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Reducing the waiting times in the manual moulding department.

- A simulation study -

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Bachelor Thesis Industrial Engineering Management

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Reducing the waiting times in the manual moulding department

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Management summary

Before the thesis report starts a short management summary of the research will follow to give the reader an idea of the research that is performed.

Introduction

Eternit is a large producer of corrugated sheets, most of these corrugated sheets are produced with the help of a large automated production line, the so called G4 Line. However there are also a few ‘special’ corrugated sheets that can only be produced manually. The production of these ‘special’ corrugated sheets takes place inside the manual moulding department of Eternit. But in this manual moulding process Eternit experiences various unnecessary waiting times that should be reduced. These waiting times should be reduced, therefore the action problem of the research is:

Action Problem: How to reduce the waiting times during the manual moulding process.

Problem identification

The manual moulding process is complex and therefore various problems could be at the basis of the unnecessary waiting times. Therefore a problem identification is used to find the core problem of these waiting times. This is done by observing the manual moulding process and producing a problem cluster. Based on this the following core problem is chosen:

Core problem: The plate delivery process is unreliable and leads to waiting times

Literature review

To come up with solutions to solve the core problem a literature review is performed. In the literature two different theories are found that could be used to optimize and reduce the waiting times in the manual moulding process.

1. Theory of Constraints: Like the name says this theory focusses on the constraint/bottleneck inside a production process. According to this theory each production process is limited in its outcome since it has at least one bottleneck that determines the pace of the entire system. Therefore the *TOC* states that all the focus should be on exploiting and improving the bottleneck to make sure that the entire system is optimized. The other parts of the processes should be subordinated to the bottleneck.
2. Drum Buffer Rope: The focus of this theory will be on the bottleneck inside the production process as well. However this theory will also involve other parts of the process to improve the bottleneck. In this theory the bottleneck is referred to as the *drum* and this *drum* should determine the pace of the entire process. When the *drum* is helped by other parts of the process the pace of the entire process can increase. With the help of *buffers* and *ropes* it is possible to help the *drum* and increase the pace of the entire process.

Simulation model and experiments

With the information already gathered so far during the research a simulation model is developed. This simulation model represents the current situation inside the manual moulding department. With this simulation model the **1st experiment** is performed to gather data for a baseline measurement. The results of this experiment are at the end used as a comparison. The simulation model will then be slightly adjusted so that a possible solution is implemented into the model. An adjusted simulation model is created for a total of five different solutions, with each of these models an experiment is performed. So together with the baseline measurement a total of six experiments is performed during this research.

For the **2nd experiment** the plate transporter in the manual moulding process is prioritised based on the *Theory of Constraints*. This led to quite a drastic decrease in waiting time of over 25% when compared to the current situation inside the manual moulding department.

With the **3rd experiment** an extra buffer is added in front of both punching machines. This idea of adding in an extra buffer is based on the *Drum Buffer Rope* theory. However this extra buffer did not lead to less waiting times, the waiting times stayed around the same level.

In the **4th experiment** the existing buffer in front of both the punching machines is removed. This is done since adding an extra buffer did not affect the waiting times at all. So maybe the existing buffer could entirely be removed from the process. However the result of the experiment was that the waiting times increased when the buffer is entirely removed.

For the **5th experiment** the plate transporter and the waste transporter will both be responsible for one punching machine, instead of being responsible for both punching machines. This solution did not give a good result since the waiting times will increase with more than 200% based on the experiment.

For the **6th experiment** two earlier tested solutions are combined, so that the effect of prioritising the plate transporter can be validated. For this experiment both transporters are once again only be responsible for one punching machine, like in the fifth experiment. But this time both transporters will also be prioritised like happened in the second experiment. Once again the waiting times increased drastically, but not as much as during the fifth experiment. Compared to the fifth experiment the waiting times decreased with more than 10% now that the transporter is prioritised. So simply said prioritising the plate transporter had a positive effect on reducing the waiting time again.

Conclusion

So based on the baseline measurement and the five other experiments that are performed the conclusion can be drawn that prioritising the plate transporter has a positive effect on decreasing the waiting times. The other solutions that are tested with the help of experiments did not have any effect on the waiting times, some solutions even led to a increase in waiting time. With the help of these results an advice should be given to Eternit.

