 during the break to prevent time exceedings.

The solutions for too many shuttering slabs in the mould are the following:

2. Do not have three or more shuttering slabs in a mould. We see in Figure 5.2 that with two shuttering slabs the work can be done in the desired time. This creates more balance in the lead times and thus reduces the variation.

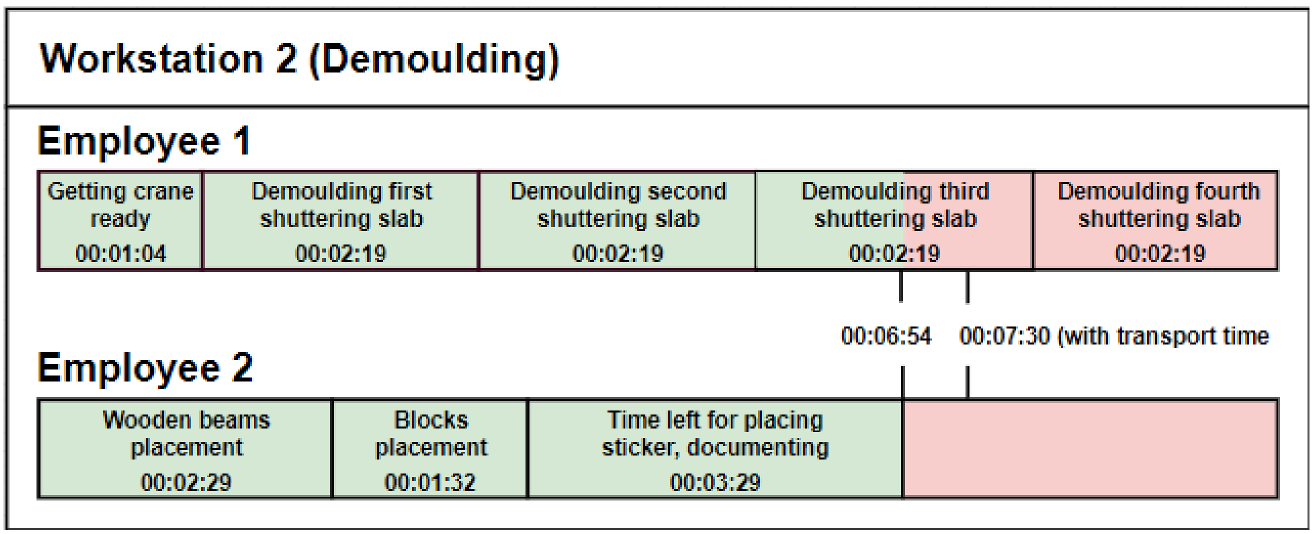

Figure 5.2: Timeline of the work at workstation 2.

The solution for the product damages cannot be implemented at this workstation but should be implemented at all the other workstations. From the Lean methodology, product damages must be reduced, because it causes rework or even reprocessing which takes unnecessary extra time. The damages come from a number of different activities:

- Due to wrong pouring of concrete mix into the mould.
- Due to not spraying in the mould well enough with an anti-sticking liquid in order for the concrete mix to not stick to the mould.
- Due to not cleaning the mould well enough.

The following solutions would prevent this from happening:

3. With a new machine the concrete can be poured in the mould with more accuracy.

4. Organisational measures:
    a. The employees need to take time for the pouring of concrete and not do this too fast at workstation 17 and 18.
    b. The employees should take time for spraying in the mould at workstation 5.
    c. Cleaning at workstation 3 needs to be done in the right way. The work description at Section 5.1.4 gives this as a solution.
    d. The lattice girders must be attached properly to the reinforcement mat at workstation 7.

5.1.4 Workstation 3

The process times at workstation 3 are sometimes too high. This is due to wrong priority decisions, not pressing the button for transport, a very dirty mould and the mould could have gone earlier from workstation 2 to 3. We can fix these problems with the inspiration from the 5S methodology by making a standardized work description that the employee can follow. We see the work description in Figure 5.3. The main principle for this work description are that the employees know exactly what to do when a certain start option presents itself. A more detailed principle is to do certain things at the same time. For example let the machine clean the mould and at the same time lift the metal shutterings onto the roller belt. Another one is to do things that can be done at any time of the day only when the work at the mould is done. All the activities that make sure that the mould can go as fast as possible from workstation 3 to workstation 4 must be done first in the right order.

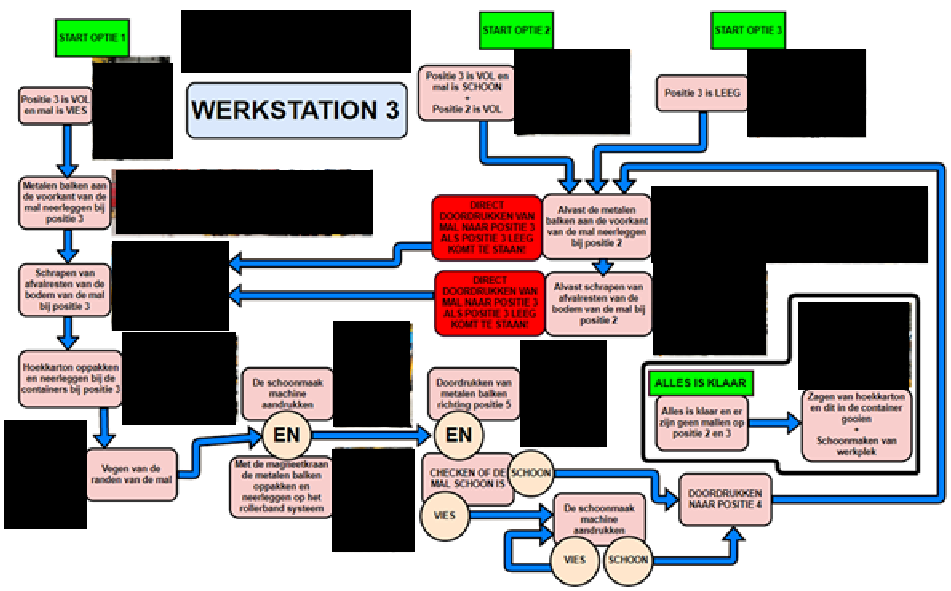

Figure 5.3: Standardized work description (censored).

With this description the time it currently takes for a mould to be processed can be decreased. We see the current time it takes in Figure 5.4 and the future time it takes when the standardized work description would be implemented in Figure 5.5. The sawing of cardboard corners can be done at any time of the day when time is left (see "other work" in Figure 5.5).

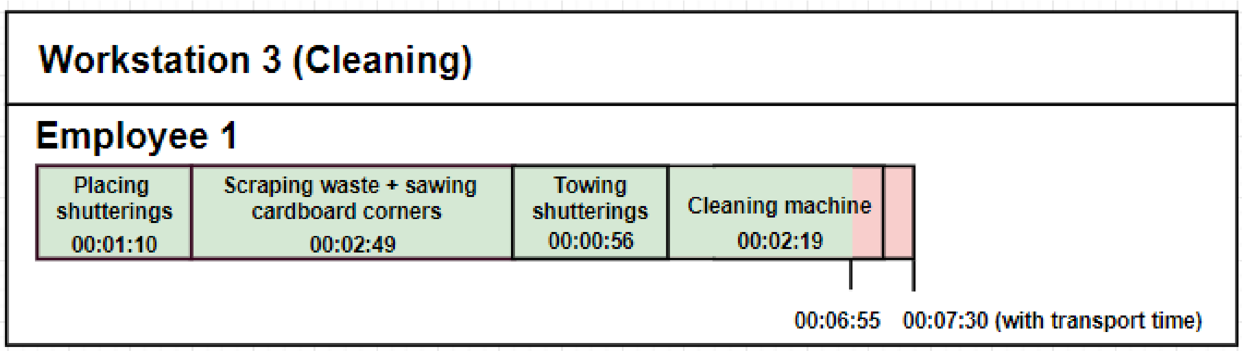

Figure 5.4: Current timeline of workstation 3.

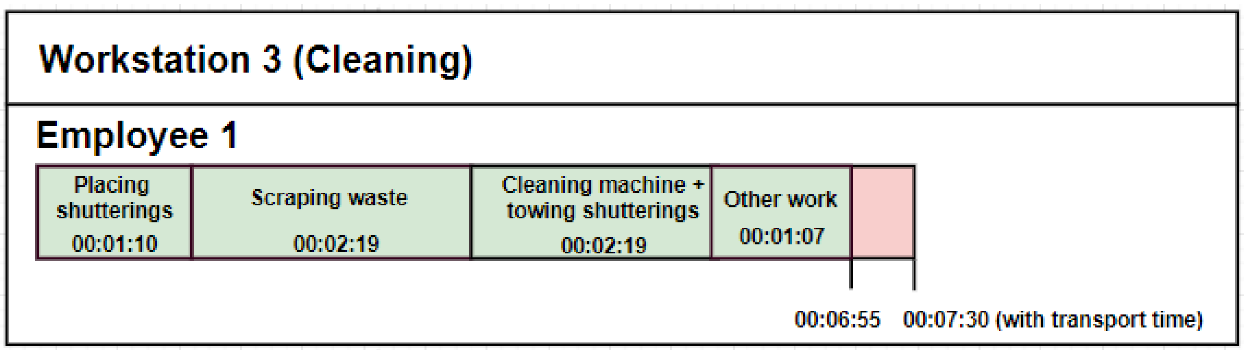

Figure 5.5: Future timeline of workstation 3

5.1.5 Workstation 5

The main problem at this workstation is that the preparation of work is not done at the right time which leads to time exceedings. The process time for placing the supplementary parts can easily be done without causing a time exceeding. We see this in Figure 5.6. The solution to this problem is the following:

1. Prepare for the next moulds in the waiting time to create a buffer for more difficult moulds (see Figure 5.7).

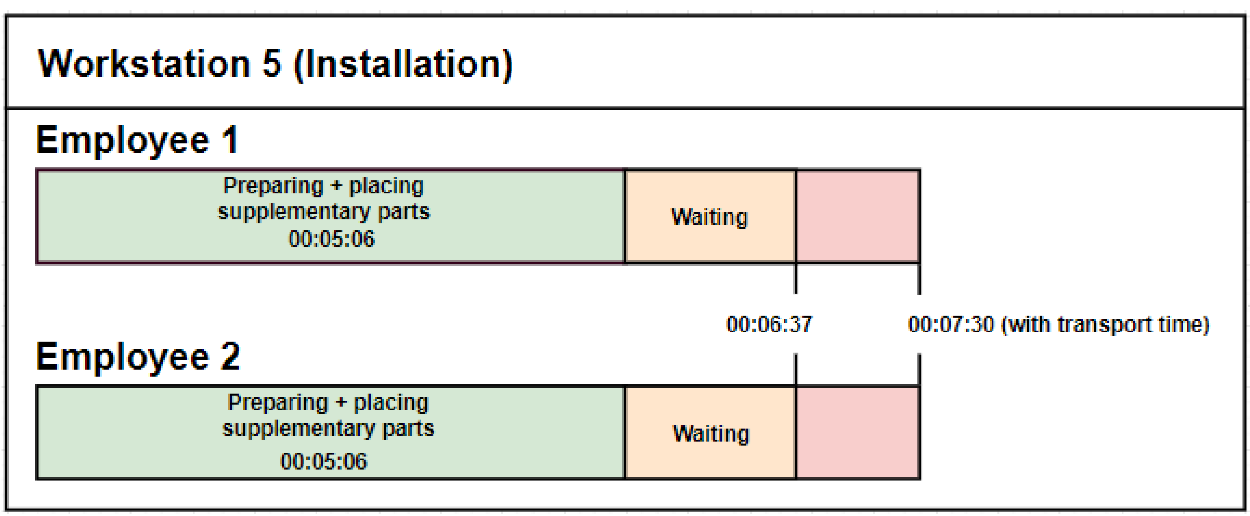

Figure 5.6: Current timeline of workstation 5.

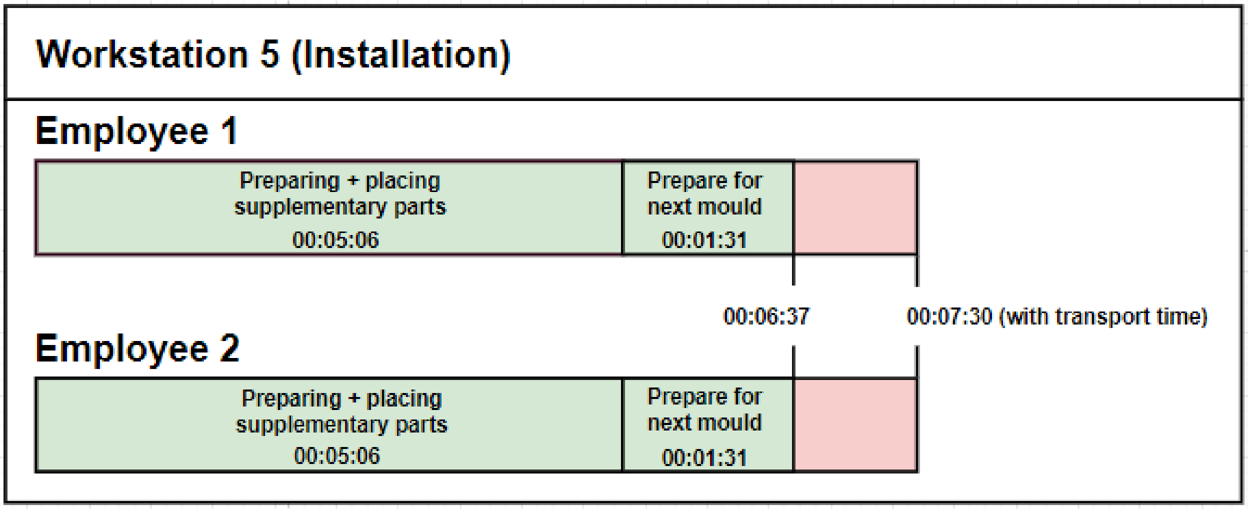

Figure 5.7: Future timeline of workstation 5.

Moreover, the button is not always pressed to transport the mould to workstation 6 when it could have been pressed. The following solution can be implemented:

2. A special system can be made where the mould is transported automatically from workstation 4 to workstation 5 in a safe manner. The system is called a light barrier. When you step into the laser then the mould stops with transport. This is a method to make sure that employees cannot do it wrong. It sort of prevents wrong decisions.

5.2 Conclusion

In this chapter we explain the solution approach for all the problems at each workstation. From this approach we formulated the solution options by answering the following research question:

"What are the solution options to tackle the problem(s) at workstations 2, 3, 5, 7, 17 and 18?

We formulated the following solution options with the inspiration from the theory in Chapter 3 to deal with the problems from Chapter 4 at the corresponding workstation:

- Potential solution options for workstations 17 and 18
    1. Communication device.
    2. Bigger concrete mix truck.
    3. Extra concrete mix truck.
    4. Bigger machine.
    5. Buffer container.
    6. New concrete mixer at the concrete mix plant.

- Potential solution options for workstation 7
    1. More inventory space at the automatic crane.
    2. Preparing for a steel coil refill.

3. Extra steel coil reels at the machine.
4. Combine the work from workstations 8 and 10 and move it all to 10.
5. Alert system to push button.

- Potential solution options for workstation 2
    1. Get an employee from another workstation during the break.
    2. Do not have more than two shuttering slabs in a mould.
    3. New machine at workstations 17 and 18.
    4. Organisational measures.

- Potential solution option for workstation 3
    1. Standardized work description.

- Potential solution options for workstation 5
    1. Prepare for the next moulds in the waiting time.
    2. Automatic transport system with light barrier.

6 Solution choice

This chapter describes what solutions are relevant to implement by answering the following research question:

"Which solution options can be implemented by Company X, taking into account the criteria from the company?"

Section 6.1 discusses the solution options from Chapter 5 to see which are relevant to implement. With the use of criteria we scored the different solutions options to see which are the best to implement. Besides this, Section 6.2 describes some first steps for implementation and Section 6.3 explains the impact of the solutions.

6.1 Solution selection

Almost all solution options have a positive impact on the performance of the production process. However, some are not feasible or too expensive. In order to decide which solutions are the best to implement for workstations 17 and 18, 7 and 2, criteria is needed. For workstations 3 and 5 no criteria is needed, because there are no solutions options that are compared. The approach that we used at workstations 3 and 5 is to observe the workstations and to see what can be made better. At the other workstation we also analysed the data from the software, but due to time constraints this is not done at workstations 3 and 5. To decide what criteria to use, a brainstorm session with the supervisor from the company is done. We see the criteria from the brainstorm in Table 6.1 The solution options from Chapter 5 are assessed with the criteria from Table 6.1. Each criterion gets a weight, which indicates how important the criterion is to the company. We see the weights for each criterion in Table 6.1. Furthermore, the solution options can get a score from 1 to 5. We gave a score of 1 when the solution option is scoring very low on the given criterion and a 5 when the solution option is scoring very high on the given criterion. Besides this, a criterion can get a X when it is not feasible or when it is too expensive. In the end we multiplied all the scores with the weights to see which solutions are the best to implement.

Table 6.1: Criteria from the company.

Corresponding letter	Criterion	Weight
A	easy to implement (technical and organisational)	4
B	expected decrease in lead time	4
C	needed extra knowledge of employee (when high extra knowledge is needed then the points given will go down)	3
D	expected costs (safety costs included)	3
E	durable for the future	2
F	increase in quality	5

We see the solution options with their corresponding scores in Table 6.2. We discussed these scores with the supervisor from the company. Furthermore, information which includes the estimated costs for the solution options are provided by the company. The total score is the sum of the scores at the letter times the weights from Table 6.1. The range of the total score is between x (not possible) and 105. A solution option is discarded when the option gets an x on any criterion. The detailed scoring calculation is shown in Appendix E.

Table 6.2: Solution scores for workstations 17 and 18, 7 and 2.

Solution option	Score
Workstation 17 and 18	
1.Communication device	A:4, B:2, C:3, D:5, E:5, F:1, Total:63

2.Bigger concrete mix truck	A:3, B:1, C:5, D:3, E:3, F:1, Total:51
3.Extra concrete mix truck	A:5, B:5, C:5, D:3, E:3, F:1, Total:75
4.Bigger machine	A:2, B:4, C:1, D:1, E:4, F:5, Total:63
5.Buffer container	A:1, B:4, C:1, D:1, E:2, F:1 Total:35
6.New concrete mixer at the concrete mix plant	A:1, B:2, C:5, D:x, E:5, F:1, Total:x
Workstation 7	
1.More inventory space at the automatic crane	A:3, B:5, C:5, D:3, E:3, F:1, Total:67
2.Preparing for a steel coil refill	A:5, B:3, C:3, D:5, E:5, F:1, Total:71
3.Extra steel coil reels at the machine	A:x, B:5, C:3, D:2, E:3, F:1, Total:x
4.Combine the work from workstation 8 and 10 and move it all to 10	A:4, B:5, C:5, D:4, E:5, F:1, Total:78
5.Alert system to push button	A:5, B:4, C:4, D:5, E:4, F:1, Total:76
Workstation 2	
1.Get an employee from another workstation during the break	A:5, B:5, C:4, D:5, E:2, F:3, Total:86
2.Do not have more than two shuttering slabs in a mould	A:5, B:4, C:5, D:3, E:2, F:3, Total:79
3.New machine at workstation 17 and 18	A:2, B:4, C:1, D:1, E:4, F:5, Total:63
4.Organisational measures	A:4, B:3, C:3, D:5, E:5, F:5, Total:87

We see in Table 6.2 that for workstation 17 and 18 solution option 6 is not possible, because the option is not possible due to too high costs. Besides this, the buffer container is also a bad option to implement with only a score of 35. Furthermore, the bigger truck is worse that the extra truck. The best option would be to get an extra truck. Besides this, a communication device would be good to implement as it is a quick and inexpensive option. The new machine however, is expensive and not easy to implement. On the other hand, It will most likely lead to a lower lead time and to better quality.

We see from Table 6.2 that for workstation 7 solution option 3 is not possible, because it is not feasible. It is very hard to implement this option. Solutions 4 and 5 are options for the same problem (not pushing the button to transport the mould towards workstation 8). Solution 4 will completely get rid of the problem and an employee is free. Solution 5 is cheaper, because no extra safety is needed (for the other options extra safety measurements must be taken). From this we conclude that solution 4 is better. Solution 2 should be implemented no matter what, because no extra costs and work will be created and the lead time will improve. Furthermore, solution 1 is also a good option to implement, because it will greatly lower the lead time.

We see from Table 6.2 that for workstation 2 solution option 3 is the same as for workstation 17 and 18. The solution is expensive and hard to implement, but will lead to more quality and to a lower lead time. Solution option 1 should be implemented immediately, because without the lead time will not decrease a lot. However, for the future this will not be a good solution. Solution 2 should also be implemented to lower the lead time, but it will decrease the turnover because of lesser products in the mould. Solution option 4 should be implemented right away. It is easy to implement, it is fairly cheap, it will decrease the lead time and it will increase the quality a lot.

From Chapter 5 we see that for workstation 3 there is only one solution option which is the standardized work description. Furthermore, for workstation 5 the options are to prepare for the next mould in the waiting time and make a special light barrier system to transport the moulds automatically to the next workstation. These two solution options for workstation 5 are both good solutions to implement in order to improve the workstation.

6.2 Solution implementation

We made a plan for the implementation of the solutions that have been selected. Section 6.2.1 explains the plan for workstation 17 and 18, Section 6.2.2 for workstation 7, Section 6.2.3 for workstation 2, Section 6.2.4 for workstation 3 and Section 6.2.5 for workstation 5.