Advice

Based on the problem approach and the main results of the six experiments performed the following advice is given to Eternit to make sure that the waiting times in the manual moulding process are reduced:

> "The response time of the operator leads to unnecessary waiting times for the plate transporter. Therefore the plate transporter inside the manual moulding department should be prioritised so that this transporter is less dependent on the operator of the G4 Line. In an ideal scenario the communication with this operator should be removed entirely so that the transporter himself can start the production of the plates."

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Readers' guide

The readers' guide is created at the beginning of this thesis report to give the reader a better understanding about the structure of this thesis report. This readers' guide will give a short explanation about the topic and content of each of the chapters.

In **Chapter 1** an introduction will be given to this thesis report. The first chapter starts with an introduction to the company Eternit and the problem identification. Based on this problem identification a core problem is chosen. Furthermore this chapter will introduce the reader to the five research questions of the thesis and the problem solving approach that will be used towards solving these research questions.

Chapter 2 contains a comprehensive explanation about the current situation inside the manual moulding department of Eternit. During this chapter a lot of diagrams and maps are used to give a good visualization of the manual moulding process to the reader. Besides that this second chapter also contains information about the various methods of data-gathering that are used, such as the observations. The goal of this chapter is to give a clear answer to the first two (sub)-research questions.

Chapter 3 is all about the literature study to find an applicable theory that can be used to reduce the waiting times in the manual moulding department. First, the chapter starts of with an explanation of two interesting theories that might give a solution towards reducing the waiting times inside a process. Secondly, it will be explained how these two theories can be applied to the manual moulding process of Eternit. At the end this chapter will introduce the readers to different solutions that are based on the two theories discussed earlier in the chapter. Hopefully this third chapter gives an answer towards the third and fourth (sub)-research question.

Chapter 4 contains information about the simulation model used in this thesis. First, the reader is introduced to the theory behind simulation models. Then more information will be presented towards the conceptual model that will be used for the eventual simulation model. Following this conceptual model there will be a further explanation how this conceptual model was programmed into a working simulation model. Finally, in this chapter the simulation model will be validated and verificated.

Chapter 5 includes the information about the different experiments that are performed and the results of these experiments. First, an introduction to the theory behind experiments will be given. Secondly, an experiment was done with the simulation model that represents the current situation in the manual moulding department. This first experiment will be used as the baseline measurement. Later five more experiments are done with a slightly adjusted simulation model that has a possible solution implemented into the model. At the end these experiments will be compared.

In **chapter 6** a final conclusion based on the simulation model and the various experiments will be given. Besides that this chapter will also give an advice towards Eternit what can be done to solve the problem that was introduced in the first chapter.

Each chapter in this bachelor thesis is structured in the same way. First of all, a short introduction to the chapter is given. Afterwards, the structure of the chapter is presented. Then all different sections in the chapter will be discussed in line with the structure presented at the beginning of the chapter.

1. Introduction

The first chapter of this report will give an introduction to the company Eternit and of the manual moulding department. This chapter also tends to give to explain the current problems inside this manual moulding department. Furthermore there will be information about the core problem and the research questions that will be used to come up with answers towards this core problem. Therefore, this chapter has the following structure:

§ 1.1 – About Eternit B.V.
§ 1.2 – Reason of the research
§ 1.3 – Problem identification
§ 1.4 – Research questions and sub-research questions
§ 1.5 – Problem solving approach
§ 1.6 – Research cycle

1.1 About Eternit B.V.

Eternit B.V. is a producer of corrugated sheets for sustainable roof and façade solutions. In ***Appendix A.1*** there some product images of these corrugated sheets to give an example about the products produced. Eternit B.V. is a part of the Etex Group, the Etex Group is a worldwide producer of building materials with companies all over the world. In total the Etex Group has around 15.000 employees and the head office is in Brussel, Belgium.

Located in Goor, Eternit B.V. and its 150 employees produce around 10 million m^2 of corrugated sheets yearly. The corrugated sheets are not only sold on the Dutch market, over 50% of the total production is destined for export to other European countries. Most of these corrugated sheets are quite 'standard' and are produced on a large automated production line. Besides these 'standard' corrugated sheets also special fittings are needed for optimal roof and façade solutions, these so called special parts are manually produced on the manual moulding department.

On the manual moulding department around 30 employees produce various special parts with the help of punching machines and moulds. For the material the manual moulding department is dependent on the large automated production line, the G4-Line. This dependency and other factors lead to unnecessary waiting times during the manual moulding process. Eternit B.V. asked me to take a closer look at their manual moulding process to investigate possible causes of these waiting times. The goal of this research project is to optimize the manual moulding process to make sure that waiting times are reduced.

1.2 Reason of the research

According to the *Managerial Problem Solving Method* (Heerkens, 2012) a problem occurs when there is a difference between the norm and the reality. The problem at Eternit can also be described as a difference between the norm and the reality. When there is a difference between the reality and the norm this is an action problem. Solving this action problem will lead to the reality and the norm matching. At the moment Eternit has some significant waiting times during their manual moulding process. If the employees are waiting for another action to happen they are unable to work, leading to a lower efficiency. Eternit wants to reduce these waiting times as much as possible and achievable. So at the moment the reality is that Eternit has waiting times and the norm is that these waiting times should be reduced. To make sure that the norm and reality are matching again an action problem should be set, this action problem is basically the same as the final goal of the research. The action problem or final goal during this research is:

Action Problem: How to reduce the waiting times during the manual moulding process.

While reducing the waiting times the efficiency of the employees should also be taken into account. Reducing waiting times while lowering the efficiency isn't a proper solution. An inefficient solution might reduce the waiting times but will probably also increase the costs. The average waiting time during the manual moulding process will be used to measure if the action problem is solved. For this research the following definition of waiting time will be used based on *The Law Dictionary*; waiting time is the period where an employee is unable to work because of factors he has no control over.

Normally the variable is used in the action problem to show the difference between the norm and the reality. But in this case Eternit has no clear knowledge about the current average waiting time during the manual moulding process. Without knowing the average waiting time in reality it is fairly difficult for Eternit to state a norm for the average waiting time this early in the research. So since both the reality and the norm are vague and don't consist of hard numbers, more information and knowledge is needed. This knowledge can then be used to get a better understanding of the exact numbers of both the norm and the reality. The missing information will be retrieved later during the research and can then be used for a more clear norm and reality.

1.3 Problem identification

Since the manual moulding process of Eternit is complicated various problems occur during the whole process. During a short observation and interview at Eternit all possible problems were noted down. Some problems affect the waiting times more than other problems while some problems don't affect the waiting times at all. All these problems are put into a problem cluster that shows the connection between the problems and the causes and consequences of these problems. The problem cluster for the manual moulding process of Eternit can be found in ***appendix A.2***

The problem cluster consists of two clusters next to each other since there are two major parts in the process where the waiting times occur. The main effect of both clusters is that the problems in the end lead to (more) waiting time. With the problem cluster it is possible to find the core problem that contributes the most to solving the action problem. In the clusters there are some problems that are impossible to influence, these problems can't be a core problem. The problems that are impossible to influence are in the orange boxes.

- Material is stiff – For the mix of their fiber cement Eternit is dependent on the quality of resources they get delivered. A small change in the quality of resources can lead to a more stiff fiber cement mix. For this project this is impossible to influence.
- Less space next to plate machine – Because of a support post close to the plate machine there is not much space next to this machine to drive. The shape of the plate machine also makes it difficult to drive there. Both these issues can't be solved since the support post can't be removed and changes to the plate machine have to be made inside another department. Besides that these possible changes might become really expensive.
- Operator of plate machine is busy – The operator in this process belongs to the G4 Line and is responsible for this G4 Line. However in the meantime this operator also handles the request for new plates from the manual moulding department. This operator is mainly busy with the G4 Line and may therefore not respond to the request immediately. No immediate response means that there is waiting time for the cart driver. But this operator is not a part of the manual moulding department and therefore this problem becomes impossible to have influence on during this project.

According to the theory most of the times a possible core problem has no causes, so possible core problems can mostly be found at the beginning of the problem cluster. In the problem cluster of Eternit there are some problems without a cause, however these problems are in orange meaning they are impossible to influence. So these three problems can't be the core problem and Eternit has to deal with their consequences. Now there are four more possible core problems left, these four problems are made green in the problem cluster. One of these possible core problems is not at the beginning of the cluster. However it's still selected as a possible core problem, since solving this problem contributes a lot to reducing the waiting times. All these four problems can be a core problem that needs to be solved to reduce the waiting time in the manual moulding process, however only one of these problems can be the core problem.