6.2.1 Plan for workstation 17 and 18

The first thing that must be done is to make the delivery of concrete mix more consistent. The best solution for this is to have a more consistent delivery. A communication device to communicate with the concrete mix plant can make the delivery more consistent. Company X already has this, but it is not used in the right way. They should get around the table with the operators at the concrete plant and discuss how they should use it. Company X and the concrete mix plant are both directed from the same holding so it is possible to discuss it with the director from the holding to show how much it can increase production. Besides this, an extra concrete mix truck would be good to implement. This will create a bigger time buffer for the trucks to get concrete mix and for the machine to pour the concrete mix into the moulds. With two trucks it should be possible to get a lead time of 7.5 minutes per mould. Furthermore, a bigger machine could be a good option. With a bigger machine more concrete mix can be poured into the machine and this means that the truck has more time to get to the concrete plant and back. The type of machine depends on the criteria of the Company X. They should analyse and discuss the different options and if it is possible to implement it at the workstations. They should also train the employees on how to work with the "new" machine.

6.2.2 Plan for workstation 7

The first thing that must be done is to get rid of the button problem. To achieve this, Company X should move the work at workstation 8 to workstation 10 and make the transport system from workstation 7 to 8, from workstation 8 to 9 and from workstation 9 to 10 automatic. Company X should also make sure that everything is safe. They already work with a company that makes all the workstations safe with barriers and sensors. The second thing that must be done is to reduce the refill times at the VGA Versa welding machine. The refill time can be reduced by preparing for steel coil refill before the reel is empty. All activities that can be done before a refill must be done before the refill. With this the time for the actual refill will be reduced. Another solution is to create a time buffer. The buffer makes sure that there are enough lattice girders at the crane for placement. To achieve this the inventory area must change. Either the amount of places must be made bigger or the lattice girders must be placed on top of each other and the crane must then be able to pick them up in stacks. Company X must discuss and analyse what the options for this are. The option to have more steel coil reels cannot be done because the implementation would be very difficult and that is why it would be better to start with the preparation of the refills.

6.2.3 Plan for workstation 2

When there is a break then one employee (of two) is taking a break. When this happens an employee from another workstation must be placed at workstation 2 to be able to still do the work in 7.5 minutes and thus to prevent time exceedings. To balance the amount of work that needs to be done can be done by not having too many shuttering slabs in the mould. It is desired to only have a maximum of 2 shuttering slabs in the mould. If more shuttering slabs are desired, then more research needs to be done at this workstation to make the work that has to be done easier and faster. Furthermore, to prevent product damages the best option is to implement some organisational measures. The employees at workstation 5 must take their time with spraying in the mould and the employee at workstation 3 should do the work according to the work description to clean the mould in a good way. This must be managed by the foremen. Furthermore, at workstations 17 and 18 the employees must work at a balanced pace and thus not too fast (currently they do the work to fast and this leads to product damages). This can be done by putting the head of production at the workstations and letting him give instructions on how they should do it. A bigger machine at workstation 17 and 18 could also be a good option to increase the quality.

6.2.4 Plan for workstation 3

At this workstation the work that has to be done must be in the right order of priority and the employees that are working here must exactly know what to do when. The work description (from Chapter 5 Figure 5.3) must be followed to do the work in the right way. Organisation is very important here, because most employees who are new, start at this workstation. The best thing to achieve this is to have someone that is experienced help them and teach them how to do the work here properly. Besides this, the mould at workstation 2 must, if possible, be transported immediately to workstation 2. The employees must learn this right from the start.

6.2.5 Plan for workstation 5

The best thing to do at workstation 5 is to prepare for the next moulds in the time that is left from the current mould. If the work is done at the mould then the employees should prepare for the upcoming moulds. With this, upcoming moulds with more work can be compensated, because these moulds could have already been prepared in the time that was left from easier moulds. Another thing that would be good to implement is a laser system that stops the mould from transporting when there is something crossing the laser. With this the mould can be transported automatic and safety will still be high. Company X already knows this kind of laser system exists and how they should implement this.

6.2.6 Overall plan for the workstations

In Table 6.3 we see what solution must be done by who at which time and what he or she has to do.

Table 6.3: Overview implementation plan for workstation 17 and 18, 7, 2, 3 and 5.

Priority of implementation	Who has to do it?	What needs to be done?
1 Communication device	Head of production and director.	They need to discuss with the director of the holding and from de concrete mix plant to keep using the device because it will benefit the company.
1 Preparing for a steel coil refill	Foremen and employees at workstation 7.	The foremen need to show the employees that refill the steel coils to prepare the refill before they are empty.
1 Combine the work from workstation 8 and 10 and move it all to 10	This is already done. But should be maintained by the foremen.	Maintain this solution.
1 Standardized work description	Head of production.	Give the new employees at this workstation the work description and place it on the fence next to workstation 2.
1 Prepare for the next moulds in the waiting time to create a buffer for more difficult moulds	Foremen and employees at workstation 5.	The foremen need to tell the employees that they need to prepare the work for the next moulds in the time they have left.
1 Organisational measures	Head of production and foremen.	They should give a clear presentation with all the employees of how it should be done.
1 Get an employee from another workstation during the break	Foremen.	The foremen should manage that there is an employee ready to take the work over.

2 Extra concrete mix truck	Head of production and director.	The head of production should look for the right concrete mix truck and discuss this with the director.
2 Not more than two shuttering slabs in the mould	Head of production.	The head of production should look if it is really beneficial to have less shuttering slabs into the mould or have more and thus have more products but a higher lead time. Currently the employees cannot do the work in the given time so something must be done.
2 Laser system	Head of production.	The head of production should look for a good laser system. Company X already works with a company that can make these.
3 More inventory space at the automatic crane	Head of production.	The head of production should look what the options are to create a bigger inventory space. You can either place the lattice girders on top of each other or make more individual places.
3 Get a bigger machine	Head of production and employees at workstation 17 and 18.	They should look what would be a good new machine at workstation 17 and 18.

6.3 Solution impact

The solutions that we choose all have an impact on the output of the production process. With the communication device and an extra truck the time exceedings that cause a late delivery can be prevented. Besides this, a new machine will increase the buffer time for the trucks and will increase the quality of the products, which will remove the time exceedings that cause the product damages at workstation 2. With the preparation of the steel coil refills and extra places for lattice girders the steel coil refill time exceedings can be removed. Furthermore, by moving the work from workstation 8 to workstation 10 and making the transport automatic from workstation 7 to 8 , the time exceedings caused by not pressing the button can be removed. At workstation 2 placing a person from another workstation when there is a break at this workstation will remove the break time exceedings. Besides this, when only two shutterings slabs are placed in the mould the time exceedings regarding more than 2 shuttering slabs can be removed. The time exceedings at workstation 3 will be removed when the standardized work description is used. At workstation 5 work must be prepared and when this is done then there should not be any time exceedings. In Table 6.3 we see the potential impact of the chosen solutions. We see that for every workstation the number of "soft" moulds per hour will increase with the solutions from Section 6.1. Besides this the variation of the lead times will go down a lot. Another thing that we see in Table 6.3 is that the output in March and April was around 6.4 "soft"moulds per hour for the whole process. This will also increase significantly, because the bottleneck (workstations 17 and 18) will improve a lot and the variation of the other workstations will go down, which creates a more balanced flow of work. However, we cannot say exactly how much the entire process will benefit from the solutions. Appendix F explains how the information in Table 6.3 are calculated.

Table 6.4: Potential impact of the chosen solutions.

Workstation	2	3	5	7	17+18
Number of time periods measured (March + April)	4027	4098	4035	4089	3574
Number of time exceedings measured (March + April)	466	472	495	504	1027
Number of time exceedings with solutions implemented	264	0	0	274	404
“soft” moulds per hour whole process	6.39	6.40	6.41	6.41	6.34 / 6.39
“soft” moulds per hour (March + April)	8.99	9.86	9.90	11.23	7.47 / 8.41
“soft” moulds per hour with solutions implemented	9.40	10.13	10.12	12.13	9.95 / 11.20
Improvement in percentage	+5%	+3%	+2%	+8%	+33% / +33%
Variation (March + April)	00:02:55	00:02:09	00:02:38	00:04:14	00:06:59 / 00:07:32
Variation with solutions implemented	00:01:49	00:01:13	00:01:14	00:03:09	00:03:46 / 00:03:41
Improvement in percentage	-38%	-43%	-53%	-26%	-46% / -51%

7 Conclusions, recommendations & discussion

This research gives solutions to improve the production process and to thus achieve a higher production rate. We answered different research questions in the conclusion of every chapter. All these conclusions help answer the main research question. The main research question of the research is:

"How can Company X achieve a higher production rate?"

Section 7.1 gives the conclusion of the research. Furthermore, Section 7.2 gives recommendations. In the end Section 7.3 gives some advice for future research.

7.1 Conclusions

This section gives the main conclusions of this research. The aim of this research is to achieve a higher production output by improving the underperforming workstations. In order to know how to achieve this the following research question is answered:

"How can Company X achieve a higher production rate?"

To answer the main research question, several other research questions have been formulated to each contribute to answering the main research question.

"What does the current production process look like?"

The current production process consists of 11 workstations and 9 other stations, which are buffers. At the workstations something is done to the mould to in the end get a "soft" production mould. All the (work)stations are forming a circular process where the end-product (shuttering slabs) are taken out of the mould at one of the workstations.

"What theories and methods, based on scientific literature and case studies, can be used to improve the process at the workstations 2, 3, 5, 7, 17 and 18?"

The relevant theories and methods that are used to improve the process at the workstations are some Lean techniques, Six Sigma and some methods from the TOC. From Lean, VSM is used to make a clear overview of the performance of the process. With this some problems can be indicated with kaizen bursts that have to be improved. Furthermore, with the 5S Methodology, Cellular Manufacturing and SMED manufacturing are used to improve different workstations. From Six Sigma the DMAIC approach to analyze the performance and to get to the root cause is used. From the TOC some scheduling rules, 5FS and DBR scheduling methodology is used. The scheduling rules are used to improve certain workstations, the 5FS to analyze and improve the bottleneck and DBR to create buffers for the bottleneck and other workstations.

"What problems are occurring at and around workstations 2, 3, 5, 7, 17 and 18?"

The problems and the causes for the problems are identified and analyzed for workstation 2, 3, 4, 7, 17 and 18. This is done by looking at the causes that make the workstations underperform. In Excel all the time periods are analyzed to see what the causes are. For workstation 17 and 18 the main cause is the late delivery of concrete mix. Besides this, some time is lost due to breaks and shift changes and the utilization rate is not optimal. For workstation 7 the main causes are that the button is not pressed quickly enough to transport the mould to workstation 8, the steel coil refills take too long and the machine has failures. Furthermore, the VGA Versa welding machine is not used optimally because there is not enough inventory space and the automatic crane stops working when a refill is done. For workstation 2 the amount of shuttering slabs in the mould is too much, during a break a lot of time is lost and product damages lead to rework. For workstation 3 the work is

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not done in the right way and the mould could have already gone to workstation 3 from workstation 2, but this is not done immediately. For workstation 5 the work is not prepared at the right time and the mould is not transported quick enough towards and from workstation 5.

“What are the solution options to tackle the problem(s) at workstations 2, 3, 5, 7, 17 and 18?

In order to get rid of the problems at workstation 17 and 18 and too improve the production process a couple of solution options are possible. A communication device can be made to communicate with the concrete mix plant. Furthermore, a bigger concrete mix truck can be bought or even get an extra one. A bigger machine is also an option or a buffer container to have some concrete mix ready for the machine. Moreover, a completely new concrete mixer at the concrete mix plant is also an option.

At workstation 7 more inventory space at the automatic crane can be made to have more lattice girders ready to be placed into the mould. Preparing for a steel coil refill is another option to reduce the lead time. Furthermore, extra steel coil reels at the machine would also reduce the lead time. In order to transport the mould from workstation 7 to workstation 8 can be done quicker by having either an alarm system to alert the employee or by combining the work from workstations 8 and 10 and moving it all to 10.

The lead time at workstation 2 can be reduced by getting an employee from another workstation during the break, because one employee from this station is having a break. Furthermore, it is recommended to not have more than two shuttering slabs in a mould. To prevent product damages a new machine at workstation 17 and 18 is an option. Besides these options some organisation measures are options to reduce the amount of product damages.

For workstation 3 there is only one option and that is the standardized work description. With the description the work can be done under 7,5 minutes which is desired to get an output of 8 “soft” production moulds per hour.

At workstation 5 the preparation of work can be done in the waiting time for the next mould. This will reduce the lead time and will help with harder moulds, because already some work is done beforehand. Besides this, the transportation can be made automatic with a light barrier added. When an employee crosses the light barrier then the mould stops moving.

“Which solution options can be implemented by Company X, taking into account the criteria from the company?”

There are a lot of solution options, but based on the criteria the following options are the best to implement:

- For workstation 17 and 18 the best option would be to get an extra concrete mix truck to create a bigger time buffer. Besides this, a communication device would be good to implement as it is a quick and inexpensive option. A new machine to pour concrete mix however, is expensive and not easy to implement. On the other hand, It will most likely lead to a lower lead time and to better quality. With these solutions the average output of these workstations could potentially go from 7.47 and 8.41 to 9.95 and 11.20 for workstations 17 and 18 respectively. Besides this the variation could go from 00:06:59 and 00:07:32 to 00:03:46 and 00:03:41 for workstations 17 and 18 respectively.
- For workstation 7 the work at workstation 8 should be moved to workstation 10 to automatically transport the mould from 7 to 8. Besides this, the inventory of lattice girders must be made bigger to create a bigger buffer for the refill of steel coils and to have the machine make more lattice girders, because it does not have to stop that often anymore because of a full inventory. Another thing that must be done is to prepare for a steel coil refill before it is empty. With these solutions the average

output of this workstation could potentially go from 11.23 to 12.13. Besides this the variation could go from 00:04:14 to 00:03:09.

- For workstation 2 the amount of work is too much and thus the amount of shuttering slabs in the mould must not be bigger than 2. Besides this, during a break an employee from another workstation must take over the work. To prevent product damages a new machine is needed and organisational measures must be taken at the other workstations to make sure the quality increases. With these solutions the average output of this workstation could potentially go from 8.99 to 9.40. Besides this the variation could go from 00:02:55 to 00:01:49.
- For workstation 3 the work needs to be done according to the standardized work description from Chapter 5 Section 5.1.3. With this solution the average output of this workstation could potentially go from 9.86 to 10.13. Besides this the variation could go from 00:02:09 to 00:01:13.
- For workstation 5 the work for the upcoming moulds needs to be prepared in the time they have left from the current mould. Also, a laser system needs to be made to make the transport faster, but also safe. When someone steps into the laser the mould stops with transporting and with the laser the mould can thus be transported automatically without leading to an unsafe situation. With these solutions the average output of this workstation could potentially go from 9.90 to 10.12. Besides this the variation could go from 00:02:38 to 00:01:14.

For best solutions for the workstations, we made a short implementation plan. The plans consist of a couple of general steps Company X has to take to implement the solutions.

All in all, Company X can improve their production process by implementing the solutions proposed in this thesis. For some solutions some further research is needed, but a good understanding is given of what goes wrong and what could be done to get rid of this.

7.2 Recommendations

The results of this research will give a good basis for improving the production process. This section describes the recommendations for Company X.

The first recommendation is to evaluate whether and to what extent the solutions have improved the production process and thus to see where further improvements have to be made. The whole process of analyzing the processes and getting to solutions can be done over and over again to achieve continuous improvement.

Another recommendation is to listen to the employees more often and to really involve them in the process of decision making. They are the eyes and ears of the process and know way more than often is thought. This will also lead to more motivated employees that think about process improvement. This recommendation can be strengthened with a saying from the Lean methodology: Tell me, I forget. Show me, I remember. Involve me, I understand.

Furthermore, with regards to data gathering a recommendation would be to have more sensors or other data gathering methods to get even more information about the performance of the production process. Currently no information is available about how long it actually takes to do the work (this is only measured by hand in this research) and thus also how long a mould is waiting to be transported to the next (work)station. Another recommendation would be to document all the failures and variations in production in some documentation system. With this, causes for underperformance are easier to trace back, because currently a lot of time exceedings are unknown.

The last recommendation is for the employees that are not working at the production process but do make decisions regarding the production process. They should go into the production hall more often to see what happens. You cannot see everything on a screen and from data.

7.3 Limitations

There are some limitations within this research. We identified the following limitations:

- For some workstations there was limited data available. An example of this is the data of the arrival times of the concrete trucks. Only 11 days (in total time) could be analysed in comparison to 25 days. Furthermore, the performance of some workstations has been measured and led to not a lot of results, which could lead to inaccurate outcomes when calculating certain things.
- Besides the limited availability of data also the quality of some data is not the highest. For the arrival times the truck drivers have to fill in a paper when they arrive and when they leave. Most of the time they just fill it in whenever they have time and they roughly estimate what time it is (a lot of the times per 5 minutes).
- The data that is used was from the months March and April. This is not very up-to-date anymore and there is a chance that some solutions do not hold anymore. However, most recommendations can still be discussed and edited where needed with new data.
- Some workstations are not analysed in much detail. Workstations 2 and 5 are analysed limited due to time constraints. The conclusions that are made are a good starting point, but future research is advised.
- The implementation plans for the solutions at the different workstations are not very detailed. This is because time is limited and because more than one workstation was analysed. It is however a good starting point where the company can build upon.

7.4 Future research

Company X can improve the production process even further. The following things can be done to further improve the production process:

- The main recommendation for the future is to further analyse the production process to see what the next bottleneck is and improve this bottleneck and thus the production process. This can be done with the methods that are described in this research.
- The research focuses on increasing the production rate of the production process and not on the amount of profit that would be generated. A recommendation for future research is to look into what the optimal production rate should be to generate the most profit. This can mean that a higher production rate may not result in more profit or maybe that it does.
- The research does not focus on inventory levels of certain parts and materials, because Company X has a policy to have as much inventory as possible to never run out of parts and materials. However, it

would maybe be better to have lower inventory levels. A recommendation for future research is to look into inventory management.

- Workstations 2 and 5 are not analysed in much detail. This is because of time constraints and because of limited data. For future research it would be a good idea to further analyse this workstation and to come up with more concrete solutions.

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Appendix A: Other (work)stations

This appendix explains the other (work)stations besides 17, 18, 7, 2, 3 and 5, because the core problems do not occur here. However, it is good to know what happens at the other workstations.

U4 (plotter)

The machine (plotter) automatically puts lines of paint (plots contours) on the bottom of the empty mould. On these plotted lines employees, who are standing at workstation 5, put certain things on the mould. We see an example of a plotted mould in Figure A.1.

Censored

Figure A.1: Plotted mould.

U6 (mesh spacer)

A machine places distance holders on the bottom of the mould to support the reinforcement that will be put in the mould after the distance holders by the mesh spacer (see Figure A.2). These distance holders are there to raise the reinforcement in order for it to be in the concrete. The distance holders can be 15, 20, 25, 30 or 35 mm high depending on what the height of the reinforcement has to be in the concrete. The machine can lay the 15 mm, 25 mm and the 30 mm types and the workers can lay the 20 mm and the 35 mm types. In the end a big crane places (a) reinforcement mat(s) onto the distance holders.

Censored

Figure A.2: Mould with reinforcement mats.

U8 (installation)

At this station the lattice girders are connected to the reinforcement with metal wires. This is done manually. Furthermore, a special part is added in order to make the stacking of the shuttering slabs easier at the construction site. This is done by 2 employees. We see the timeline of the work at this workstation in Figure A.3.

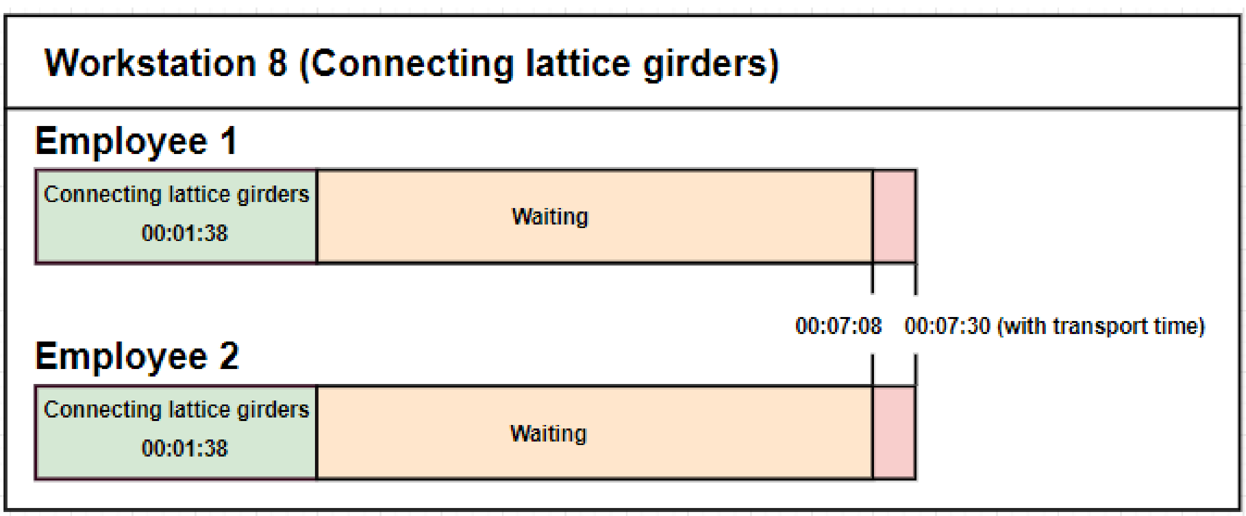

Figure A.3: Timeline of the work at workstation 8.

U9 (buffer)

This station is used as a buffer in order to have a place ready to transport a mould from U8 to this station or to have a mould ready to transport to U10.

U10 (installation)

Other supplementary parts like electro boxes, and metal casings for the EPS circles are added to the whole frame (see Figure A.4). The electro boxes are added, because at these places a light connection will be placed. The metal casings for the EPS circles are added, because a ventilation system or something else needs to be placed there and the metal casings form a strong frame around the EPS circles. These parts can be easily removed in comparison to the concrete of the shuttering slab itself. Besides this, labels are added to the lattice girders and a piece of paper with information is placed on the mould. This is done by 3 employees and an inspection is done to see if the reinforcement is placed correctly. We see the parts with explanations in Table A.1 and the timeline of the work at this workstation in Figure A.5.

Censored

Figure A.4: Moulds with supplementary parts added.

Table A.1: List of supplementary parts.

Part name	Explanation	Picture
1. Electric boxes	These are placed onto the mould and strapped to the lattice girders. They are there because later on light boxes or other electrical applications can be made here.	 
2. Metal casings	These are placed around the styrofoam circles to form a stronger frame.	

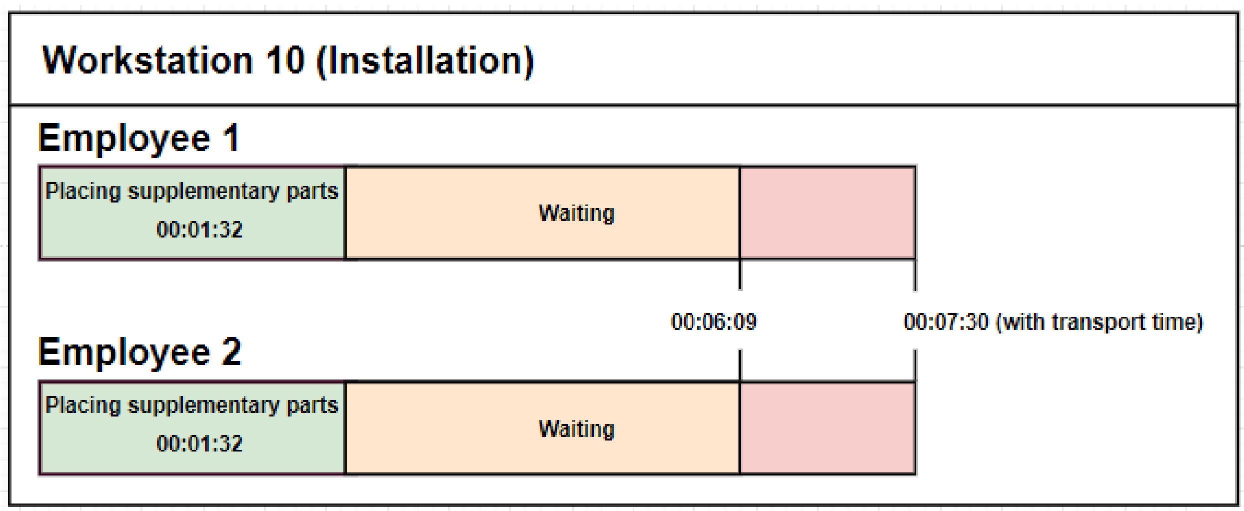

Figure A.5: Timeline of the work at workstation 10.

U11, U12, U13, U14, U15 (buffers)

These stations are used as a buffer in order to have a place ready to transport a mould from workstation 10 to these stations or to have a mould ready for workstation 17.

U16

This station is currently not used for production. However, it is used for repairs.

U19 (checking)

The mould is transported to this station and a last check is done to see if the concrete mix is well distributed. Also, the clamps are taken off and the number of the shuttering slab is etched into the concrete mix. The person at workstation 19 will also bevel the concrete mix at the sides of the mould to make sure that the slab stays in the 3000mm range. The person from U18 does this.

U20 (buffer)

The mould with everything in it is transported to this station to wait before going to U24.

U24 (curing chamber)

The “soft” production mould is transported into the curing chamber and stacked at the previously made “soft” production moulds. A large crane tows the “soft” production mould to the right stack to harden.

U1 (curing chamber)

The mould, with the shuttering slab in it, is placed on this station by a large crane. This large crane is the same one used at U24. The mould with the shuttering slab(s) comes out of the curing chamber and goes to workstation U2 via a transport system.

Appendix B: Production process observations and measurements

Section B.1 explains the bottleneck calculations. In addition, Section B.2 explains the individual workstation performance calculations.

B.1 Bottleneck calculations

Data from the GPA software is collected from every (work)station from every shift from the months March and April. An example of one shift can be seen in Figure B.1. The data that is used includes 42 shifts from March and 28 shifts from April. These shifts are divided into morning and afternoon shifts. A morning shift is from 6:00:00 to 14:30:00 (8.5 hours including 2*15 minutes break) and an afternoon shift is from 14:30:00 to 00:30:00 (10 hours including 2*15 minutes break).

1	TP 1	TP 2	TP 3	TP 4	TP 5	TP 6	TP 7	TP 8	TP 9	TP 10	TP 11	TP 12	TP 13	TP 14	TP 15	T
2	03/05/2021 06:27	03/05/2021 06:11	03/05/2021 06:10	03/05/2021 06:10	03/05/2021 06:09	03/05/2021 06:09	03/05/2021 06:05	03/05/2021 06:10	03/05/2021 06:03	03/05/2021 06:03	03/05/2021 06:05	03/05/2021 06:16	03/05/2021 06:16	########	########	
3	03/05/2021 06:30	03/05/2021 06:28	03/05/2021 06:21	03/05/2021 06:16	03/05/2021 06:16	03/05/2021 06:15	03/05/2021 06:10	03/05/2021 06:11	03/05/2021 06:03	03/05/2021 06:05	03/05/2021 06:16	03/05/2021 06:20	03/05/2021 06:18	########	########	
4	00:02:41	00:17:46	00:10:45	00:06:17	00:06:37	00:06:25	00:04:30	00:01:44	00:00:28	00:01:50	00:10:56	00:03:26	00:02:37	00:03:55	00:03:43	
5	81	55	56	57	58	59	60	60	61	61	61	61	62	63	82	
6	320, 209			005, 003	068, 202	067, 203	066, 213	066, 213	065, 214, 201	065, 214, 201	065, 214, 201	065, 214, 201	064, 425	003, 424	205, 220	
7	03/05/2021 06:32	03/05/2021 06:30	03/05/2021 06:28	03/05/2021 06:21	03/05/2021 06:16	03/05/2021 06:16	03/05/2021 06:15	03/05/2021 06:19	03/05/2021 06:11	03/05/2021 06:12	03/05/2021 06:18	03/05/2021 06:20	03/05/2021 06:20	########	########	
8	03/05/2021 06:35	03/05/2021 06:34	03/05/2021 06:32	03/05/2021 06:25	06:23:21	03/05/2021 06:22	03/05/2021 06:19	03/05/2021 06:20	03/05/2021 06:12	03/05/2021 06:18	03/05/2021 06:20	03/05/2021 06:30	03/05/2021 06:29	########	########	
9	00:03:13	00:04:31	00:03:42	00:04:02	00:06:58	00:06:31	00:03:39	00:01:44	00:00:30	00:05:46	00:02:34	00:10:03	00:09:14	00:10:27	00:10:14	
10	80	81	55	56	57	58	59	59	60	60	60	60	61	62	63	
11	321, 208			001, 004	005, 003	068, 202	067, 203	067, 203	066, 213	066, 213	066, 213	066, 213	065, 214, 201	064, 425	003, 424	
12	03/05/2021 06:36	03/05/2021 06:35	03/05/2021 06:34	03/05/2021 06:32	03/05/2021 06:25	03/05/2021 06:23	03/05/2021 06:22	03/05/2021 06:25	03/05/2021 06:20	03/05/2021 06:21	03/05/2021 06:23	03/05/2021 06:31	03/05/2021 06:30	########	########	
13	03/05/2021 06:41	03/05/2021 06:41	03/05/2021 06:41	03/05/2021 06:35	03/05/2021 06:32	03/05/2021 06:30	03/05/2021 06:25	03/05/2021 06:27	03/05/2021 06:21	03/05/2021 06:23	03/05/2021 06:31	03/05/2021 06:37	03/05/2021 06:35	########	########	
14	00:05:09	00:05:56	00:06:34	00:03:16	00:07:17	00:07:26	00:02:54	00:02:18	00:00:31	00:02:05	00:07:59	00:05:42	00:04:52	00:06:07	00:05:57	
15	79	80	81	55	56	57	58	58	59	59	59	59	60	61	62	
16	324, 323, 322			002, 004	001, 004	005, 003	068, 202	068, 202	067, 203	067, 203	067, 203	067, 203	066, 213	065, 214, 2	064, 425	
17	03/05/2021 06:44	03/05/2021 06:41	03/05/2021 06:41	03/05/2021 06:41	03/05/2021 06:35	03/05/2021 06:32	03/05/2021 06:30	03/05/2021 06:34	03/05/2021 06:27	03/05/2021 06:28	03/05/2021 06:32	03/05/2021 06:37	03/05/2021 06:37	########	########	
18	03/05/2021 07:43	03/05/2021 07:42	03/05/2021 07:42	03/05/2021 06:44	03/05/2021 06:38	03/05/2021 06:37	03/05/2021 06:34	03/05/2021 06:35	03/05/2021 06:28	03/05/2021 06:32	03/05/2021 06:37	03/05/2021 06:41	03/05/2021 06:40	########	########	
19	00:59:17	01:00:40	01:01:06	00:03:04	00:02:02	00:04:47	00:03:31	00:01:36	00:00:30	00:04:30	00:04:51	00:03:50	00:03:00	00:04:13	00:04:02	
20	78	79	80	81	55	56	57	57	58	58	58	58	59	60	61	
21	306, 1858			157, 235	002, 004	001, 004	005, 003	005, 003	068, 202	068, 202	068, 202	068, 202	067, 203	066, 213	065, 214, 20	
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23	03/05/2021 07:52	03/05/2021 07:52	03/05/2021 07:51	03/05/2021 07:51	03/05/2021 06:45	03/05/2021 06:44	03/05/2021 06:40	03/05/2021 06:41	03/05/2021 06:36	03/05/2021 06:39	03/05/2021 06:42	03/05/2021 07:01	03/05/2021 06:59	########	########	
24	00:08:16	00:08:40	00:08:55	00:08:38	00:01:22	00:06:55	00:02:44	00:01:08	00:00:29	00:02:58	00:02:48	00:19:03	00:18:14	00:19:29	00:19:19	
25	77	78	79	80	81	55	56	56	57	57	57	57	58	59	60	
26	307, 1859			161, 205, 201	157, 235	002, 004	001, 004	001, 004	005, 003	005, 003	005, 003	005, 003	068, 202	067, 203	066, 213	
27	03/05/2021 07:54	03/05/2021 07:52	03/05/2021 07:52	03/05/2021 07:51	03/05/2021 07:51	03/05/2021 06:45	03/05/2021 06:44	03/05/2021 06:48	03/05/2021 06:41	03/05/2021 06:41	03/05/2021 06:49	03/05/2021 07:01	03/05/2021 07:01	########	########	
28	03/05/2021 07:58	03/05/2021 07:58	03/05/2021 07:55	03/05/2021 07:55	03/05/2021 07:54	03/05/2021 06:56	03/05/2021 06:48	03/05/2021 06:50	03/05/2021 06:41	03/05/2021 06:49	03/05/2021 07:01	03/05/2021 07:05	03/05/2021 07:04	########	########	
29	00:04:38	00:05:18	00:03:44	00:03:39	00:03:11	00:11:19	00:03:44	00:01:35	00:00:30	00:07:53	00:12:11	00:03:37	00:02:51	00:04:02	00:03:51	
30	76	77	78	79	80	81	55	55	56	56	56	56	57	58	59	
31	310, 1857			058, 202	161, 205, 201	157, 235	002, 004	002, 004	001, 004	001, 004	001, 004	001, 004	005, 003	068, 202	067, 203	
32	03/05/2021 08:00	03/05/2021 07:58	03/05/2021 07:58	03/05/2021 07:55	03/05/2021 07:55	03/05/2021 07:54	03/05/2021 06:56	03/05/2021 06:59	03/05/2021 06:50	03/05/2021 06:50	03/05/2021 07:05	03/05/2021 07:06	03/05/2021 07:05	########	########	
33	03/05/2021 08:03	03/05/2021 08:02	03/05/2021 08:01	03/05/2021 08:01	03/05/2021 08:01	03/05/2021 08:00	03/05/2021 06:59	03/05/2021 07:01	03/05/2021 06:50	03/05/2021 07:05	03/05/2021 07:06	03/05/2021 07:14	03/05/2021 07:13	########	########	
34	00:02:50	00:03:33	00:03:47	00:05:33	00:05:52	00:06:14	00:02:55	00:02:10	00:00:29	00:14:14	00:01:04	00:08:37	00:07:47	00:08:59	00:08:50	
35	75	76	77	78	79	80	81	81	55	55	55	55	56	57	58	
36	1853, 1856			059, 203	058, 202	161, 205, 201	157, 235	157, 235	002, 004	002, 004	002, 004	002, 004	001, 004	005, 003	068, 202	
37	03/05/2021 08:04	03/05/2021 08:03	03/05/2021 08:02	03/05/2021 08:01	03/05/2021 08:01	03/05/2021 08:01	03/05/2021 08:00	03/05/2021 08:03	03/05/2021 07:01	03/05/2021 07:05	03/05/2021 07:14	03/05/2021 07:15	03/05/2021 07:14	########	########	
38	03/05/2021 08:10	03/05/2021 08:10	03/05/2021 08:09	03/05/2021 08:08	03/05/2021 08:08	03/05/2021 08:07	03/05/2021 08:03	03/05/2021 08:05	03/05/2021 07:05	03/05/2021 07:14	03/05/2021 07:15	03/05/2021 07:19	03/05/2021 07:18	########	########	

... | 4-3-2021 middag | **5-3-2021 ochtend** | 8-3-2021 ochtend | 8-3-2021 middag | 9-3-2021 ochtend | 9-3-2021 midd ...

Figure B.1: Raw data from the morning shift of March the 5th.

The date, mould number and time period from the mould on a certain (work)station are also listed (see Figure B.1). From this data the time periods are extracted to different sheets. The data from one shift can be seen in Figure B.2.

1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		17	18	19	20	24
11	00:04:02	00:07:03	00:07:34	00:07:09	00:07:32	00:07:04	00:03:54	00:09:27	00:00:30	00:01:52	00:00:38	00:01:21	00:00:28	00:41:50	00:41:40		00:41:25	00:40:53	00:00:30	00:01:25	00:00:22
12	00:07:59	00:10:09	00:07:26	00:07:01	00:07:24	00:06:56	00:07:03	00:02:39	00:00:34	00:02:53	00:00:37	00:01:24	00:00:28	00:00:21	00:05:07		00:04:50	00:04:18	00:01:10	00:01:28	00:00:56
13	00:18:05	00:18:50	00:19:24	00:06:49	00:07:11	00:06:44	00:04:11	00:02:13	00:00:31	00:03:50	00:00:36	00:01:23	00:00:28	00:00:22	00:05:58		00:06:03	00:05:40	00:01:02	00:01:28	00:00:22
14	00:09:29	00:09:44	00:10:03	00:05:56	00:08:04	00:07:35	00:03:58	00:02:58	00:00:41	00:06:12	00:00:35	00:01:24	00:00:28	00:00:22	00:06:03		00:06:21	00:05:50	00:01:39	00:01:28	00:00:24
15	00:08:59	00:10:22	00:06:19	00:03:09	00:06:10	00:06:59	00:02:57	00:02:47	00:00:30	00:04:43	00:00:35	00:01:22	00:00:27	00:00:21	00:00:31		00:07:55	00:07:26	00:01:27	00:01:26	00:00:22
16	00:03:19	00:03:45	00:03:48	00:04:45	00:04:34	00:05:09	00:04:15	00:05:19	00:00:29	00:04:30	00:00:36	00:01:23	00:00:28	00:00:20	00:01:29		00:05:18	00:03:15	00:02:12	00:01:37	00:00:22
17	00:05:47	00:06:32	00:07:07	00:04:20	00:07:53	00:04:24	00:04:27	00:03:02	00:00:28	00:02:06	00:00:36	00:01:23	00:00:28	00:00:22	00:04:10		00:08:51	00:08:22	00:01:42	00:01:29	00:01:32
18	00:11:38	00:12:23	00:04:46	00:04:20	00:07:02	00:06:16	00:06:47	00:02:43	00:00:29	00:05:39	00:00:37	00:01:27	00:00:30	00:00:21	00:02:06		00:03:36	00:03:08	00:01:37	00:01:29	00:00:22
19	00:07:17	00:08:04	00:02:48	00:05:28	00:05:49	00:05:51	00:04:34	00:02:17	00:00:29	00:01:40	00:00:36	00:01:21	00:00:31	00:00:20	00:03:38		00:07:46	00:07:13	00:01:31	00:01:29	00:01:46
20	00:03:42	00:05:43	00:03:35	00:03:42	00:05:58	00:05:29	00:03:38	00:00:34	00:00:28	00:01:23	00:00:37	00:01:21	00:00:28	00:00:14	00:00:31		00:03:51	00:03:11	00:01:14	00:01:30	00:00:22
21	00:04:32	00:04:51	00:02:45	00:04:00	00:05:35	00:06:44	00:06:19	00:04:29	00:03:11	00:01:25	00:00:35	00:03:31	00:07:44	00:17:48	00:20:08		00:38:38	00:39:37	00:01:09	00:01:30	00:00:58
22	00:05:32	00:05:44	00:02:41	00:04:59	00:04:48	00:05:27	00:04:45	00:01:03	00:01:31	00:02:17	00:00:35	00:01:22	00:03:13	00:04:25	00:04:14		00:03:57	00:03:22	00:01:34	00:01:30	00:00:22
23	00:04:21	00:05:18	00:02:52	00:06:07	00:06:28	00:07:04	00:03:49	00:01:53	00:01:56	00:02:09	00:00:32	00:01:22	00:00:28	00:04:17	00:04:06		00:03:55	00:02:51	00:01:02	00:01:29	00:00:59
24	00:06:24	00:06:41	00:06:53	00:07:38	00:07:58	00:07:31	00:05:41	00:03:52	00:00:28	00:01:41	00:00:37	00:01:20	00:03:46	00:05:48	00:08:12		00:07:56	00:07:22	00:01:42	00:01:24	00:01:13
25	00:05:46	00:06:05	00:06:15	00:06:15	00:08:32	00:07:04	00:07:09	00:01:48	00:00:22	00:02:28	00:00:36	00:01:20	00:03:37	00:05:21	00:05:10		00:04:54	00:03:07	00:01:19	00:01:25	00:00:22
26	00:12:39	00:13:21	00:13:57	00:13:58	00:14:09	00:06:33	00:04:23	00:02:05	00:00:28	00:02:06	00:00:38	00:01:18	00:00:28	00:03:15	00:03:06		00:02:49	00:02:22	00:01:40	00:01:29	00:00:37
27	00:07:09	00:07:41	00:08:14	00:07:51	00:08:12	00:07:54	00:07:09	00:01:53	00:00:28	00:01:23	00:00:36	00:01:44	00:03:32	00:10:45	00:19:14		00:18:56	00:18:28	00:01:49	00:01:39	00:00:53
28	00:06:14	00:09:17	00:09:51	00:09:28	00:09:48	00:09:20	00:04:25	00:02:06	00:00:27	00:01:21	00:00:37	00:01:20	00:02:11	00:03:23	00:03:12		00:02:58	00:02:14	00:01:24	00:01:35	00:00:20
29	00:06:10	00:06:15	00:06:48	00:06:22	00:06:43	00:06:00	00:03:36	00:01:36	00:00:27	00:04:01	00:00:40	00:01:17	00:09:25	00:09:27	00:09:16		00:08:04	00:07:33	00:00:47	00:01:36	00:00:22
30	00:07:36	00:07:47	00:08:09	00:07:51	00:08:09	00:06:26	00:03:48	00:00:57	00:00:29	00:01:21	00:00:37	00:01:20	00:00:27	00:00:21	00:02:50		00:02:35	00:02:49	00:00:52	00:01:28	00:00:25
31	00:05:26	00:05:34	00:05:59	00:05:45	00:06:00	00:05:36	00:03:28	00:02:23	00:00:28	00:01:37	00:00:37	00:01:19	00:00:28	00:00:22	00:00:30		00:03:13	00:02:44	00:01:21	00:01:34	00:00:19
32	00:04:19	00:05:57	00:06:39	00:06:26	00:06:47	00:06:22	00:03:30	00:01:15	00:00:31	00:02:43	00:00:34	00:01:22	00:06:29	00:12:21	00:17:42		00:23:25	00:25:15	00:01:29	00:01:27	00:01:07
33	00:34:43	00:35:44	00:08:20	00:07:48	00:08:12	00:07:11	00:02:54	00:02:26	00:00:28	00:02:01	00:00:37	00:01:31	00:04:33	00:07:28	00:07:17		00:07:01	00:06:31	00:01:23	00:01:31	00:00:22
34	00:04:48	00:04:32	00:04:25	00:07:33	00:07:56	00:07:13	00:03:41	00:01:28	00:00:28	00:04:16	00:00:36	00:01:19	00:05:32	00:06:53	00:07:04		00:05:18	00:04:48	00:03:10	00:01:34	00:01:10
35	00:04:06	00:04:29	00:04:35	00:04:09	00:09:47	00:09:17	00:04:23	00:03:35	00:03:53	00:04:20	00:00:36	00:01:23	00:09:35	00:13:31	00:13:10		00:10:25	00:11:01	00:11:14	00:01:35	00:00:24
36	00:09:44	00:10:29	00:11:08	00:11:13	00:08:29	00:06:10	00:04:01	00:02:40	00:00:29	00:01:26	00:00:37	00:04:36	00:06:48	00:08:12	00:08:01		00:07:48	00:02:52	00:01:56	00:01:32	00:00:22
37	00:04:42	00:05:11	00:05:11	00:04:44	00:05:00	00:04:11	00:04:37	00:02:32	00:00:29	00:01:57	00:00:35	00:11:08	00:14:39	00:16:04	00:16:15		00:16:37	00:14:54	00:02:03	00:01:34	00:00:20
38	00:10:45	00:10:49	00:11:22	00:11:34	00:11:54	00:04:56	00:02:56	00:02:03	00:00:28	00:03:26	00:03:32	01:38:22	01:37:36	01:38:44	01:38:20		01:37:44	01:36:36	00:00:45	00:01:33	00:00:22

ochtend 5 maart | ochtend 8 maart | middag 8 maart | ochtend 9 maart | middag 9 maart | ochtend 10 maart | m ...