Out of these four problems the core problem should be the problem that contributes the most to reducing waiting times and is the most cost-effective to solve. When looking at the four problems the following two problems can be eliminated immediately:

- Punching takes more time – On the current punching machines it is nearly impossible to reach a higher punching speed. So dealing with this problem most likely means that two totally new punching machines should be purchased. This is very expensive, making solving this problem not really cost-effective.
- Driving the cart is difficult – The cart driving is difficult because of the layout of the factory and the G4 Line, changing this layout however is not an option because of various reasons. Most likely this problem can be solved by purchasing a new cart system that can be used to transport the plates. But this new cart system probably requires quite a big investment. So this problem is not really cost-effective to solve. Next to that solving this problem doesn't help too much with reducing the waiting times.

After elimination there are two more problems left that could be a possible core problem. The problem that there is no immediate response or that the request is forgotten looks not too difficult to solve and might therefore not be complex enough for a bachelor thesis research. Next to that solving this problem will most likely reduce the waiting times with less amount than the other possible core problem. So solving the problems with the requesting of the plates will not be the core problem. However this problem will still be looked into since it is partly connected with the problem that occurs at the punching machine. Besides that it should also be an easy way to reduce the waiting time in the whole process a little. But for now only one option remains as a possible core problem, so this problem will be the core problem:

Core problem: New fiber plates don't arrive at the right time.

At the moment Eternit has two punching machines that are being used during the manual moulding process. As stated in the problem cluster sometimes the cart with new plates doesn't always arrive at the right time. This gives Eternit waiting time for the following reasons:

- The cart with plates arrives at the punching machine with new fiber cement plates for the next punching job, but sometimes it happens that the cart arrives while the previous punching job is still going. Then the plate transporter has to wait until this job is fully finished before he can load the new plates onto the punching machine. This waiting of the driver is of course waiting time.

- The employees at the punching machine are done with a punching job and are ready to start with the next punching job. However sometimes it happens that the plate transporter is too late with new fiber cement plates. Then the employees at the punching machine can't do anything besides waiting for new plates to arrive, so this is waiting time.

Later on during the process of solving this core problem the conclusion was that the core problem and the problem cluster should be changed a bit. At that moment the core problem stated, like mentioned above, that both the plate transporter as well the punching employees were responsible for the waiting times that occurred in the manual moulding process. Although later on in the research after some more investigation and observation the conclusion could be drawn that mainly the plate transporter and the plate delivery process were responsible for the waiting times. This is mainly based on the observation and the measurements that were performed, this is further explained in chapter two and chapter three. This observation can be found in ***Appendix B.8*** and these measurements can be found in ***Appendix C.1*** and ***C.2***.

Based on the further research, the observation and the measurements the core problem was changed a bit so that the focus would only be on the plate transporter and the plate delivery process from now on. The waiting times that occurred by the G4 Line in the plate delivery process were not addressed in the last core problem, but this will also be part of the new core problem. The now core problem will be changed to:

Core problem: The plate delivery process is unreliable and leads to waiting times

In this core problem the plate transporter and the G4 Line together form the plate delivery process. Now that the core problem has changed to a focus only on the plate transporter the problem cluster should also be changed. This new problem cluster can be found in ***Appendix A.3***.

With good research it should be possible to solve this problem in a cost-effective way, making it a perfect core problem. Besides that solving this problem will most likely give a large contribution to reducing the waiting times while in the meantime the efficiency can also be improved, that makes this problem a good core problem as well.

1.4 Research questions and sub-research questions

As mentioned in the last paragraph the final goal of this research is to reduce the waiting times during the manual moulding process. At the moment of writing possible options to reach this goal are still unclear, so more research is needed. To be able to reach the final goal the following main research question should be answered:

How can the waiting times at the manual moulding department of Eternit be reduced?

To be able to answer this main research question more information is needed. The following sub-research questions will be used to solve the main research question and the problem. Each sub-research questions comes with a short explanation why it is necessary to solve the specific sub-research question.

Question 1 – What is the current situation in the manual moulding department?

At the moment some general information about the manual moulding process is known, but most of this information is just general information. For the solution generation and the rest of the research more in-depth information about the current situation of the manual moulding process is needed. This question should also give more information about why and where the waiting times occur. All the processes inside the manual moulding process should be visualized with the help of flow diagrams, spaghetti diagrams and other diagrams.

Question 2 – How are fresh plates requested and what is the role of the G4 Line in this requesting process?