Figure B.2: Extracted data from the morning shift of March the 5th.

The data from workstations 2, 3, 4, 5, 6, 7, 10, 17 and 18 are put in different sheets to analyse the causes. Furthermore, the time periods are put in such a way that the time periods horizontally represent the moulds at the workstations at the "same" time and the time periods vertically represent the moulds that are on that workstation after each other. With this the time exceedings that were caused by the next workstation first are marked red (see Figure B.3), then deleted (see Figure B.4) and replaced with the average time period of moulds at that workstation (see Figure B.5).

ochtend 1 april	1	2	3	4	5	6	7		10	17	18
	00:07:24	00:07:35	00:07:59	00:08:37	00:08:57	00:08:31	00:08:37	**unknown**	00:02:37	00:08:09	00:02:38
	00:11:50	00:13:56	00:14:25	00:14:13	00:14:31	00:14:01	00:14:08	**niet doordrukken van 8**	00:02:47	00:12:28	00:08:36
	00:04:36	00:05:34	00:05:55	00:05:38	00:05:59	00:05:24	00:05:34		00:03:54	00:16:34	00:16:01
	00:05:25	00:05:42	00:05:39	00:05:10	00:05:30	00:05:01	00:05:15		00:01:38	00:04:16	00:03:43
	00:02:05	00:04:41	00:05:15	00:05:12	00:05:53	00:05:25	00:05:27		00:02:28	00:06:05	00:05:35
	00:04:23	00:04:29	00:05:04	00:04:45	00:05:22	00:04:53	00:05:01		00:07:28	00:06:23	00:05:49
	00:07:19	00:07:26	00:08:05	00:07:44	00:08:04	00:07:37	00:07:45	**unknown**	00:02:12	00:09:50	00:09:18
	00:07:26	00:07:33	00:08:12	00:06:43	00:07:03	00:06:35	00:06:42		00:06:25	00:04:16	00:03:44
	00:04:16	00:04:29	00:04:23	00:03:58	00:04:51	00:04:23	00:04:33		00:03:15	00:09:10	00:07:34
	00:04:00	00:05:27	00:06:08	00:06:27	00:06:46	00:06:34	00:06:42		00:02:49	00:03:25	00:02:47
	00:04:57	00:05:17	00:05:57	00:05:31	00:05:27	00:04:59	00:05:20		00:06:39	00:18:07	00:17:35
	00:07:32	00:07:52	00:08:17	00:07:52	00:08:10	00:08:07	00:08:13	**niet doordrukken van 8**	00:03:53	00:04:06	00:02:55
	00:05:57	00:06:18	00:06:41	00:06:28	00:06:48	00:06:20	00:06:26		00:03:27	00:03:46	00:03:17
	00:10:50	00:11:15	00:11:53	00:11:41	00:12:01	00:11:32	00:11:40	**storten**	00:17:01	00:09:30	00:09:01
	00:07:14	00:07:12	00:05:30	00:05:05	00:05:27	00:04:29	00:04:12		00:02:36	00:04:04	00:02:43
	00:02:02	00:05:05	00:03:11	00:04:52	00:05:10	00:04:42	00:05:14		00:05:37	00:08:13	00:16:48
	00:02:04	00:04:58	00:03:27	00:05:27	00:06:02	00:05:34	00:04:08		00:03:31	00:03:37	00:03:08
	00:04:51	00:06:37	00:05:27	00:05:11	00:05:39	00:05:11	00:05:01		00:03:24	00:04:36	00:02:27
	00:04:55	00:05:03	00:04:47	00:05:47	00:08:07	00:07:37	00:07:48	**storten**	00:03:16	00:03:32	00:02:56
	00:07:08	00:07:20	00:04:58	00:05:28	00:06:11	00:04:17	00:04:11		00:02:52	00:03:14	00:02:42
	00:04:02	00:07:51	00:07:56	00:09:01	00:09:20	00:08:41	00:10:16	**storten**	00:12:58	00:18:37	00:18:05
	00:03:39	00:04:05	00:04:42	00:04:51	00:05:38	00:04:47	00:04:31		00:02:56	00:03:25	00:02:53
	00:15:30	00:16:16	00:16:40	00:16:15	00:16:35	00:17:08	00:17:39	**steel coil changeover**	00:05:33	00:05:34	00:03:01
	00:06:58	00:06:54	00:06:56	00:06:46	00:07:04	00:06:35	00:06:44		00:03:53	00:03:56	00:02:43
	00:10:39	00:10:37	00:11:02	00:11:10	00:11:32	00:11:04	00:11:12	**niet doordrukken van 8**	00:02:58	00:03:08	00:02:37
	00:02:26	00:04:08	00:03:21	00:03:10	00:03:28	00:03:01	00:02:48		00:06:48	00:16:10	00:15:31
	00:03:56	00:06:06	00:06:15	00:04:39	00:04:57	00:04:34	00:03:46		00:04:47	00:07:31	00:06:59
	00:03:54	00:04:57	00:05:40	00:05:46	00:05:23	00:04:20	00:03:56		00:06:17	00:08:47	00:05:36

Figure B.3: Data from the morning shift of April the 1st with time exceedings marked.

ochtend 1 april	1	2	3	4	5	6	7		10	17	18
	00:07:24	TWO	THREE	FOUR	FIVE	SIX	00:08:37	**unknown**	00:02:37	00:08:09	00:02:38
	ONE	TWO	THREE	FOUR	FIVE	SIX	00:14:08	**niet doordrukken van 8**	00:02:47	00:12:28	00:08:36
	00:04:36	00:05:34	00:05:55	00:05:38	00:05:59	00:05:24	00:05:34		00:03:54	00:16:34	00:16:01
	00:05:25	00:05:42	00:05:39	00:05:10	00:05:30	00:05:01	00:05:15		00:01:38	00:04:16	00:03:43
	00:02:05	00:04:41	00:05:15	00:05:12	00:05:53	00:05:25	00:05:27		00:02:28	00:06:05	00:05:35
	00:04:23	00:04:29	00:05:04	00:04:45	00:05:22	00:04:53	00:05:01		00:07:28	00:06:23	00:05:49
	00:07:19	00:07:26	THREE	FOUR	FIVE	SIX	00:07:45	**unknown**	00:02:12	00:09:50	00:09:18
	00:07:26	TWO	00:08:12	00:06:43	00:07:03	00:06:35	00:06:42		00:06:25	00:04:16	00:03:44
	00:04:16	00:04:29	00:04:23	00:03:58	00:04:51	00:04:23	00:04:33		00:03:15	00:09:10	00:07:34
	00:04:00	00:05:27	00:06:08	00:06:27	00:06:46	00:06:34	00:06:42		00:02:49	00:03:25	00:02:47
	00:04:57	00:05:17	00:05:57	00:05:31	00:05:27	00:04:59	00:05:20		00:06:39	00:18:07	00:17:35
	ONE	TWO	THREE	FOUR	FIVE	SIX	00:08:13	**niet doordrukken van 8**	00:03:53	00:04:06	00:02:55
	00:05:57	00:06:18	00:06:41	00:06:28	00:06:48	00:06:20	00:06:26		00:03:27	00:03:46	00:03:17
	ONE	TWO	THREE	FOUR	FIVE	SIX	SEVEN	**storten**	TEN	00:09:30	00:09:01
	00:07:14	00:07:12	00:05:30	00:05:05	00:05:27	00:04:29	00:04:12		00:02:36	00:04:04	00:02:43
	00:02:02	00:05:05	00:03:11	00:04:52	00:05:10	00:04:42	00:05:14		00:05:37	00:08:13	00:16:48
	00:02:04	00:04:58	00:03:27	00:05:27	00:06:02	00:05:34	00:04:08		00:03:31	00:03:37	00:03:08
	00:04:51	00:06:37	00:05:27	00:05:11	00:05:39	00:05:11	00:05:01		00:03:24	00:04:36	00:02:27
	00:04:55	00:05:03	00:04:47	00:05:47	FIVE	SIX	SEVEN	**storten**	00:03:16	00:03:32	00:02:56
	00:07:08	00:07:20	00:04:58	00:05:28	00:06:11	00:04:17	00:04:11		00:02:52	00:03:14	00:02:42
	00:04:02	TWO	THREE	FOUR	FIVE	SIX	SEVEN	**storten**	TEN	00:18:37	00:18:05
	00:03:39	00:04:05	00:04:42	00:04:51	00:05:38	00:04:47	00:04:31		00:02:56	00:03:25	00:02:53
	ONE	TWO	THREE	FOUR	FIVE	SIX	00:17:39	**steel coil changeover**	00:05:33	00:05:34	00:03:01
	00:06:58	00:06:54	00:06:56	00:06:46	00:07:04	00:06:35	00:06:44		00:03:53	00:03:56	00:02:43
	ONE	TWO	THREE	FOUR	FIVE	SIX	00:11:12	**niet doordrukken van 8**	00:02:58	00:03:08	00:02:37
	00:02:26	00:04:08	00:03:21	00:03:10	00:03:28	00:03:01	00:02:48		00:06:48	00:16:10	00:15:31
	00:03:56	00:06:06	00:06:15	00:04:39	00:04:57	00:04:34	00:03:46		00:04:47	00:07:31	00:06:59
	00:03:54	00:04:57	00:05:40	00:05:46	00:05:23	00:04:20	00:03:56		00:06:17	00:08:47	00:05:36

Figure B.4: Data from the morning shift of April the 1st with causes from other workstation deleted.

ochtend 1 april	1	2	3	4	5	6	7		10	17	18
	00:07:24	00:06:47	00:06:05	00:05:29	00:05:50	00:05:13	00:08:37	**unknown**	00:02:37	00:08:09	00:02:38
	00:05:29	00:06:47	00:06:05	00:05:29	00:05:50	00:05:13	00:14:08	**niet doordrukken van 8**	00:02:47	00:12:28	00:08:36
	00:04:36	00:05:34	00:05:55	00:05:38	00:05:59	00:05:24	00:05:34		00:03:54	00:16:34	00:16:01
	00:05:25	00:05:42	00:05:39	00:05:10	00:05:30	00:05:01	00:05:15		00:01:38	00:04:16	00:03:43
	00:02:05	00:04:41	00:05:15	00:05:12	00:05:53	00:05:25	00:05:27		00:02:28	00:06:05	00:05:35
	00:04:23	00:04:29	00:05:04	00:04:45	00:05:22	00:04:53	00:05:01		00:07:28	00:06:23	00:05:49
	00:07:19	00:07:26	00:06:05	00:05:29	00:05:50	00:05:13	00:07:45	**unknown**	00:02:12	00:09:50	00:09:18
	00:07:26	00:06:47	00:08:12	00:06:43	00:07:03	00:06:35	00:06:42		00:06:25	00:04:16	00:03:44
	00:04:16	00:04:29	00:04:23	00:03:58	00:04:51	00:04:23	00:04:33		00:03:15	00:09:10	00:07:34
	00:04:00	00:05:27	00:06:08	00:06:27	00:06:46	00:06:34	00:06:42		00:02:49	00:03:25	00:02:47
	00:04:57	00:05:17	00:05:57	00:05:31	00:05:27	00:04:59	00:05:20		00:06:39	00:18:07	00:17:35
	00:05:29	00:06:47	00:06:05	00:05:29	00:05:50	00:05:13	00:08:13	**niet doordrukken van 8**	00:03:53	00:04:06	00:02:55
	00:05:57	00:06:18	00:06:41	00:06:28	00:06:48	00:06:20	00:06:26		00:03:27	00:03:46	00:03:17
	00:05:29	00:06:47	00:06:05	00:05:29	00:05:50	00:05:13	00:06:00	**storten**	00:05:08	00:09:30	00:09:01
	00:07:14	00:07:12	00:05:30	00:05:05	00:05:27	00:04:29	00:04:12		00:02:36	00:04:04	00:02:43
	00:02:02	00:05:05	00:03:11	00:04:52	00:05:10	00:04:42	00:05:14		00:05:37	00:08:13	00:16:48
	00:02:04	00:04:58	00:03:27	00:05:27	00:06:02	00:05:34	00:04:08		00:03:31	00:03:37	00:03:08
	00:04:51	00:06:37	00:05:27	00:05:11	00:05:39	00:05:11	00:05:01		00:03:24	00:04:36	00:02:27
	00:04:55	00:05:03	00:04:47	00:05:47	00:05:50	00:05:13	00:06:00	**storten**	00:03:16	00:03:32	00:02:56
	00:07:08	00:07:20	00:04:58	00:05:28	00:06:11	00:04:17	00:04:11		00:02:52	00:03:14	00:02:42
	00:04:02	00:06:47	00:06:05	00:05:29	00:05:50	00:05:13	00:06:00	**storten**	00:05:08	00:18:37	00:18:05
	00:03:39	00:04:05	00:04:42	00:04:51	00:05:38	00:04:47	00:04:31		00:02:56	00:03:25	00:02:53
	00:05:29	00:06:47	00:06:05	00:05:29	00:05:50	00:05:13	00:17:39	**steel coil changeover**	00:05:33	00:05:34	00:03:01
	00:06:58	00:06:54	00:06:56	00:06:46	00:07:04	00:06:35	00:06:44		00:03:53	00:03:56	00:02:43
	00:05:29	00:06:47	00:06:05	00:05:29	00:05:50	00:05:13	00:11:12	**niet doordrukken van 8**	00:02:58	00:03:08	00:02:37
	00:02:26	00:04:08	00:03:21	00:03:10	00:03:28	00:03:01	00:02:48		00:06:48	00:16:10	00:15:31
	00:03:56	00:06:06	00:06:15	00:04:39	00:04:57	00:04:34	00:03:46		00:04:47	00:07:31	00:06:59
	00:03:54	00:04:57	00:05:40	00:05:46	00:05:23	00:04:20	00:03:56		00:06:17	00:08:47	00:05:36

Figure B.5: Data from the morning shift of April the 1st with replaced average time period.

From this data the production rate per workstation is calculated. A better overview of the performance is obtained, because the time exceedings that were caused by other workstations are deleted. The calculation for the production rate per workstation per shift can be seen in Figure B.6. The sum of all the time periods represent the times the moulds were on the workstations, the number of moulds is the total amount of moulds produced and the average production per station is the production rate per workstation that was achieved. The real number of moulds per hour is the overall production rate that was achieved during the whole shift.

1	ochtend 1 april	1	2	3	4	5	6	7		10	17	18
80	sum of production times (when mould is at station)	05:59:34	07:09:49	06:52:44	06:31:22	07:03:50	06:29:21	07:26:55		05:43:05	08:24:29	07:24:35
81	number of moulds (with the "average ones")	70	70	71	72	72	72	72		74	74	75
82	average production per station	11,68073	9,771608	10,32143	11,03824	10,19269	11,09542	9,666232		12,94146	8,801084	10,12184
83												
84	begin	06:00:00	06:00:00	06:00:00	06:00:00	06:00:00	06:00:00	06:00:00		06:00:00	06:00:00	06:00:00
85	end	14:30:00	14:30:00	14:30:00	14:30:00	14:30:00	14:30:00	14:30:00		14:30:00	14:30:00	14:30:00
86	total time	08:30:00	08:30:00	08:30:00	08:30:00	08:30:00	08:30:00	08:30:00		08:30:00	08:30:00	08:30:00
87	real number of moulds per hour	8,235294	8,235294	8,352941	8,470588	8,470588	8,470588	8,470588		8,705882	8,705882	8,823529

Figure B.6: Calculation of the production rate per workstation and the overall production rate from the morning shift of March the 1st.

All the production rates of the different workstations of all the different shifts of the month March and April are summed up and in Figure B.7 a part of the performances of the workstations are given. Furthermore, in Figure B.8 the "real" production rates, which are the production rates that the process actually achieved, are given.

together	1	2	3	4	5	6	7		10	17	18
	11,54999	7,590212	11,57676	10,52681	9,330714	9,140738	13,91388		14,70773	7,396637	8,434156
	11,22287	8,831401	11,0153	10,52518	9,237787	8,896211	11,54265		14,78889	7,502316	8,421417
	11,64271	8,620174	10,1083	9,699354	9,091273	8,496928	12,45538		12,9148	8,263606	8,798541
	12,21696	10,06102	9,734553	10,30092	9,050532	9,13551	11,81344		14,4888	8,768415	9,880915
	10,96258	9,277945	9,285246	9,445037	8,691382	9,359563	11,10026		9,541217	7,213903	6,434522
	10,81831	9,36212	9,573054	10,27973	8,741793	9,354775	11,14551		15,4803	7,338381	8,924303
	11,96141	8,656531	9,77918	10,20209	8,326698	8,759124	13,41024		15,03435	7,191648	8,114888
	12,1476	9,10946	10,23431	10,30423	9,821583	9,617505	12,30837		13,99914	8,859029	9,930382
	11,78085	9,119054	9,916055	9,886661	9,906526	8,873587	11,14825		11,3582	6,619325	7,534319
	12,05479	8,68383	10,29106	10,04134	9,254916	9,575346	11,56659		12,35513	7,079978	7,838334
	10,98338	9,254499	9,409129	9,474575	8,974708	9,588842	12,89818		10,72902	6,384394	6,880898
	11,40933	8,566408	10,42316	9,93926	8,505689	9,2419	11,35158		17,60584	7,628083	8,002877
	11,86296	9,36869	9,324759	10,14134	9,018725	9,496953	14,74264		13,274	7,391931	8,685347
	11,82501	9,698432	9,765973	9,566873	8,186539	10,39342	11,94613		13,8477	8,164923	8,754112
	11,08869	9,105975	7,95853	12,53615	9,91319	11,60465	15,75136		11,84739	7,962213	8,880341
	12,46512	8,877928	10,6979	11,07893	8,80292	12,89575	11,26346		14,29406	7,959345	8,595807
	11,21797	8,56756	8,506824	10,56466	10,22629	12,53377	14,05587		11,06653	7,377589	8,760266
	12,19623	8,337416	8,574962	10,80582	9,150455	11,44394	9,66044		12,61076	5,984745	6,776716
	11,08933	9,494655	9,171975	10,29938	9,553073	9,954081	10,80675		9,604044	7,484685	8,173857
	12,03268	9,675528	9,194762	11,8499	13,01262	11,34801	12,69801		16,19446	7,220217	9,396801
	12,44957	9,461761	10,03573	11,94281	11,1767	10,66491	10,4952		11,00254	7,883293	8,831151
	12,74181	10,32471	10,37464	12,48988	9,683155	11,28409	9,596964		10,37202	6,825142	7,511968
	11,89352	9,175648	9,595613	12,64508	11,15452	10,63356	10,78172		13,21933	8,268634	9,208142
	11,8009	9,58545	11,06383	12,59758	10,388	11,09503	10,11408		13,22931	9,003752	10,59614
	12,03954	9,06801	9,802089	11,41559	10,44608	10,60686	9,885995		12,00836	8,560919	8,606328
average moulds per hour	**11,36402**	**8,988131**	**9,861316**	**10,81167**	**9,898925**	**10,64593**	**11,23059**		**12,92322**	**7,470819**	**8,412879**

Figure B.7: Part of the performances of the workstations.

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together	1	2	3	4	5	6	7		10	17	18
	6,3	6,4	6,3	6,3	6,3	6,3	6,3		6,4	6,2	6,3
	6,823529	7,058824	7,058824	7,058824	7,058824	7,058824	7,176471		7,294118	7,294118	7,294118
	5,9	5,9	5,9	5,9	5,9	6	6		5,8	5,5	5,6
	6,117647	6,235294	6,352941	6,352941	6,352941	6,235294	6,352941		6,588235	6,588235	6,588235
	6,2	6,2	6,2	6,1	6,1	6,2	6,2		6,2	6,2	6,2
	7,294118	7,294118	7,294118	7,294118	7,411765	7,411765	7,294118		7,411765	7,411765	7,411765
	6,2	6,3	6,3	6,3	6,3	6,3	6,3		6,2	5,8	5,9
	6,470588	6,470588	6,470588	6,588235	6,705882	6,823529	6,823529		7,176471	7,411765	7,529412
	6,588235	6,588235	6,588235	6,588235	6,470588	6,470588	6,470588		6,117647	5,647059	5,647059
	6,4	6,5	6,5	6,5	6,5	6,6	6,6		6,7	6,7	6,8
	6,823529	6,823529	6,823529	6,823529	6,941176	6,823529	6,823529		6,823529	6,705882	6,705882
	6,6	6,7	6,7	6,7	6,7	6,7	6,8		6,9	6,7	6,8
	6,823529	6,823529	6,823529	6,941176	6,941176	6,941176	6,823529		6,941176	6,941176	6,941176
	6,7	6,8	6,8	6,8	6,7	6,8	6,8		6,8	6,7	6,8
	6,823529	6,823529	6,823529	6,823529	6,941176	6,823529	6,823529		6,941176	6,588235	6,588235
	5,2	5,2	5,2	5,2	5,2	5,2	5,2		5,1	5,1	5,2
	6,470588	6,588235	6,588235	6,588235	6,705882	6,588235	6,588235		6,705882	6,588235	6,588235
	6,352941	6,470588	6,470588	6,470588	6,470588	6,470588	6,470588		6,705882	6,470588	6,470588
	7,2	7,1	7,1	7,1	7,1	7,2	7,1		7,1	7,1	7,1
	6,823529	6,941176	7,058824	7,058824	6,941176	7,058824	6,941176		6,705882	6,117647	6
	7	7	7	6,9	6,9	6,9	6,9		7	7,1	7,2
	7,647059	7,647059	7,647059	7,647059	7,647059	7,764706	7,764706		7,647059	7,764706	7,882353
	6,8	6,7	6,7	6,7	6,7	6,7	6,6		6,7	6,4	6,4
real average moulds per hour	**6,352101**	**6,391345**	**6,398319**	**6,401681**	**6,405042**	**6,433445**	**6,407647**		**6,438487**	**6,342521**	**6,393445**

Figure B.8: Part of "real" production rates of the workstations.

B.2 Workstation performance calculations

Data from the bottleneck calculations from Appendix B.1 are used to further analyze the performance per workstation.

B.2.1 Lead times

The lead time (LT) represents the time between the mould arriving at the current (work)station and the mould arriving at the next (work)station. Because of this, this also includes the transport time from the current (work)station to the next (work)station. The lead times are from the software program of Company X from the month March and April.

The lead times for (work)stations 1 - 7, 10, 17 and 18 are calculated by summing up all the time periods with the time exceedings caused by other workstations replaced with the average of the workstation of the moulds standing at the workstations. This can be seen in Figure B.9 in the yellow row.

6	1	2	3	4	5	6	7		10	17	18	
4471	00:03:58	00:05:07	00:05:31	00:04:11	00:03:34	00:04:30	00:03:34		00:03:59	00:04:02	00:03:28	
4472	00:02:23	00:05:39	00:05:36	00:03:13	00:02:55	00:04:49	00:03:36		00:10:38	00:04:08	00:03:37	
4473	00:04:03	00:06:16	00:05:44	00:04:30	00:03:22	00:04:14	00:03:37		00:04:39	00:12:32	00:11:57	
4474	00:05:05	00:05:33	00:05:54	00:04:31	00:03:51	00:04:26	00:02:52		00:04:08	00:04:51	00:04:19	
4475	00:05:03	00:05:35	00:06:09	00:06:04	00:03:34	00:04:20	00:02:53		00:05:31	00:08:19	00:07:47	
4476	00:03:20	00:04:59	00:05:28	00:04:59	00:05:17	00:05:21	00:02:52		00:04:10	00:04:57	00:03:55	
4477	00:04:44	00:06:54	00:07:31	00:06:31	00:06:48	00:06:06	00:05:36		00:16:30	00:18:39	00:18:08	
4478	00:05:58	00:06:23	00:06:39	00:06:14	00:07:11	00:06:30	00:04:14		00:03:55	00:03:56	00:04:15	
4479	00:06:56	00:06:33	00:06:14	00:08:14	00:06:02	00:05:39	00:03:36		00:05:37	00:05:34	00:04:34	
4480										00:13:11	00:12:32	
4481											00:06:37	
4482												
4483	9	3	5	7	4	6	8		10	1	2	importance
4484	00:05:16	00:06:40	00:06:08	00:05:40	00:06:12	00:05:44	00:05:25		00:04:45	00:07:53	00:07:09	average/mean
4485												
4486	00:05:10	00:06:33	00:06:14	00:05:43	00:06:10	00:05:26	00:04:18		00:03:59	00:05:35	00:04:37	median
4487												
4488	00:00:10	00:00:07	00:00:24	00:02:14	00:01:22	00:01:09	00:01:26		00:00:11	00:00:04	00:00:54	min
4489	00:35:06	00:50:32	01:01:06	00:32:02	01:06:40	01:46:14	01:06:39		01:10:52	01:37:44	01:43:29	max

Figure B.9: Lead time calculations for (work)stations 1 - 7, 10, 17 and 18.

The lead times for (work)stations 8, 9, 11 - 15, 19, 20 and 24 are calculated by summing up all the time periods (also caused by other workstations) of the moulds standing at the workstations and taking the average from this. This can be seen in Figure B.10. In this figure also the other (work)stations are given, but these give a wrong indication of the performance of these (work)stations. The performance of (work)stations 8, 9, 11-15, 19, 20 and 24 are not that relevant and that is why no detailed calculation is used as with (work)stations 1 - 7, 10, 17 and 18.

1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		17	18	19	20	24	
4300	00:04:07	00:08:52	00:09:31	00:09:19	00:09:37	00:08:07	00:04:40	00:01:42	00:02:28	00:02:17	00:00:35	00:01:19	00:00:28	00:06:28	00:06:16		00:06:38	00:05:29	00:02:56	00:01:23	00:00:21	
4301	00:05:26	00:05:47	00:06:22	00:05:55	00:06:15	00:04:28	00:05:10	00:01:11	00:01:31	00:08:02	00:00:34	00:01:20	00:01:58	00:06:14	00:06:04		00:05:49	00:04:41	00:02:57	00:01:22	00:00:21	
4302	00:12:29	00:07:06	00:07:41	00:07:22	00:07:41	00:04:18	00:06:14	00:02:58	00:00:24	00:03:27	00:00:34	00:01:19	00:00:28	00:04:43	00:08:00		00:07:45	00:07:15	00:02:00	00:01:24	00:00:22	
4303	00:17:42	00:13:43	00:14:20	00:13:56	00:14:16	00:13:46	00:04:59	00:13:56	00:00:27	00:08:05	00:00:36	00:01:19	00:00:26	00:06:36	00:06:25		00:06:11	00:04:52	00:02:46	00:01:24	00:00:21	
4304	00:08:02	00:18:03	00:18:40	00:14:32	00:14:36	00:12:48	00:07:32	00:01:16	00:00:28	00:05:35	00:00:34	00:01:21	00:00:30	00:03:30	00:05:19		00:05:05	00:04:33	00:01:58	00:01:23	00:00:20	
4305	00:04:04	00:08:26	00:09:03	00:08:39	00:12:40	00:06:03	00:03:49	00:02:53	00:03:23	00:05:45	00:00:34	00:01:19	00:01:24	00:01:49	00:04:39		00:04:27	00:03:58	00:02:24	00:01:24	00:00:53	
4306	00:09:55	00:04:35	00:05:09	00:04:47	00:05:07	00:04:27	00:08:58	00:00:52	00:01:25	00:03:23	00:00:34	00:01:21	00:00:29	00:00:19	00:22:41		00:22:26	00:21:53	00:02:09	00:01:24	00:00:22	
4307	00:05:04	00:09:57	00:10:34	00:10:13	00:10:19	00:08:38	00:02:56	00:01:59	00:00:30	00:03:38	00:00:34	00:01:21	00:00:28	00:00:21	00:01:19		00:03:51	00:03:20	00:02:02	00:01:23	00:01:58	
4308	00:04:34	00:07:38	00:08:15	00:07:51	00:08:10	00:07:09	00:03:50	00:00:46	00:00:42	00:03:40	00:00:34	00:01:21	00:00:30	00:00:21	00:01:33		00:04:30	00:04:00	00:04:45	00:01:23	00:00:21	
4309	00:06:41	00:04:46	00:05:24	00:04:59	00:05:19	00:04:47	00:02:54	00:01:08	00:00:28	00:03:27	00:00:35	00:01:21	00:00:29	00:00:21	00:07:02		00:08:13	00:07:40	00:03:01	00:01:23	00:00:19	
4310	00:02:52	00:06:52	00:07:22	00:06:58	00:06:57	00:05:41	00:04:48	00:02:24	00:00:30	00:04:42	00:00:35	00:01:21	00:00:28	00:08:32	00:12:26		00:04:43	00:04:10	00:03:46	00:01:25	00:00:21	
4311	00:14:35	00:05:51	00:06:22	00:06:04	00:06:23	00:05:24	00:08:25	00:01:57	00:00:29	00:03:32	00:00:35	00:01:20	00:00:28	00:00:49	00:01:42		00:01:25	00:05:29	00:13:02	00:01:24	00:00:21	
4312		00:14:50	00:15:20	00:07:39	00:08:00	00:07:26	00:04:41	00:02:35	00:00:29	00:04:13	00:00:34	00:01:21	00:00:27	00:06:52	00:10:12		00:09:56	00:09:30	00:02:22	00:01:22	00:00:23	
4313			00:05:32	00:05:13	00:06:26	00:05:58	00:06:45		00:01:01	00:05:49		00:01:23		00:02:58	00:06:02		00:05:25	00:04:22	00:03:05	00:01:23	00:00:21	
4314										00:04:48		00:01:22						00:16:35		00:01:23		
4315																						
4316																						
4317																						
4318	00:07:20	00:08:09	00:07:23	00:07:01	00:07:21	00:06:39	00:05:39	00:03:46	00:02:27	00:05:06	00:02:51	00:04:47	00:04:56	00:06:54	00:07:52		00:07:53	00:07:09	00:02:20	00:01:29	00:00:43	average/mean
4319																						
4320	00:06:00	00:06:41	00:06:31	00:05:59	00:06:24	00:05:38	00:04:18	00:02:37	00:00:30	00:03:59	00:00:36	00:03:17	00:03:26	00:05:17	00:05:45		00:05:35	00:04:37	00:01:51	00:01:24	00:00:22	median
4321																						
4322	00:00:10	00:00:07	00:00:03	00:02:14	00:01:22	00:01:09	00:01:26	00:00:06	00:00:02	00:00:11	00:00:01	00:00:04	00:00:02	00:00:01	00:00:16		00:00:04	00:00:54	00:00:03	00:00:03	00:00:01	min
4323	01:46:47	01:47:04	01:47:40	01:47:17	01:47:37	01:46:14	01:06:39	01:08:55	01:05:29	01:15:07	01:20:22	01:38:22	01:37:36	01:38:44	01:38:20		01:37:44	01:43:29	00:26:30	00:25:13	01:39:00	max
4324																						
4325	00:05:47	00:05:43	00:04:56	00:04:50	00:04:49	00:04:31	00:04:40	00:04:20	00:04:06	00:04:39	00:04:35	00:05:25	00:05:50	00:06:22	00:06:55		00:06:59	00:07:31	00:01:56	00:00:48	00:01:52	standard deviation

Figure B.10: Lead time calculations for (work)stations 8, 9, 11 - 15, 19, 20 and 24.

The lead time for the making of lattice girders at workstation 7 is calculated a bit differently, because this process happens next to workstation 7 and not on it. The lead time for making lattice girders can be calculated by adding the process time and the waiting time together and dividing this with the number of moulds (transport time is not included because this is almost 0). This can be seen in Figure B.11. The process time (making lattice girders in Figure B.11) calculation can be seen at B.2.2 and the waiting time (machine is waiting in Figure B.11) calculation can be seen at B.2.4.

number of moulds	**49**
total time	**06:36:49**
making lattice girders	**04:44:24**
machine is waiting	**01:52:25**
average lead time per mould	**00:08:06**

Figure B.11: Lead time calculation making lattice girders.

All the lead times of all the workstations are in Table B.5 in Appendix B.2.8.

B.2.2 Process times

The process time (PT) represents the time the work takes at the workstations. The data is from measurements, observations and the software program. The process times are calculated by first measuring the times at the workstations and then processing these times in Excel.

Workstation 2

The measurements can be seen in Figure B.12. The number of openings are the number of gaps in the shuttering slabs. More gaps mean more work, because there is more waste to remove. The waste to remove are the EPS cylinders, EPS beams and cardboard corners. The process time is the time between picking up the first shuttering slab and picking up the second shuttering slab. This is because this represents picking up one slab out of the mould. In Figure B.13 all the measurements that have been done of picking up one slab out of the mould are given.

mold number:	72	intervals
number of openings	0	
number of shuttering slabs	2	
begin time (when mould is at workstation):	10:27:50	
demoulding 1		
crane picks up first shuttering slab	10:28:15	00:00:25
demoulding 2		
crane picks up second shuttering slab	10:29:58	00:01:43
end time (mould can be transported to next station):	10:32:31	00:02:33
production time	00:04:41	

Figure B.12: Measurements workstation 2 of one hardened production mould.

	stacking one shuttering slab with the crane
	00:01:43
	00:02:04
	00:02:40
	00:03:13
	00:02:50
	00:02:11
	00:03:09
	00:01:18
	00:00:29
	00:01:46
	00:03:40
	00:02:40
averagetime per shuttering slab:	00:02:19
minimal time:	00:00:29
maximum time:	00:03:40

Figure B.13: Process times of picking one shuttering slab out of the hardened production mould.

Workstation 3

At workstation 3 several things happen and are measured. First the process time of the cleaning machine is measured. This can be seen in Figure B.14. Furthermore, the process time of the employee is measured. The tasks that are measured are placing metal shutterings at the front of the mould (have to be taken out of the mould and then placing them at the front), towing the metal shutterings on the roller bar system and scraping the waste from the bottom of the floor (see Figure B.15). Besides this some smaller tasks are done at workstation 3. These include cutting the cardboard corners, brooming the sides of the mould and pushing the metal shutterings onto the conveyor belt. However, these tasks can be done during transport of the mould or when the other tasks are finished.

speed cleaning machine		
begin	**end**	**time period**
13:12:07	13:14:08	00:02:01
13:14:45	13:16:31	00:01:46
13:20:27	13:22:27	00:02:00
13:27:35	13:29:41	00:02:06
13:34:21	13:36:22	00:02:01
	average	00:01:59

Figure B.14: Measurements cleaning machine.

speed employee			speed employee			speed employee			
speed of placing metal shutterings at the front of the mould			speed of towing metal shutterings			speed scraping waste			
begin	end	time period	begin	end	time period	begin	eind	interval	a lot, normal or low amount of waste
12:43:53	12:45:02	00:01:09	12:48:41	12:49:35	00:00:54	10:22:35	10:27:48	00:05:13	a lot
12:58:35	12:59:36	00:01:01	12:56:19	12:57:15	00:00:56	10:35:35	10:36:43	00:01:08	low
13:46:41	13:47:50	00:01:09	13:02:20	13:03:15	00:00:55	10:41:21	10:44:15	00:02:54	normal
13:53:23	13:54:45	00:01:22	13:11:37	13:12:18	00:00:41	10:48:13	10:50:08	00:01:55	normal
			13:19:53	13:20:39	00:00:46	10:54:42	10:57:36	00:02:54	normal
			13:26:46	13:27:49	00:01:03				
			13:50:19	13:51:37	00:01:18				
	average	00:01:10		average	00:00:56		average	00:02:49	

Figure B.15: Measurements process time employee.

Workstation 4

The process time of the plotter machine is measured and can be seen in Figure B.16.

workstation 4				
date	mouldnumber	begin	end	time period
27/May	37	15:04:58	15:09:35	00:04:37
27/May	38	15:12:54	15:15:28	00:02:34
27/May	39	15:20:14	15:24:15	00:04:01
27/May	40	15:27:06	15:32:47	00:05:41
27/May	41	15:36:08	15:40:29	00:04:21
27/May	42	15:47:36	15:51:25	00:03:49
			average	00:04:10

Figure B.16: Measurements plotter machine.

Workstation 5

The process time of the placing of supplementary parts is measured and can be seen in Figure B.17.

workstation 5				
date	mouldnumber	begin	end	time period
27/May	18	15:03:17	15:09:11	00:05:54
27/May	38	15:18:48	15:23:08	00:04:20
27/May	39	15:25:47	15:31:32	00:05:45
27/May	40	15:34:38	15:39:27	00:04:49
27/May	41	15:41:01	15:45:45	00:04:44
			average	00:05:06

Figure B.17: Measurements placing supplementary parts.

Workstation 6

The process time of the work done at workstation 6 is measured from the GPA software because everything here is done automatically and thus can be easily measured from previous data. The measurements can be seen in Figure B.18.

date	mouldnumber	begin	end	time period
10/Mar	57	12:05:12	12:10:16	00:05:04
10/Mar	59	12:26:59	12:31:24	00:04:25
10/Mar	60	12:36:31	12:41:53	00:05:22
10/Mar	61	12:43:11	12:48:31	00:05:20
10/Mar	62	12:49:47	12:55:43	00:05:56
22/Apr	32	19:50:13	19:54:32	00:04:19
22/Apr	38	23:30:16	23:33:36	00:03:20
22/Apr	39	23:35:16	23:39:04	00:03:48
22/Apr	40	23:41:21	23:45:19	00:03:58
22/Apr	41	23:47:04	23:51:39	00:04:35
			average	00:04:37

Figure B.18: Measurements work at workstation 6.

Workstation 7

2 processes happen at the same time at workstation 7. The first one is the making of lattice girders by the VGA Versa welding machine and the second is the placement of the lattice girders on the reinforcement mats in the mould by the automatic crane. For the process time of the making of lattice girders the production times are measured from different kinds of heights and lengths (see Figure B.19). With this data the average process time can be calculated per meter per type of height (see Figure B.20). Furthermore, for each mould the time needed to make the lattice girders can be calculated with the amount of meters times 8 seconds plus 2 seconds cutting time for each lattice girder (see Figure B.21). In the end the process times per mould can be summed up and divided by the amount of moulds to get the average process time of the lattice girders per mould (see Figure B.22).

lattice girder number	lenght (mm)	height (mm)	begin	end	production time
14/Apr					
1039727	7200	160	14:47:37	14:48:30	00:00:53
1039728	7200	160	14:48:33	14:49:26	00:00:53
1039729	5400	160	14:49:28	14:50:09	00:00:41
1039730	5400	160	14:50:11	14:50:51	00:00:40
1039731	7200	160	14:50:53	14:52:02	00:01:09
1039732	3200	180	14:52:04	14:52:28	00:00:24
1039733	3200	180	14:52:30	14:52:55	00:00:25
1039734	3200	180	14:52:57	14:53:21	00:00:24
1039735	3200	180	14:53:24	14:53:49	00:00:25
1039736	3200	180	14:53:50	14:54:14	00:00:24
1039737	3000	180	14:54:16	14:54:39	00:00:23
1039738	3000	180	14:54:41	14:55:07	00:00:26
1039739	3000	180	14:55:10	14:55:44	00:00:34
1039740	7200	160	14:55:46	14:56:39	00:00:53
1039741	7200	160	14:56:41	14:57:35	00:00:54
1039742	7200	160	14:57:37	14:58:30	00:00:53
1039759	6400	210	15:30:50	15:31:40	00:00:50
1039760	6400	210	15:31:42	15:32:31	00:00:49
1039761	6400	210	15:32:33	15:33:22	00:00:49
1039762	4800	210	15:33:25	15:34:02	00:00:37
1039763	4800	210	15:34:04	15:34:41	00:00:37
1039764	4800	210	15:34:43	15:35:20	00:00:37
1039765	7800	210	15:35:22	15:36:22	00:01:00
1039766	7800	210	15:36:24	15:37:24	00:01:00

Figure B.19: Part of the measurements of the making of lattice girders.

height (mm)	lenght (mm)	lenght (m)	production time	average production time per meter
110	29400	29,4	00:03:54	00:00:08
160	61200	61,2	00:06:56	00:00:07
170	86800	86,8	00:10:53	00:00:08
180	88400	88,4	00:11:38	00:00:08
190	69200	69,2	00:08:55	00:00:08
210	167800	167,8	00:21:47	00:00:08

Figure B.20: Average production time per meter lattice girder.

lattice girder number	length (mm)	height (mm)
1040643	3800	180
1040644	3800	180
1040645	3800	180
1040646	3800	180
1040647	6200	190
1040648	6200	190
1040649	5400	190
1040650	5400	190
1040651	6200	190
total length + duration of production	44,6	00:06:15

Figure B.21: Process time calculation making of lattice girders of one mould.

1		making lattice girders
40		00:04:38
41		00:04:20
42		00:06:53
43		00:06:08
44		00:06:12
45		00:05:39
46		00:06:02
47		00:03:30
48		00:05:25
49		00:05:36
50		00:04:58
51	**sum**	**04:44:24**
52	**average**	**00:05:48**

Figure B.22: Average process time for making lattice girders for one mould.

Measurements for the placement of lattice girders can be seen in Figure B.23. The average process time (see Figure B.24) per mould can be calculated by summing up all the intervals that the crane is placing lattice girders and then get the average plus the average transport time per mould (including the transport of lattice girders with the crane). The calculations for the average placing time and the average transport time is explained below.

number of placings:	3	intervals
begin time production (when crane goes down):	13:05:26	
mold number:	28	
placing 1		
lattice girders in inventory:	9	
lattice girders that are placed:	4	
crane starts with picking lattice girders:		
crane starts with placing lattice girders:	**13:05:37**	00:00:11
crane is done placing lattice girders:	**13:05:48**	00:00:11
placing 2		
lattice girders in inventory:	9	
lattice girders that are placed:	4	
crane starts with picking lattice girders:	13:05:48	
crane starts with placing lattice girders:	13:09:03	**00:03:15**
crane is done placing lattice girders:	13:09:15	**00:00:12**
placing 3		
lattice girders in inventory:	8	
lattice girders that are placed:	**1**	
crane starts with picking lattice girders:	**13:09:15**	
crane starts with placing lattice girders:	13:09:58	00:00:43
crane is done placing lattice girders:	**13:09:59**	00:00:01
End time production (mould is transported away):	13:11:14	00:01:15
leadtime (transport to 8 excluded)	00:05:48	

Figure B.23: Measurements for the placement of lattice girders of one mould.

total number of moulds	**49**
total time placing lattice girders	**00:20:51**
placing time lattice girders on average per mould	**00:00:26**
total transport time crane	**01:43:51**
crane transport time on average per mould	**00:02:07**
average process time per mould	**00:02:33**

Figure B.24: Average process time of placing lattice girders.

In Figure B.25 two different sheets are put together to show how the time calculations are done. The similar shapes and colors means that for example the time in the red circle on the left side in the figure is the same as the time in the red circle on the right side of the figure.

In Figure B.25 certain things can be seen. Only transport time means that the crane is able to pick the lattice girders from the inventory and directly place them on the reinforcement mats in the mould without having to wait. These transport times lay in the range of 00:00:11 - 00:00:50. All the times above that range also include waiting time and these times can be seen in the column transport + waiting. To separate the waiting from the transport time the average transport time is subtracted from the transport + waiting time. This can be seen in Figure 64 as the time in the green circle (00:03:15) minus the average transport time of 00:00:43 is 00:02:32, which is waiting time. The time in the light blue circle (00:01:15) is pure waiting time because the mould could have already gone to workstation 8. This waiting time is added with the first interval time of the next mould (black square "00:01:04"), because there is also waiting time included in this interval. This is because it is higher than the 00:00:11 - 00:00:50 transport range. These times are added and again the average transport time is subtracted to get the waiting time. This is done for all the moulds that are measured.

To get the average placing time from Figure B.24, all the placing times are summed up and divided by the total number of moulds (see Figure B.25 column "placing time"). Furthermore, to get the average transport time from Figure B.24, all the transport times (columns "only transport times" + "transport time" from Figure B.25) are summed up and divided by the number of moulds.

only transport time	transport +waiting	transport time	waiting time	placing time
00:00:11	00:03:15	00:00:43	00:02:32	00:00:11
00:00:43	00:01:15	00:00:43	00:01:36	00:00:12
00:00:47	00:01:04			00:00:01
00:00:43	00:03:44	00:00:43	00:07:19	00:00:11
00:00:43	00:04:18			00:00:01
00:00:43	00:00:11	00:00:43	00:10:15	00:00:12
00:00:43	00:10:47			00:00:01
00:00:45	00:00:40	00:00:43	00:04:07	00:00:11
00:00:44	00:04:10			00:00:12
00:00:44	00:00:14	00:00:43	00:03:15	00:00:01
00:00:46	00:03:44			00:00:12
00:00:46	00:00:15	00:00:43	00:11:48	00:00:10
00:00:44	00:12:16			00:00:07
00:00:45	00:00:13	00:00:43	00:03:25	00:00:11
00:00:42	00:03:55			00:00:01
00:00:49	00:00:13	00:00:43	00:07:57	00:00:10
00:00:46	00:08:27			00:00:18
00:00:47	00:00:15	00:00:43	00:03:32	00:00:11
00:00:44	00:04:00			00:00:06
00:00:42	00:01:18	00:00:43	00:11:22	00:00:11

1	number of placings:	3	intervals
2	**begin time production (when crane goes down):**	13:05:26	
3	**mold number:**	28	
4	**placing 1**		
5	lattice girders in inventory:	9	
6	lattice girders that are placed:	4	
7	crane starts with picking lattice girders:		
8	crane starts with placing lattice girders:	**13:05:37**	00:00:11
9	crane is done placing lattice girders:	**13:05:48**	00:00:11
10	**placing 2**		
11	lattice girders in inventory:	9	
12	lattice girders that are placed:	4	
13	crane starts with picking lattice girders:	13:05:48	
14	crane starts with placing lattice girders:	13:09:03	**00:03:15**
15	crane is done placing lattice girders:	13:09:15	**00:00:12**
16	**placing 3**		
17	lattice girders in inventory:	8	
18	lattice girders that are placed:	**1**	
19	crane starts with picking lattice girders:	**13:09:15**	
20	crane starts with placing lattice girders:	13:09:58	00:00:43
21	crane is done placing lattice girders:	**13:09:59**	00:00:01
22	**End time production (mould is transported away):**	13:11:14	00:01:15
23	**leadtime (transport to 8 excluded)**	00:05:48	

Figure B.25: Time calculation for workstation 7.

All the process times of all the workstations are in Table B.5 in Appendix B.2.8.

B.2.3 Transport times

The transport time (TT) represents the time between the mould leaving the (work)station and the mould arriving at the next (work)station.

The transport times are measured at the production process between the relevant (work)stations and can be seen in Figure B.26 and B.27. The transport times on the last row of the figure is used in the calculation as the average transport time.

transport time 1 to 2	transport time 2 to 3	transport time 3 to 4	transport time 4 to 5	transport time 5 to 6	transport time 6 to 7	transport time 7 to 8
00:00:59	00:00:39	00:00:35	00:00:54	00:00:55	00:00:35	00:01:28
00:00:59	00:00:35	00:00:35	00:00:54	00:00:56	00:00:33	00:01:28
00:00:58	00:00:36	00:00:36	00:00:51	00:00:52	00:00:35	00:01:18
00:00:57	00:00:36	00:00:35	00:00:52	00:00:52	00:00:35	00:01:22
00:00:57	00:00:36	00:00:36	00:00:51	00:00:53	00:00:35	00:01:18
00:00:58	00:00:37	00:00:37	00:00:51	00:00:53	00:00:35	00:01:15
00:00:58	00:00:37	00:00:35	00:00:51	00:00:53	00:00:35	00:01:19
00:00:59	00:00:37	00:00:35	00:00:51	00:00:53	00:00:35	00:01:16
00:00:58	00:00:36	00:00:35	00:00:51	00:00:53	00:00:35	00:01:16
00:00:57	00:00:35	00:00:35	00:00:51	00:00:53	00:00:35	00:01:15
00:00:58	00:00:36	00:00:35	00:00:52	00:00:53	00:00:35	00:01:20

Figure B.26: Transport times of (work)stations part 1.

transport time 8 to 9	transport time 9 to 10	transport time 10 to 11	transport time 15 to 17	transport time 17 to 18	transport time 18 to 19
00:00:22	00:00:32	00:01:20	00:00:33	00:01:03	00:00:25
00:00:22	00:00:32	00:01:17	00:00:33	00:01:03	00:00:25
00:00:22	00:00:30	00:01:18	00:00:33	00:01:01	00:00:25
00:00:22	00:00:32	00:01:20	00:00:33	00:01:01	00:00:25
00:00:22	00:00:32	00:01:22	00:00:31	00:01:00	00:00:25
00:00:22	00:00:31	00:01:23	00:00:33	00:01:01	00:00:25
00:00:22	00:00:32	00:01:26	00:00:33	00:01:03	00:00:25
00:00:22	00:00:32	00:01:22	00:00:33	00:01:01	00:00:25
00:00:22	00:00:31	00:01:23	00:00:33	00:01:01	00:00:25
00:00:22	00:00:32	00:01:20	00:00:33	00:01:01	00:00:25
00:00:22	00:00:32	00:01:21	00:00:33	00:01:01	00:00:25

Figure B.27: Transport times of (work)stations part 2.

All the transport times of all the workstations are in Table B.5 in Appendix B.2.8.

B.2.4 Waiting times

The waiting time (WT) represents the time the mould can go to the next station, but is not able to. Important to take into account is that this time does not include the waiting time that no mould is at the (work)station.

The waiting times are calculated by subtracting the transport and the process time from the lead time. This can be seen in Table B.1.

Table B.1: Waiting times of the relevant (work)stations.

(work)station	Lead time (LT)	Process time (PT)	Transport time (TT)	Waiting time (WT)
2	00:06:40	00:04:38 - 00:06:57	00:00:36	00:01:26 - 00:00:00
3	00:06:08			
4	00:05:40	00:04:10	00:00:52	00:00:38
5	00:06:10	00:05:06	00:00:53	00:00:11
6	00:05:44	00:04:37	00:00:35	00:00:32
7 (overall)	00:05:25	00:02:33	00:01:20	00:02:52
7 (VGA Versa)	00:08:06	00:05:48	00:00:00	00:02:18
7 (placing crane)	00:05:25	00:02:33	00:01:20	00:02:52
8	00:03:32	00:01:38	00:00:22	00:01:32
10	00:04:45	00:01:40	00:01:21	00:01:44
17	00:07:53	00:02:27	00:01:01	00:04:25
18	00:07:09	00:04:04	00:00:25	00:02:40
19	00:02:20	00:00:41		

All the waiting times of all the workstations are in Table B.5 in Appendix B.2.8.

B.2.6 Refill times

The refill times (RT) represent the time it takes to refill a resource material. For workstation 7 it represents the time to change a steel coil. Furthermore, for workstation 17 it represents the time it takes to fill the machine with 4.5 m3 of concrete mix. The refill times at workstations 7 and 17 do not happen at every new mould. However, they are linked to the amount of steel or concrete mix that is needed per mould.

The refill times of workstations 7 and 17-18 is measured and can be seen in Figure B.28 and Table B.2.

current refill	activity	time	interval	internal or external
measured with 1 employee	working at 8 and notice refill	13:07:58		external
	at machine to see what is wrong	13:08:27	00:00:29	external
	got the crane and placed it near the steel coil	13:11:09	00:02:42	external
	walked to the reel that is almost empty	13:11:20	00:00:11	internal
	cut the wire and placed it in weldingmachine	13:11:52	00:00:32	internal
	reel has been made ready	13:12:34	00:00:42	internal
	walked to the steel coil where the crane must be placed in	13:12:37	00:00:03	internal
	placed the crane in the steel coil	13:13:11	00:00:34	internal
	coil is towed on reel	13:14:26	00:01:15	internal
	reel is made ready again	13:14:51	00:00:25	internal
	crane has been placed in other steel coil for safety reasons	13:15:15	00:00:24	internal
	walked to steel coil	13:15:36	00:00:21	internal
	done with cutting	13:15:57	00:00:21	internal
	done with welding	13:17:42	00:01:45	internal
	walked to steel coil	13:17:58	00:00:16	internal
	done smoothing	13:19:02	00:01:04	internal
	starting machine again	13:20:09	00:01:07	internal
		total time:	00:12:11	

Figure B.28: Refill time of workstation 7.

Table B.2: Refill time of workstations 17 and 18.

Begin	End	Time period
10:19:39	10:22:55	00:03:16
10:58:16	11:00:48	00:02:32
11:36:03	11:38:32	00:02:29
11:49:14	11:52:25	00:03:11
12:12:05	12:14:45	00:02:40
	Average: 00:02:50	

All the refill times of all the workstations are in Table B.5 in Appendix B.2.8.

B.2.5 Standard deviation

The standard deviation (STD) is the average amount of variability in the dataset. It means how much time each time period is away from the mean on average (Bhandari, 2020). Furthermore, the higher the standard deviation the higher the variability in the dataset.

The standard deviation per station has been calculated in Excel with the STDEV.S function with the range from the data from March and April. The standard deviation per (work)station can be seen in Figure B.29.

6	1	2	3	4	5	6	7		10	17	18	
4491	00:01:35	00:02:55	00:02:09	00:01:38	00:02:27	00:02:38	00:04:14		00:03:47	00:06:59	00:07:32	standard deviation

Figure B.29: Standard deviation for the relevant (work)stations.

All the standard deviations of all the workstations are in Table B.5 in Appendix B.2.8.

B.2.7 Utilization rates

The utilization rate (UT) is the percentage of time that a mould is on the (work)station. For the VGA Versa machine it is the time the machine could make lattice girders. The first number is the utilization rate where the breaks are excluded and the second number is the utilization rate where the breaks are included.

The utilization rates of the workstations have been calculated with the following formulas:

- Total available production time = sum of all the shifts where the time periods data is from
- Total transport time = transport time of previous station to current station * number of moulds produced
- Total real available production time = total available production time - total transport time
- Total production time = sum of all the time periods data
- Utilization rate = (total production time / total real available production time) * 100

The utilization rates together with the other information can be seen in Table B.3 and B.4. The utilization rate of the VGA Versa welding machine is calculated by looking at the percentage of time the machine is making lattice girders and this is from the measurements in Excel.

Table B.3: Utilization rates of the workstations with break times excluded.

(work)station	Total available production time (in days)	Total transport time (in days)	Total real available production time (in days)	Total production time (in days)	Utilization rate
2	25,27083	2,750301	22,52053	23,17311	97%
3	25,27083	1,727315	23,54352	21,03299	84%
4	25,27083	1,680271	23,59056	19,96884	80%
5	25,27083	2,455152	22,81568	20,93505	86%
6	25,27083	2,542237	22,7286	19,01213	79%
7	25,27083	1,653403	23,61743	16,12934	64%
7 (VGA Versa welding machine)	-	-	0,27557	0,19750	72%
8	25,27083	3,779931	21,4909	10,75495	47%
10	25,27083	1,502463	23,76837	14,55667	58%
17	25,27083	1,53712	23,73371	22,1594	88%
18	25,27083	2,910573	22,36026	20,28654	85%

Table B.4: Utilization rates of the workstations with break times included.

(work)station	Total available production time (in days)	Total transport time (in days)	Total real available production time (in days)	Total production time (in days)	Utilization rate
2	26,72917	2,750301	23,97887	23,17311	100%
3	26,72917	1,727315	25,00185	21,03299	89%

4	26,72917	1,680271	25,0489	19,96884	85%
5	26,72917	2,455152	24,27402	20,93505	92%
6	26,72917	2,542237	24,18693	19,01213	84%
7	26,72917	1,653403	25,07576	16,12934	68%
7 (VGA Versa welding machine)	-	-	0,27557	0,19750	72%
8	26,72917	3,779931	22,94924	10,75495	50%
10	26,72917	1,502463	25,2267	14,55667	61%
17	26,72917	1,53712	25,19205	22,1594	93%
18	26,72917	2,910573	23,81859	20,28654	91%

All the standard deviations of all the workstations are in Table B.5 in Appendix B.2.8.

B.2.8 Performance of the (work)stations

Table B.5 shows all the performances of the (work)stations.

Table B.5: All the different times per (work)station.

(work)station	Lead time (LT)	Process time (PT)	Transport time (TT)	Waiting time (WT)	Refill time (RT)	Standard deviation (STD)	Utilization rate (UT)
1	00:05:16	-	00:00:58	00:04:18	-	00:01:35	-
2	00:06:40	00:05:42 - 00:08:01	00:00:36	00:01:26 - 00:00:00	-	00:02:55	97-100%
3	00:06:08	00:06:57	00:00:35	00:00:00	-	00:02:09	84-89%
4	00:05:40	00:04:10	00:00:52	00:00:38	-	00:01:38	80-85%
5	00:06:10	00:05:06	00:00:53	00:00:11	-	00:02:27	86-92%
6	00:05:44	00:04:37	00:00:35	00:00:32	-	00:02:38	79-84%
7 (overall)	00:05:25	00:02:33	00:01:20	00:02:52	00:12:11	00:04:14	64-68%
7 (VGA versa)	00:08:06	00:05:48	00:00:00	00:02:18	00:12:11	00:00:57	72%
7 (placing crane)	00:05:25	00:02:33	00:01:20	00:02:52	-	00:04:14	64-68%
8	00:03:32	00:01:38	00:00:22	00:01:32	-	-	47-50%
9	00:02:27	-	00:00:32	00:01:55	-	-	-
10	00:04:45	00:01:38	00:01:21	00:01:46	-	00:03:47	58-61%
11 - 15	00:27:20	-	00:00:33 (from 15 to 17)	Not relevant	-	-	-
17	00:07:53	00:02:27	00:01:01	00:04:25	00:02:50 / 4.5 m3	00:06:59	88-93%
18	00:07:09	00:04:04	00:00:25	00:02:40	-	00:07:32	85-91%
19	00:02:20	00:00:41	00:00:31	00:00:58	-	-	-
20	00:01:29	-	00:01:16	00:00:13	-	-	-
24	00:00:43	-	-	00:00:43	-	-	-

Appendix C: Problems and causes

Section C.1 explains the problems and causes at workstation 2. Section C.2 explains the problems and causes at workstation 7. In the end Section C.3 explains the problems and causes at workstation 17 and 18.

C.1 Problems and causes workstation 2

This section gives a more detailed explanation of the problems and causes at workstation 2. The data that is used consists of 42 shifts from March and 28 shifts from April.

C.1.1 List of product damages that had to be repaired at workstation 2

In Figure C.2 to C.5 the list of product damages can be seen. When the shuttering slabs are towed out of the mould damages can be seen or can happen during the towing. These damages are documented. From this list the date and time it happened could be traced back.

legend	explanation
CEN	central stuffing box
CON	outline
SP	openings (EPS + GB)
PLB	shutteringtear
RK	casing
TR	lattice girder
WAP	reinforcement
OIV	remainge collapse things
PP	places where concrete is sticking to the mould
OV	remaining things

Figure C.1: Legend for the list of product damages.

weeknumber	projectnumber	shuttering slab number	reason + extra info	day	time	mouldnumber	x if a time exceeding occured
9	1203	4	CON	02/Mar	9.45	84	
9	6980	1302	MV drilling	04/Mar	17.13	42	x
9	6920	3611	PP, adding concrete mix	05/Mar	8.25	28	x
9	736	209	PP	03/Mar	14.55	67	
9	874	18	SP, saw	03/Mar	15.37	88	
9	855	12	PP, adding concrete mix	05/Mar	12.56	38	
9	855	14	PP, adding concrete mix	05/Mar	14.14	43	
10	1093	210	CON, saw	10/Mar	11.05	90	
10	1379	27	PP, adding concrete mix	10/Mar	12.51	75	
10	6922	990	OIV, MV drilling	10/Mar	13.42	36	
10	6922	989	CON, saw	10/Mar	13.50	35	
10	1005	72	PP, adding concrete mix	11/Mar	11.18	28	
10	583	854	PP				
11	6653	820	CEN, drilling	12/Mar	12.28	39	
11	858	23	PP, adding concrete mix	17/Mar	15.26	36	
11	872	79	PP, adding concrete mix	17/Mar	15.45	35	x
11	858	22	PP, adding concrete mix	17/Mar	15.45	35	x
11	6922	988 of 88 (rare 9 of een 0)	PP, adding concrete mix	17/Mar	17.09	7	
11	1096	3044	PP, adding concrete mix	17/Mar	17.09	7	
11	6922	987	PP, adding concrete mix	17/Mar	17.17	6	
11	1069	3098	PP, adding concrete mix				
11	980	301	PP, adding concrete mix (22-3)	16/Mar	16.56	59	
11	646	44	PP, adding concrete mix	18/Mar	14.36	39	x
12	1079	2051	PLB,	19/Mar	13.23	46	
12	1195	55	PP, adding concrete mix	23/Mar	9.59	41	
12	1195	53	PP, adding concrete mix	23/Mar	10.17	40	
12	1195	51	PP, adding concrete mix	23/Mar	10.35	39	
14	968	21	stack hit transport car	07/Apr	19.16		

Figure C.2: List of product damages at workstation 2 part 1.

weeknumber	projectnumber	shuttering slab number	reason + extra info	day	time	mouldnumber	x if a time exceeding occured
9	1203	4	CON	02/Mar	9.45	84	
9	6980	1302	MV drilling	04/Mar	17.13	42	x
9	6920	3611	PP, adding concrete mix	05/Mar	8.25	28	x
9	736	209	PP	03/Mar	14.55	67	
9	874	18	SP, saw	03/Mar	15.37	88	
9	855	12	PP, adding concrete mix	05/Mar	12.56	38	
9	855	14	PP, adding concrete mix	05/Mar	14.14	43	
10	1093	210	CON, saw	10/Mar	11.05	90	
10	1379	27	PP, adding concrete mix	10/Mar	12.51	75	
10	6922	990	OIV, MV drilling	10/Mar	13.42	36	
10	6922	989	CON, saw	10/Mar	13.50	35	
10	1005	72	PP, adding concrete mix	11/Mar	11.18	28	
10	583	854	PP				
11	6653	820	CEN, drilling	12/Mar	12.28	39	
11	858	23	PP, adding concrete mix	17/Mar	15.26	36	
11	872	79	PP, adding concrete mix	17/Mar	15.45	35	x
11	858	22	PP, adding concrete mix	17/Mar	15.45	35	x
11	6922	988 of 88 (rare 9 of een 0)	PP, adding concrete mix	17/Mar	17.09	7	
11	1096	3044	PP, adding concrete mix	17/Mar	17.09	7	
11	6922	987	PP, adding concrete mix	17/Mar	17.17	6	
11	1069	3098	PP, adding concrete mix				
11	980	301	PP, adding concrete mix (22-3)	16/Mar	16.56	59	
11	646	44	PP, adding concrete mix	18/Mar	14.36	39	x
12	1079	2051	PLB,	19/Mar	13.23	46	
12	1195	55	PP, adding concrete mix	23/Mar	9.59	41	
12	1195	53	PP, adding concrete mix	23/Mar	10.17	40	
12	1195	51	PP, adding concrete mix	23/Mar	10.35	39	
14	968	21	stack hit transport car	07/Apr	19.16		

Figure C.3: List of product damages at workstation 2 part 2.

weeknumber	projectnumber	shuttering slab number	reason + extra info	day	time	mouldnumber	x if a time exceeding occured
14	968	23	stack hit transport car	07/Apr	19.29	43	x
14	1280	3	PP, adding concrete mix	09/Apr	12.34	48	
14	1025	8	PP, adding concrete mix	09/Apr	13.22	67	x
14	1011	50	PP, adding concrete mix	09/Apr	9.37	39	x
14	518	1113	falling defence is skewed	08/Apr	13.32	44	
14	872	120	MV-mouth, drilling	09/Apr	13.22	67	
14	872	105	MV-mouth, drilling	09/Apr	9.04	17	x
14	964	155	PP, adding concrete mix	08/Apr	12.07	16	x
15	6920	2114	PP, adding concrete mix, 10:20	14/Apr	10.15	70	x
15	6755	636	PP, adding concrete mix, 10:46	14/Apr	10.43	67	x
15	880	326	PP, adding concrete mixadding concrete mix, 11:00	14/Apr	10.55	66	x
15	1321	1	PP, adding concrete mix, 11:20	14/Apr	11.16	64	x
15	1321	3	PP, adding concrete mix, 11:40	14/Apr	11.35	89	x
15	1351	17	PP, adding concrete mix, 13:05	14/Apr	12.57	84	x
15	1351	19	PP, adding concrete mix, 13:25	14/Apr	13.18	82	x
15	1079	3003	PP, adding concrete mix, 14:00	14/Apr	13.51	60	x
15	1287	10	PP, adding concrete mix, 14:25	14/Apr	14.20	56	
15	1287	8	PP, adding concrete mix, 14:25	14/Apr	14.20	56	
15	558	322	PP, adding concrete mix	14/Apr	16.49	31	x
15	1432	209	PP, adding concrete mix	14/Apr	16.18	28	x
15	685	1098	PP, adding concrete mix	14/Apr	17.57	3	x
15	685	1099	PP, adding concrete mix	14/Apr	19.08	6	x
15	361	409	PP, adding concrete mix	14/Apr	17.57	3	x
15	361	408	PP, adding concrete mix	14/Apr	18.44	4	x
15	1181	9	PP, adding concrete mix, 8:36				
15	1062	334	PP, adding concrete mix, 11:40	15/Apr	11.28	33	x
15	978	125	PP, adding concrete mix	13/Apr	8.41	15	x
15	1096	4094	CON, saw	13/Apr	9.31	18	x

Figure C.4: List of product damages at workstation 2 part 3.

weeknumber	projectnumber	shuttering slab number	reason + extra info	day	time	mouldnumber	x if a time exceeding occured
15	1096	4093	CON, saw	13/Apr	9.42	37	
15	6922	1137	CON, saw	13/Apr	6.06	33	x
15	912	208	PP, adding concrete mix, mal 82	13/Apr	15.40	82	x
15	912	206	PP, adding concrete mix, mal 84	13/Apr	16.05	84	
15	912	202	PP, adding concrete mix, mal 87	13/Apr	16.33	87	
15	685	1104	CEN, repaired	13/Apr	14.58	71	
15	1286	302	PP, adding concrete mix, 14:20, mould 67	13/Apr	14.15	67	x
15	558	318	PP, adding concrete mix	13/Apr	12.42	52	x
15	1096	4107	PP, adding concrete mix, 16:00, mould 19	13/Apr	10.51	19	x
15	880	332	PP, adding concrete mix, mould 56	13/Apr	17.36	56	x
15	880	331	PP, adding concrete mix	13/Apr	18.30	59	x
15	6755	643	PP, adding concrete mix	13/Apr	19.59	78	x
15	912	203	PP, adding concrete mix, mould 86	13/Apr	16.23	86	
16	1104	203	CON, saw	19/Apr	10.14	78	x
16	1226	21	PP, adding concrete mix, 13:09	23/Apr	13.05	59	

Figure C.5: List of product damages at workstation 2 part 4.

	number of moulds	number of moulds where a time exceeding occured
total number	67	36
percentage	100	53,73134328

Figure C.6: Percentage of damages that caused a time exceeding.

C.1.2 Analysis of causes

In Figure C.7 a part of the analysis is shown of the causes for the time exceedings. From the raw data the times are put behind the time exceedings and then the cause for the time exceedings is put behind it.

ochtend 7 april		middag 7 april	
workstation 2		workstation 2	
00:06:47		00:06:51	
00:07:59	3 slabs	00:05:37	
00:05:41		00:04:54	
00:05:27		00:05:19	
00:06:00		00:06:31	
00:05:30		00:06:47	
00:06:47		00:07:20	
00:07:00		00:06:52	
00:06:47		00:06:39	
00:06:23		00:04:17	
00:06:47		00:07:07	
00:05:39		00:16:41	unknown
00:05:32		00:08:06	3 slabs
00:06:47		00:05:37	
00:06:44		00:04:18	
00:10:23	unknown	00:09:51	unknown
00:07:03		00:04:32	
00:06:47		00:12:58	unknown
00:06:47		00:13:26	3 slabs
00:06:46		00:16:02	unknown
00:04:06		00:36:06	pauze
00:06:47		00:06:47	
00:06:10		00:04:54	

Figure C.7: Part of the analysis of the causes for the time exceedings of the 7th of April.

With this information the total amount of causes can be calculated together with the amount of time that is lost per cause. The total time exceeded is calculated by subtracting the aloud 7.5 minutes per mould from the total time per cause. Furthermore, the average can be calculated by dividing the total exceeded time by the total number of moulds of that cause. This can be seen in Figure C.8 and C.9.

	cause			cause			cause	
march	total number of breaks	33	arpil	total number of breaks	16	together	total number of breaks	49
	total number of shiftchange	3		total number of shiftchange	2		total number of shiftchange	5
	total number of 3 slabs	45		total number of 3 slabs	59		total number of 3 slabs	104
	total number of 4 slabs	9		total number of 4 slabs	3		total number of 4 slabs	12
	total number of 5 slabs	1		total number of 5 slabs	0		total number of 5 slabs	1
	total number of unknown	114		total number of unknown	145		total number of unknown	259
	total number of product damages	5		total number of product damages	31		total number of product damages	36
	total sum of breaks	10:44:07		total sum of breaks	06:00:59		total sum of breaks	0,697986
	total sum of shiftchange	00:26:28		total sum of shiftchange	00:31:59		total sum of shiftchange	0,04059
	total sum of 3 slabs	07:38:07		total sum of 3 slabs	09:26:17		total sum of 3 slabs	0,711389
	total sum of 4 slabs	01:18:03		total sum of 4 slabs	00:41:38		total sum of 4 slabs	0,083113
	total sum of 5 slabs	00:07:55		total sum of 5 slabs	00:00:00		total sum of 5 slabs	0,005498
	total sum of unknown	21:32:59		total sum of unknown	23:58:24		total sum of unknown	1,896794
	total sum of product damages	01:01:13		total sum of product damages	06:49:00		total sum of product damages	07:50:13

Figure C.8: Causes and time information.

cause	average amount of time per cause	total time exceeded per cause	average time exceeding per cause
breaks	00:20:31	10:37:36	00:13:01
shiftchange	00:11:41	00:20:57	00:04:11
3 slabs	00:09:51	04:04:24	00:02:21
4 slabs	00:09:58	00:29:41	00:02:28
5 slabs	00:07:55	00:00:25	00:00:25
unknown	00:10:33	13:08:53	00:03:03
product damages	00:13:04	03:20:13	00:05:34

Figure C.9: Time exceeded per cause

C.2 Problems and causes workstation 7

This section gives a more detailed explanation of the problems and causes at workstation 7. The data that is used consists of 42 shifts from March and 28 shifts from April.

C.2.1 Steel coil changeovers, welding blocks changeovers and machine failures

In Figure C.10 to C.15 the list of causes is given. This list is made with the information from the Teams channel of Company X.

Datum	tijd	wat
01/03/2021	09:50:00	steel coil changeover
01/03/2021	14:54:00	steel coil changeover
01/03/2021	15:23:00	steel coil changeover
01/03/2021	15:43:00	steel coil changeover
01/03/2021	18:56:00	steel coil changeover
02/03/2021	11:34:00	steel coil changeover
02/03/2021	14:53:00	steel coil changeover
02/03/2021	17:14:00	steel coil changeover
02/03/2021	18:24:00	lasblokken vervangen
02/03/2021	18:26:00	steel coil changeover
03/03/2021	07:36:00	steel coil changeover
03/03/2021	13:08:00	steel coil changeover
03/03/2021	13:38:00	steel coil changeover
03/03/2021	16:03:00	steel coil changeover
03/03/2021	20:18:00	steel coil changeover
03/03/2021	21:47:00	welding blocks changed
04/03/2021	10:54:00	steel coil changeover
04/03/2021	13:19:00	steel coil changeover
04/03/2021	14:07:00	steel coil changeover
04/03/2021	16:52:00	steel coil changeover
04/03/2021	16:59:00	steel coil changeover
04/03/2021	20:51:00	steel coil changeover
05/03/2021	10:59:00	steel coil changeover
05/03/2021	14:37:00	steel coil changeover
09/03/2021	07:14:00	versa ligt eruit
10/03/2021	00:07:00	steel coil changeover
10/03/2021	11:30:00	steel coil changeover
10/03/2021	12:22:00	steel coil changeover

Figure C.10: Part 1 of the list of causes.

Datum	tijd	wat
11/03/2021	07:40:00	steel coil changeover
11/03/2021	11:31:00	steel coil changeover
11/03/2021	13:19:00	steel coil changeover
11/03/2021	18:25:00	steel coil changeover
11/03/2021	18:25:00	steel coil changeover
11/03/2021	21:36:00	rond 8 lostrekken
11/03/2021	22:33:00	rond 8 zit vast
12/03/2021	14:52:00	steel coil changeover
15/03/2021	07:00:00	steel coil changeover
15/03/2021	08:26:00	steel coil changeover
15/03/2021	11:23:00	steel coil changeover
15/03/2021	13:56:00	steel coil changeover
16/03/2021	06:18:00	steel coil changeover
16/03/2021	11:00:00	steel coil changeover
16/03/2021	17:15:00	steel coil changeover
16/03/2021	21:43:00	steel coil changeover
17/03/2021	00:11:00	steel coil changeover
17/03/2021	09:41:00	steel coil changeover
17/03/2021	09:50:00	buigcilinder eruit
17/03/2021	10:16:00	assen eruit
17/03/2021	15:32:00	steel coil changeover
18/03/2021	07:18:00	steel coil changeover
18/03/2021	15:17:00	steel coil changeover
18/03/2021	20:39:00	steel coil changeover
19/03/2021	09:05:00	steel coil changeover
19/03/2021	09:05:00	steel coil changeover
19/03/2021	11:17:00	steel coil changeover
19/03/2021	11:18:00	steel coil changeover

Figure C.11: Part 2 of the list of causes.

Datum	tijd	wat
22/03/2021	16:24:00	steel coil changeover
22/03/2021	19:01:00	steel coil changeover
22/03/2021	19:01:00	steel coil changeover
22/03/2021	20:36:00	steel coil changeover
22/03/2021	23:19:00	steel coil changeover
23/03/2021	20:04:00	steel coil changeover
23/03/2021	20:45:00	steel coil changeover
23/03/2021	20:46:00	steel coil changeover
24/03/2021	07:54:00	steel coil changeover
24/03/2021	13:11:00	steel coil changeover
24/03/2021	19:27:00	steel coil changeover
24/03/2021	22:14:00	steel coil changeover
25/03/2021	11:36:00	steel coil changeover
25/03/2021	19:06:00	steel coil changeover
26/03/2021	00:06:00	steel coil changeover
26/03/2021	06:38:00	steel coil changeover
29/03/2021	07:39:00	steel coil changeover
29/03/2021	21:57:00	steel coil changeover
29/03/2021	23:10:00	steel coil changeover
30/03/2021	00:48:00	steel coil changeover
30/03/2021	07:16:00	steel coil changeover
30/03/2021	08:59:00	cooling fluid leaking
30/03/2021	10:20:00	steel coil changeover
30/03/2021	22:22:00	steel coil changeover
30/03/2021	23:14:00	steel coil changeover
31/03/2021	10:10:00	steel coil changeover
31/03/2021	11:14:00	steel coil changeover
31/03/2021	20:53:00	steel coil changeover

Figure C.12: Part 3 of the list of causes.

Datum	tijd	wat
01/04/2021	06:51:00	bolts centring tongs broken
01/04/2021	07:13:00	steel coil changeover
01/04/2021	08:33:00	steel coil changeover
01/04/2021	11:50:00	steel coil changeover
01/04/2021	11:57:00	steel coil changeover
06/04/2021	09:29:00	steel coil changeover
06/04/2021	09:15:00	steel coil changeover
06/04/2021	16:18:00	steel coil changeover
06/04/2021	19:55:00	steel coil changeover
07/04/2021	12:28:00	steel coil replacement
07/04/2021	12:47:00	steel coil changeover
07/04/2021	19:51:00	steel coil changeover
08/04/2021	07:33:00	steel coil changeover
08/04/2021	16:00:00	steel coil changeover
08/04/2021	16:01:00	steel coil changeover
08/04/2021	17:08:00	steel coil changeover
08/04/2021	20:06:00	steel coil changeover
09/04/2021	07:42:00	steel coil changeover
12/04/2021	11:33:00	steel coil changeover
12/04/2021	11:34:00	steel coil changeover
12/04/2021	14:27:00	steel coil changeover
12/04/2021	16:09:00	steel coil changeover
12/04/2021	17:05:00	steel coil changeover
12/04/2021	19:49:00	steel coil changeover
13/04/2021	11:34:00	steel coil changeover
13/04/2021	16:45:00	steel coil changeover
13/04/2021	18:47:00	steel coil changeover
14/04/2021	08:02:00	buig ding eruit

Figure C.13: Part 4 of the list of causes.

Datum	tijd	wat
14/04/2021	12:20:00	steel coil changeover
14/04/2021	13:53:00	steel coil changeover
14/04/2021	19:44:00	steel coil changeover
14/04/2021	21:37:00	steel coil changeover
14/04/2021	22:54:00	steel coil changeover
15/04/2021	11:43:00	steel coil changeover
15/04/2021	19:01:00	steel coil changeover
16/04/2021	06:22:00	steel coil changeover
16/04/2021	07:05:00	steel coil changeover
16/04/2021	08:55:00	steel coil changeover
19/04/2021	10:16:00	steel coil changeover
19/04/2021	22:06:00	steel coil changeover
19/04/2021	22:06:00	steel coil changeover
19/04/2021	22:25:00	steel coil changeover
20/04/2021	06:34:00	steel coil changeover
20/04/2021	08:34:00	steel coil changeover
20/04/2021	20:25:00	steel coil changeover
20/04/2021	23:20:00	steel coil changeover
20/04/2021	23:20:00	steel coil changeover
21/04/2021	01:36:00	steel coil changeover
21/04/2021	13:09:00	steel coil changeover
21/04/2021	16:55:00	steel coil changeover
21/04/2021	23:10:00	steel coil changeover
21/04/2021	23:19:00	steel coil changeover
22/04/2021	00:28:00	steel coil changeover
22/04/2021	14:44:00	steel coil changeover
22/04/2021	21:28:00	steel coil changeover
22/04/2021	21:28:00	steel coil changeover

Figure C.14: Part 5 of the list of causes.

Datum	tijd	wat
22/04/2021	21:37:00	weld broken of steel coils
23/04/2021	07:23:00	steel coil changeover
23/04/2021	08:52:00	steel coil changeover
28/04/2021	06:46:00	steel coil changeover

Figure C.15: Part 6 of the list of causes.

C.2.2 Analysis of causes

In Figure C.16 a part of the analysis can be seen to find other causes for the time exceedings at workstation 7. For every time exceeding first the time when this happens from the raw data is put behind the time exceeding. The next step is to look in the GPA software program what happens at the time exceeding. When the time exceeding happens due to a time exceeding at workstation 17 then "storten" is put behind it. Furthermore, when the time exceeding happens and workstation 8 is free, then it is assumed that the mould could have gone to workstation 8. "Niet doordrukken van 8" is then put behind the time exceeding. All the other time exceedings cannot be coupled to a cause. These are labeled with "unknown".

ochtend 1 april		ochtend 6 april	
U7		U7	
00:07:49	storten	00:04:10	
00:07:41	storten	00:03:02	
00:04:20		00:08:09	unknown
00:05:13		00:04:57	
00:09:19	storten	00:03:12	
00:11:51	storten	00:03:35	
00:18:23	steel coil changeover	00:04:13	
00:07:28		00:03:20	
00:05:20		00:03:34	
00:03:40		00:03:39	
00:05:39		00:03:41	
00:05:54		00:03:45	
00:04:56		00:04:28	
00:07:18		00:03:37	
00:05:57		00:03:51	
00:09:11	unknown	00:02:50	
00:14:13	steel coil changeover	00:18:31	steel coil changeover
00:08:39	niet doordrukken van 8	00:11:57	steel coil changeover
00:04:50		00:03:33	
00:06:34		00:05:42	
00:05:27		00:03:37	
00:08:37	unknown	00:09:39	unknown
00:14:08	niet doordrukken van 8	00:10:43	niet doordrukken van 8
00:05:34		00:03:00	

Figure C.16: Part of the analysis for the causes of workstation 7.

In Figure C.17 all the causes are summed up and also the corresponding times. Besides this the average time exceeded per cause is calculated by dividing the total exceeded time with the total number of the corresponding cause. The total exceeded time is calculated with the formula: total time in days - (total number * 00:07:30).

march	total time in days	total exceeded time	total number	average time per cause
number of steel coil changeovers	0,578472222	07:15:30	53	00:08:13
number of not pressing button	0,552002315	06:07:23	57	00:06:27
number of unknown	1,010451389	08:15:03	128	00:03:52
number of cause at 17	0,953773148	09:53:26	104	00:05:42
number of failure machine	0,082893519	01:06:52	7	00:09:33
number of changeover welding	0,051550926	00:44:14	4	00:11:04
april	**total time in days**	**total exceeded time**	**total number**	**average time per cause**
number of steel coil changeovers	0,472696759	01:50:41	76	00:01:27
number of not pressing button	0,729155093	11:59:59	44	00:16:22
number of unknown	1,05005787	09:27:05	126	00:04:30
number of cause at 17	0,266585648	02:38:53	30	00:05:18
number of failure machine	0,129340278	01:58:45	9	00:13:12
number of changeover welding	0	00:00:00	0	00:00:00
together	**total time in days**	**total exceeded time**	**total number**	**average time per cause**
number of steel coil changeovers	1,051168981	09:06:11	129	00:04:14
number of not pressing button	1,281157407	18:07:22	101	00:10:46
number of unknown	2,060509259	17:42:08	254	00:04:11
number of cause at 17	1,220358796	12:32:19	134	00:05:37
number of failure machine	0,212233796	03:05:37	16	00:11:36
number of changeover welding	0,051550926	00:44:14	4	00:11:04

Figure C.17: Number of causes with the corresponding times.

C.3 Problems and causes workstation 17 and 18

This section gives a more detailed explanation of the problems and causes at workstation 17 and 18.

C.3.1 Concrete mix deliveries

The days of the deliveries of concrete mix where data was known from can be seen in Figure C.18. Figure C.19 shows one delivery ticket. Furthermore, on a day almost every 45-60 minutes a delivery is done.

morning 5th of March	morning 1th of April
afternoon 9th of March	morning 7th of April
morning 11th of March	afternoon 7th of April
afternoon 11th of March	morning 8th of April
morning 17th of March	afternoon 8th of April
afternoon 17th of March	morning 12th of April
morning 22th of March	morning 13th of April
afternoon 22th of March	afternoon 13th of April
morning 23th of March	morning 16th of April
afternoon 23th of March	morning 19th of April
afternoon 24th of March	afternoon 19th of April
afternoon 25th of March	morning 20th of April
morning 29th of March	afternoon 20th of April
afternoon 29th of March	afternoon 21th of April
morning 30th of March	morning 22th of April
afternoon 30th of March	afternoon 22th of April
morning 31th of March	morning 23th of April
afternoon 31th of March	afternoon 28th of April

Figure C.18: Days where data was known.

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Figure C.19: A delivery ticket from the 26th of May.

C.3.2 Analysis of causes

Figure C.20 shows a part of the data analysis from the morning of March the 5th. The first column shows the time periods of the moulds at workstation 17 and the second column that of workstation 18. From the raw data the time that the time exceeding happens is put behind the corresponding time exceeding. With the information from the delivery tickets the cause “late delivery of concrete mix” is put behind the corresponding time exceedings. Furthermore, for the cause “possibly a more complex mould” this is also done. The rest of the time exceedings are labeled as unknown, because nothing is known about those time exceedings.

ochtend 5-3-2021			
00:07:55		00:07:26	pauze
00:05:18		00:03:15	
00:08:51		00:08:22	geen betonmix
00:03:36		00:03:08	
00:07:46		00:07:13	unknown
00:03:51		00:03:11	
00:38:38		00:39:37	geen betonmix
00:03:57		00:03:22	
00:03:55		00:02:51	
00:07:56		00:07:22	hogere moeilijkheid mal
00:04:54		00:03:07	
00:02:49		00:02:22	
00:18:56		00:18:28	geen betonmix
00:02:58		00:02:14	
00:08:04		00:07:33	hogere moeilijkheid mal
00:02:35		00:02:49	
00:03:13		00:02:44	
00:23:25		00:25:15	geen betonmix
00:07:01		00:06:31	
00:05:18		00:04:48	
00:10:25		00:11:01	geen betonmix
00:07:48		00:02:52	geen betonmix
00:16:37		00:14:54	pauze
01:37:44		01:36:36	geen betonmix
00:03:07		00:02:36	
00:04:16		00:02:53	
00:04:40		00:04:17	

Figure C.20: Part of analysis of causes for time exceedings at workstation 17 and 18.

With all the causes added to the corresponding time exceedings the causes are summed up (see Figure C.21). Besides this the number of times means the number of times the cause happened. The time in days means the time exceedings all summed up together. Furthermore, the number of measurements means the number of time periods that are summed up (time periods from 17 and 18). This is used to get an average time exceeding for workstation 17 and 18. With all this data the average time that is lost (average exceeded time in Figure C.21) per time that the corresponding cause happens is calculated. This is done by dividing the lost time (time exceeded in Figure C.21) by the number of measurements.

march	what	number of times	time in days	number of measurements	average time
	no conrete mix	159	3,787	301	00:18:07
	possibly a more complex mold	57	0,796	100	00:11:28
	unknown	57	0,997	103	00:13:57

april	what	number of times	time in days	number of measurements	average time
	no conrete mix	177	3,947	322	00:17:39
	possibly a more complex mold	41	0,509	72	00:10:11
	unknown	60	0,796	99	00:11:35

march + april	what	number of times	time in days	number of measurements	time exceeded	average exceeded time
	no conrete mix	336	7,733	623	4,488657407	00:10:23
	possibly a more complex mold	98	1,305	172	0,409513889	00:03:26
	unknown	117	1,794	202	0,741875	00:05:17

Figure C.21: Causes with time information.

Appendix D: Solution approach

This Appendix explains the solution approach in more detail. Section D.1 gives the delivery of concrete mix calculations. Furthermore, section D.2 gives the calculations for the solutions for workstation 7.

D.1: Concrete mix delivery calculations

In Table D.1 the calculations for the amount of concrete mix on average per mould can be seen together with the amount that can be in a full machine and in a full truck. Furthermore, in Table D.2 it can be seen how long the concrete mix truck has to travel and how long it takes to fill the truck with concrete mix and in Table D.3 and D.4 the possible future traveling and filling times can be seen for solution 1, 3, 4 and 5 and 2 respectively.

Table D.1: Average amount of concrete mix per mould.

	average mould	minimum mould	maximum mould
maximum surface area mould (mm2)	36600000	36600000	36600000
average utilization rate of surface area mould (%)	80	80	80
average thickness of shuttering slab (mm)	65	50	80
amount of concrete mix needed (mm3)	1903200000	1464000000	2342400000
amount of concrete mix needed (m3)	1,9032	1,464	2,3424
concrete mix that can be in machine (m3)	4,5	4,5	4,5
amount of moulds per full machine	2,36443884	3,073770492	1,921106557
concrete mix in truck (m3)	9	9	9
amount of moulds per full truck	4,72887768	6,147540984	3,842213115

Table D.2: Current travel time and filling time of the concrete mix truck.

What	Time	What	Time period
leaving the factory	11:52:58	outward journey	00:02:57
start filling	11:55:55	filling truck	00:12:46
end filling	12:08:41	return journey	00:03:19
arriving at factory	12:12:00	**total: 0:19:02**	
		if there is a truck just in front of the truck: 0:31:48 (+ filling time of truck)	

Table D.3: Future travel time and filling time solution 1, 3, 4 and 5.

What		Time period
outward journey		00:02:57
filling truck	weighing second batch + blending first batch (3 m3)	00:03:00
	weighing third batch + blending second batch (3 m3)	00:03:00
	blending third batch (3 m3)	00:03:00
	filling (3 times)	3*00:00:15 = 00:00:45
return journey		00:03:19
	Total time truck is gone: 00:16:01	

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Table D.4: Future travel time and filling time solution 2.

What		Time period
outward journey		00:02:57
filling truck	weighing second batch + blending first batch (3 m3)	00:03:00
	weighing third batch + blending second batch (3 m3)	00:03:00
	Weighing fourth batch + blending third batch (3 m3)	00:03:00
	Blending fourth batch (3m3)	00:03:00
	filling (4 times)	4*00:00:15 = 00:00:45
return journey		00:03:19
	Total time truck is gone: 00:19:16	

D.2: Solution calculations workstation 7

This section gives a more detailed explanation of the solutions for workstation 7.

D.2.1: Solution 1 calculations

We see in Figure D.1 the lead times at workstation 7 excluding transport times and waiting times for other (work)stations. The inventory column means the amount of lattice girders in inventory and the second row means the number of lattice girders that have to be placed in the mould.

lead times	inventory	# of lattice girders in Mould 1												
		4	5	6	7	8	9	10	11	12	13	14	15	16
	0	00:03:41	00:04:11	00:04:51	00:05:41	00:06:11	00:06:51	00:07:41	00:08:11	00:08:50	00:09:41	00:10:10	00:10:50	00:11:41
	1	00:03:01	00:03:31	00:04:11	00:05:01	00:05:31	00:06:11	00:07:01	00:07:31	00:08:10	00:09:01	00:09:30	00:10:10	00:11:01
	2	00:02:21	00:02:51	00:03:31	00:04:21	00:04:51	00:05:31	00:06:21	00:06:51	00:07:30	00:08:21	00:08:50	00:09:30	00:10:21
	3	00:01:41	00:02:11	00:02:51	00:03:41	00:04:11	00:04:51	00:05:41	00:06:11	00:06:50	00:07:41	00:08:10	00:08:50	00:09:41
	4	00:01:41	00:01:41	00:02:11	00:03:01	00:03:31	00:04:11	00:05:01	00:05:31	00:06:10	00:07:01	00:07:30	00:08:10	00:09:01
	5	00:01:41	00:01:41	00:01:41	00:02:31	00:02:51	00:03:31	00:04:21	00:04:51	00:05:30	00:06:21	00:06:50	00:07:30	00:08:21
	6	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:51	00:03:41	00:04:11	00:04:50	00:05:41	00:06:10	00:06:50	00:07:41
	7	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:31	00:04:10	00:05:01	00:05:30	00:06:10	00:07:01
	8	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:30	00:04:21	00:04:50	00:05:30	00:06:21
	9	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:04:11	00:04:10	00:04:50	00:05:42
	10	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:04:11	00:04:10	00:04:10	00:05:02
	11	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:04:11	00:04:10	00:04:10	00:05:02
	12	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:04:11	00:04:10	00:04:10	00:05:02
	13	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:04:11	00:04:10	00:04:10	00:05:02

Figure D.1: Lead times of moulds with a certain number of lattice girders to be placed with inventory levels.

We see the calculation in Figure D.2. It takes 50 seconds on average to place a set of lattice girders and it takes 40 seconds on average to make a lattice girder. The amount of lattice girders per placement is on average 2.7, but for simplicity we take 3. The VGA Versa machine will always make up to 3 lattice girders to be in inventory for placement. This means that when there are 0 in inventory then 3 will first be made before placement. During placement 1.25 lattice girders can be made and after the placemet 1.75 have to be made for example before another placement can be done.

0-16	making 3	placing + making 3	placing + making 3	placing + making 3	placing + making 3	placing + making 1	placing	total time
	00:02:00	00:00:50	00:00:50	00:00:50	00:00:50	00:00:50	00:00:50	0:11:41
		00:01:10	00:01:10	00:01:10	00:01:10			
1--16	making 2	placing + making 3	placing + making 3	placing + making 3	placing + making 3	placing + making 1	placing	total time
	00:01:20	00:00:50	00:00:50	00:00:50	00:00:50	00:00:50	00:00:50	0:11:01
		00:01:10	00:01:10	00:01:10	00:01:10			
2--16	making 1	placing + making 3	placing + making 3	placing + making 3	placing + making 3	placing + making 1	placing	total time
	00:00:40	00:00:50	00:00:50	00:00:50	00:00:50	00:00:50	00:00:50	0:10:21
		00:01:10	00:01:10	00:01:10	00:01:10			
3--16	making 0	placing + making 3	placing + making 3	placing + making 3	placing + making 3	placing + making 1	placing	total time
	00:00:00	00:00:50	00:00:50	00:00:50	00:00:50	00:00:50	00:00:50	0:09:41
		00:01:10	00:01:10	00:01:10	00:01:10			
4--16	making 0	placing + making 2	placing + making 3	placing + making 3	placing + making 3	placing + making 1	placing	total time
	00:00:00	00:00:50	00:00:50	00:00:50	00:00:50	00:00:50	00:00:50	0:09:01
		00:00:30	00:01:10	00:01:10	00:01:10			

Figure D.2: Lead time calculations.

In Figure D.3 the lead times can be seen when a refill of 00:12:11 (current situation) has to be done. we see that the work can only be done in 7.5 minutes when there are as many lattice girders in inventory as that have to be placed. If there are 1 or more lattice girders in inventory than these can be placed during the refill time. Furthermore, for example when there are 6 lattice girders then these can already be placed in the refill time. For Figure D.3 and D.4 this is the same. However the refill times are different and for a refill time of 00:04:12 an inventory of one less than the amount of lattice girders is sometimes possible to still keep within the 7.5 minutes.

refill time	inventory	# of lattice girders in Mould 1												
		4	5	6	7	8	9	10	11	12	13	14	15	16
00:12:11	0	00:15:52	00:16:22	00:17:02	00:17:52	00:18:22	00:19:02	00:19:52	00:20:22	00:21:01	00:21:52	00:22:21	00:23:01	00:23:52
	1	00:15:01	00:15:52	00:16:22	00:17:02	00:17:52	00:18:22	00:19:02	00:19:52	00:20:22	00:21:01	00:21:52	00:22:21	00:23:01
	2	00:14:21	00:15:01	00:15:52	00:16:22	00:17:02	00:17:52	00:18:22	00:19:02	00:19:52	00:20:22	00:21:01	00:21:52	00:22:21
	3	00:13:41	00:14:21	00:15:01	00:15:52	00:16:22	00:17:02	00:17:52	00:18:22	00:19:02	00:19:52	00:20:22	00:21:01	00:21:52
	4	00:01:41	00:13:41	00:14:21	00:15:01	00:15:52	00:16:22	00:17:02	00:17:52	00:18:22	00:19:02	00:19:52	00:20:22	00:21:01
	5	00:01:41	00:01:41	00:13:41	00:14:21	00:15:01	00:15:52	00:16:22	00:17:02	00:17:52	00:18:22	00:19:02	00:19:52	00:20:22
	6	00:01:41	00:01:41	00:01:41	00:13:41	00:14:21	00:15:01	00:15:52	00:16:22	00:17:02	00:17:52	00:18:22	00:19:02	00:19:52
	7	00:01:41	00:01:41	00:01:41	00:02:31	00:13:41	00:14:21	00:15:01	00:15:52	00:16:22	00:17:02	00:17:52	00:18:22	00:19:02
	8	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:13:41	00:14:21	00:15:01	00:15:52	00:16:22	00:17:02	00:17:52	00:18:22
	9	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:13:41	00:14:21	00:15:01	00:15:52	00:16:22	00:17:02	00:17:52
	10	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:13:41	00:14:21	00:15:01	00:15:52	00:16:22	00:17:02
	11	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:13:41	00:14:21	00:15:01	00:15:52	00:16:22
	12	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:13:41	00:14:21	00:15:01	00:15:52
	13	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:04:11	00:13:41	00:14:21	00:15:01

Figure D.3: Lead times with refill time of 00:12:11.

refill time	inventory	# of lattice girders in Mould 1												
		4	5	6	7	8	9	10	11	12	13	14	15	16
00:09:11	0	00:12:52	00:13:22	00:14:02	00:14:52	00:15:22	00:16:02	00:16:52	00:17:22	00:18:01	00:18:52	00:19:21	00:20:01	00:20:52
	1	00:12:01	00:12:52	00:13:22	00:14:02	00:14:52	00:15:22	00:16:02	00:16:52	00:17:22	00:18:01	00:18:52	00:19:21	00:20:01
	2	00:11:21	00:12:01	00:12:52	00:13:22	00:14:02	00:14:52	00:15:22	00:16:02	00:16:52	00:17:22	00:18:01	00:18:52	00:19:21
	3	00:10:41	00:11:21	00:12:01	00:12:52	00:13:22	00:14:02	00:14:52	00:15:22	00:16:02	00:16:52	00:17:22	00:18:01	00:18:52
	4	00:01:41	00:10:41	00:11:21	00:12:01	00:12:52	00:13:22	00:14:02	00:14:52	00:15:22	00:16:02	00:16:52	00:17:22	00:18:01
	5	00:01:41	00:01:41	00:10:41	00:11:21	00:12:01	00:12:52	00:13:22	00:14:02	00:14:52	00:15:22	00:16:02	00:16:52	00:17:22
	6	00:01:41	00:01:41	00:01:41	00:10:41	00:11:21	00:12:01	00:12:52	00:13:22	00:14:02	00:14:52	00:15:22	00:16:02	00:16:52
	7	00:01:41	00:01:41	00:01:41	00:02:31	00:10:41	00:11:21	00:12:01	00:12:52	00:13:22	00:14:02	00:14:52	00:15:22	00:16:02
	8	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:10:41	00:11:21	00:12:01	00:12:52	00:13:22	00:14:02	00:14:52	00:15:22
	9	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:10:41	00:11:21	00:12:01	00:12:52	00:13:22	00:14:02	00:14:52
	10	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:10:41	00:11:21	00:12:01	00:12:52	00:13:22	00:14:02
	11	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:10:41	00:11:21	00:12:01	00:12:52	00:13:22
	12	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:10:41	00:11:21	00:12:01	00:12:52
	13	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:04:11	00:10:41	00:11:21	00:12:01

Figure D.4: Lead times with refill time of 00:09:11.

refill time	inventory	# of lattice girders in Mould 1												
		4	5	6	7	8	9	10	11	12	13	14	15	16
00:04:12	0	00:07:53	00:08:23	00:09:03	00:09:53	00:10:23	00:11:03	00:11:53	00:12:23	00:13:02	00:13:53	00:14:22	00:15:02	00:15:53
	1	00:07:02	00:07:53	00:08:23	00:09:03	00:09:53	00:10:23	00:11:03	00:11:53	00:12:23	00:13:02	00:13:53	00:14:22	00:15:02
	2	00:06:22	00:07:02	00:07:53	00:08:23	00:09:03	00:09:53	00:10:23	00:11:03	00:11:53	00:12:23	00:13:02	00:13:53	00:14:22
	3	00:05:42	00:06:22	00:07:02	00:07:53	00:08:23	00:09:03	00:09:53	00:10:23	00:11:03	00:11:53	00:12:23	00:13:02	00:13:53
	4	00:01:41	00:05:42	00:06:22	00:07:02	00:07:53	00:08:23	00:09:03	00:09:53	00:10:23	00:11:03	00:11:53	00:12:23	00:13:02
	5	00:01:41	00:01:41	00:05:42	00:06:22	00:07:02	00:07:53	00:08:23	00:09:03	00:09:53	00:10:23	00:11:03	00:11:53	00:12:23
	6	00:01:41	00:01:41	00:01:41	00:05:42	00:06:22	00:07:02	00:07:53	00:08:23	00:09:03	00:09:53	00:10:23	00:11:03	00:11:53
	7	00:01:41	00:01:41	00:01:41	00:02:31	00:05:42	00:06:22	00:07:02	00:07:53	00:08:23	00:09:03	00:09:53	00:10:23	00:11:03
	8	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:05:42	00:06:22	00:07:02	00:07:53	00:08:23	00:09:03	00:09:53	00:10:23
	9	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:05:42	00:06:22	00:07:02	00:07:53	00:08:23	00:09:03	00:09:53
	10	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:05:42	00:06:22	00:07:02	00:07:53	00:08:23	00:09:03
	11	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:05:42	00:06:22	00:07:02	00:07:53	00:08:23
	12	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:05:42	00:06:22	00:07:02	00:07:53
	13	00:01:41	00:01:41	00:01:41	00:02:31	00:02:31	00:02:31	00:03:21	00:03:21	00:03:21	00:04:11	00:05:42	00:06:22	00:07:02

Figure D.5: Lead times with refill time of 00:04:12.

See Table D.5 for the inventory / buffer calculations.

Table D.5: Inventory / buffer calculations.

Refill time	Number of lattice girders per mould (1 mould takes 00:07:30)	Extra time to cover due to refill time	Time to make up to 9 / 16 girders and place them	Amount of girders to make and place in the time of previous column	Total inventory / buffer places needed
00:12:11	9	00:12:11 - 00:07:30 = 00:04:41	00:07:30 - 00:04:41 = 00:02:49	3	9 + 9 - 3 = 15
00:09:11	9	00:09:11 - 00:07:30 = 00:01:41	00:07:30 - 00:01:41 = 00:05:49	7	9 + 9 - 7 = 11
00:04:12	9	00:04:12 - 00:07:30 = - 00:03:18	00:07:30 + 00:03:18 = 00:10:48	14	9 + 9 - 14 = 4
00:12:11	16	00:12:11 - 00:07:30 =	00:07:30 - 00:04:41 =	3	16 + 16 - 3 = 29

		00:04:41	00:02:49		
00:09:11	16	00:09:11 - 00:07:30 = 00:01:41	00:07:30 - 00:01:41 = 00:05:49	7	16 + 16 - 7 = 25
00:04:12	16	00:04:12 - 00:07:30 = - 00:03:18	00:07:30 + 00:03:18 = 00:10:48	14	16 + 16 - 14 = 18

D.2.2: Solution 2 and 3 calculations

We see in Table D.6 the current refill situation. In Table D.7 we see the refill time when solution 2 is implemented and in Table D.8 we see the refill time when solution 3 is implemented.

Table D.6: Current refill situation.

activity	time	interval	internal or external
working at 8 and notice refill	13:07:58		external
at machine to see what is wrong	13:08:27	00:00:29	external
got the crane and placed it near the steel coil	13:11:09	00:02:42	external
walked to the reel that is almost empty	13:11:20	00:00:11	internal
cut the wire and placed it in welding machine	13:11:52	00:00:32	internal
reel has been made ready	13:12:34	00:00:42	internal
walked to the steel coil where the crane must be placed in	13:12:37	00:00:03	internal
placed the crane in the steel coil	13:13:11	00:00:34	internal
coil is towed on reel	13:14:26	00:01:15	internal
reel is made ready again	13:14:51	00:00:25	internal
crane has been placed in other steel coil for safety reasons	13:15:15	00:00:24	internal
walked to steel coil	13:15:36	00:00:21	internal
done with cutting	13:15:57	00:00:21	internal
done with welding	13:17:42	00:01:45	internal
walked to steel coil	13:17:58	00:00:16	internal
done smoothing	13:19:02	00:01:04	internal
starting machine again	13:20:09	00:01:07	internal
total internal time:		**00:12:11**	

Tabel D.7: Solution 2 refill time.

activity	interval	internal or external
employee at 7 sees that steel coil		external

is almost empty		
got the crane and placed it near the steel coil	00:02:42	external
stop machine		internal
walked to the reel that is almost empty	00:00:22	internal
cut the wire and placed it in weldingmachine	00:00:32	internal
reel has been made ready	00:00:42	internal
walked to the steel coil where the crane must be placed in	00:00:03	internal
placed the crane in the steel coil	00:00:34	internal
coil is towed on reel	00:01:15	internal
reel is made ready again	00:00:25	internal
crane has been placed in other steel coil for safety reasons	00:00:24	internal
walked to steel coil	00:00:21	internal
done with cutting	00:00:21	internal
done with welding	00:01:45	internal
walked to steel coil	00:00:16	internal
done smoothen	00:01:04	internal
starting machine again	00:01:07	internal
total internal time:	**00:09:11**	

Table D.8: Solution 3 refill time.

activity	interval	internal or external
employee at 7 sees that steel coil is almost empty		external
got the crane and placed it near the steel coil	00:02:42	external
walked to the reel that is almost empty	00:00:58	external
cut the wire and placed it in welding machine	00:00:32	external
reel has been made ready	00:00:42	external
walked to the steel coil where the crane must be placed in	00:00:03	external
placed the crane in the steel coil	00:00:34	external
coil is towed on reel	00:01:15	external
reel is made ready again	00:00:25	external
crane has been placed in other steel coil for safety reasons	00:00:24	external
walked to steel coil	00:00:21	external
done with cutting	00:00:21	external
stop machine		internal
walked to the reel that is almost empty	00:00:22	internal

done with welding	00:01:45	internal
walked to steel coil	00:00:16	internal
done smoothen	00:01:04	internal
starting machine again	00:01:07	internal
total internal time:	**00:04:12**	

Appendix E: Solution selection

This appendix shows the calculations for the solution options selection. For example in Table E.1 we can see that for the total score in column 4 for criterion A the weight (4) is multiplied with the score (4) to get the total (16). This is done for all criteria for all solution options to in the end see which solution options are the best. The same is done in Table E.2 and E.3.

Table E.1: Decision matrix workstations 17 and 18.

crite rion	weighting 1 - 5	option 1		option 2		option 3		option 4		option 5		option 6	
		score	total	score	total	score	total	score	total	score	total	score	total
A	4	4	16	3	12	5	20	2	8	1	4	1	4
B	4	2	8	x	x	5	20	4	16	4	16	2	8
C	3	3	9	5	15	5	15	1	3	1	3	5	15
D	3	5	15	3	9	3	9	1	3	1	3	x	x
E	2	5	10	3	6	3	6	4	8	2	4	5	10
F	5	1	5	1	5	1	5	5	25	1	5	1	5
total			63		x		75		63		35		x

Table E.2: Decision matrix workstation 7.

criterion	weighting 1 - 5	option 1		option 2		option 3		option 4		option 5	
			total	score	total	score	total	score	total	score	total
A	4	3	12	5	20	x	x	4	16	5	20
B	4	5	20	3	12	5	20	5	20	4	16
C	3	5	15	3	9	3	9	5	15	4	12
D	3	3	9	5	15	2	6	4	12	5	15
E	2	3	6	5	10	3	6	5	10	4	8
F	5	1	5	1	5	1	5	1	5	1	5
total			67		71		x		78		76

Table E.3: Decision matrix workstation 2.

criterion	weighting 1 - 5	option 1		option 2		option 3		option 4	
		score	total	score	total	score	total	score	total
A	4	5	20	5	20	2	8	4	16

B	4	5	20	4	16	4	16	3	12
C	3	4	12	5	15	1	3	3	9
D	3	5	15	3	9	1	3	5	15
E	2	2	4	2	4	4	8	5	10
F	5	3	15	3	15	5	25	5	25
total			86		79		63		87

Appendix F: Potential impact of the chosen solutions

The impact of the chosen solutions is calculated in this appendix. The is done with the information from all the Excell files that are collected, measured and calculated during the other chapters.

Table F.1: Calculation information.

Workstation	2	3	5	7	17+18
Time periods (March + April)	2418 + 1609 = 4027	2487 + 1611 = 4028	2420 + 1615 = 4035	4089	1787 + 1806 = 3593
Time exceedings (March and April)	210 + 256 = 466	216 + 256 = 472	158 + 337 = 495	504	1027
Time exceeding with solutions implemented	466 – 49 (Breaks) – 117 (Number of slabs) – 36 (Product damages) = 264	472 – 472 = 0	495 – 495 = 0	504 – 129 (steel coil refill) – 101 (Not pressing button) = 274	1027 – 623 (Late delivery of concrete mix) = 404
"soft"moulds per hour with solutions implemented	01:00:00 / 00:06:23 = 9.40	01:00:00 / 00:05:55 = 10.13	01:00:00 / 00:05:56 = 10.12	01:00:00 / 00:04:57 = 12.13	01:00:00 / 00:06:02 = 9.95 and 01:00:00 / 00:05:21 = 11.20

The output calculations are done by replacing the time exceedings when the solutions are implemented. For workstation 2 the time exceedings caused by the breaks, number of slabs and product damages are replaced with the average lead time of the workstation, which is 00:06:41. For workstation 3 potentially all time exceedings can be replaced with 00:07:30, because with the standardized work description there should not be any time exceeding at this workstation. In practice this will most likely not be the case, however this is a potential improvement. For workstation 5 the same applies as for workstation 3. Potentially all time exceedings can be replaced with 00:07:30. For workstation 7 the time exceedings caused by steel coil refills are replaced by 00:07:30. This is because with the solutions the steel coil refill should not exceed the 00:07:30 anymore. Furthermore, the exceedings caused by not pressing the button can be replaced with the average lead time of workstation 7, which is 00:05:21. For workstation 17 and 18 only the information from certain shifts could be used, because from the other shifts data was missing of the delivery of concrete mix. From these shifts the time exceedings caused by a late delivery of concrete mix are replaced by the average 00:07:30, because the lead time should not exceed the 00:07:30 anymore with the solutions. With all this information the new output is calculated and also the new variation of the lead times.