Probably the most important step in the process is the supply of new materials, new plates are requested by the cart driver. When the cart driver request new plates the G4 line gets a notification and can then start producing the new plates. Good collaboration and communication is the key in this requesting process. But right now there are various difficulties in the collaboration and communication and this leads to unnecessary waiting times. So by optimizing this requesting process it might be possible to reduce the waiting times. But before being able to optimize this process more information about the requesting process is needed. As mentioned in the requesting process both the supervisor of the G4 Line and the cart driver are involved. To get an objective view on the requesting process it is important to gather data on 'both sides', so both the G4 Line and the cart driver.

Question 3 – Which existing theories can be used to reduce the waiting time in the manual moulding process?

In literature a lot of different theories are known to optimize a production process. But only a few of these theories can be used to optimize the manual moulding process and to reduce the waiting times. This question should answer which of all these theories are useful to optimize the manual moulding department.

Question 4 – How can the chosen solution(s) be implemented into the manual moulding process?

The first three sub-research questions are really useful to gather information that can be used to come up with solutions towards the main research question. But only giving some possible solutions is not enough to give a comprehensive answer to the main research question. To give a full and comprehensive answer to the research question it is also necessary to research the implementation of the solutions. So this sub-research question will further answer how theories and solutions can be implemented into the manual moulding process.

Question 5– Which solution gives the best results when implemented into the Plant Simulation model?

The fourth research questions gives an answer on how the various solutions could be implemented into the actual manual moulding process. However this research questions will not give any information if the chosen solutions will really reduce the waiting times in the manual moulding department. For the fifth and last research question all these different solutions will be implemented into a simulation model that represents the manual moulding department. Then for each solution the average waiting time can be measured to give an answer to this research question and to come up with a recommendation for Eternit.

1.5 Problem solving approach

The main research questions and the five sub-research questions will be answered with the help of observations, interviews and literature research. This paragraph will be about the approach that will be used when gathering information and throughout the rest of the research.

1.5.1 Stakeholders

Before starting with gathering information it is important to have an image of who is involved in to the problem and how much their influence is. In this case all employees of the manual moulding department are involved, since they all need to deal with waiting times. But besides the employees of the manual moulding department there are some more stakeholders. Each of these stakeholders has different interests and influence towards the problem, to show this the stakeholders are put in a model that can be found in ***Appendix A.4*** This stakeholder diagram is used as a general overview while doing the observations and the interviews.

1.5.2 Information gathering

Before starting with the observations and interviews some information about the manual moulding process is already known from earlier visits to Eternit. All this information should be listed down to make it clear immediately which information is still missing. When listing the already available information it becomes more clear which information is still needed and where the focus of the observations and interviews should be.

To solve the action problem the causes of this particular problem should be known. So to start things off a research will be done to gather more information on the current situation and to find possible causes. The focus of this research is on both punching machines and the requesting process, since these two parts are responsible for the waiting times. So during the observations and interviews there are two sub-research questions that should be answered, namely:

Q1: What is current situation of the manual moulding department?

Q2: How are fresh plates requested and what is the role of the G4 Line in this?

The rest of this paragraph will explain more about the observations and interviews that will performed to solve these two questions. The answers to both of these questions can be found later on in the second chapter of this research.

1.5.3 Observations

This data gathering process will start with an observation of the manual moulding process, in this observation the employees of the manual moulding department will be observed during their activities for a short time. The main reason of this observation is to be able to answer the two sub-research questions above.

So the main focus of this observation will be on the process around both punching machines, and the requesting process of the new plates. However also the other parts of the manual moulding process should be observed sufficient enough to find other possible bottlenecks.. With the results of the observation a spaghetti diagram should be made in which all the flows off both the employees and carts are visible during the manual moulding process. Besides this spaghetti diagram the two sub-research questions should already be answered partly. Possibly the problem cluster should be updated since new bottlenecks where noticed during the observation.

Another thing that should happen during the observation is that certain activities, like punching time and driving time, should be measured. These measurements can be used later when designing a simulation model. These punching times, driving times and other measurements can then be used when designing the simulation model. These measurements should be done several times to exclude and remove possible exceptions.

1.5.4 Interviews

After the observation some interviews should take place to get more information about certain parts inside the manual moulding process. The goal is to perform an interview with the operator of the large plate machine, the driver of the cart and with two employees that are involved in the process at the punching machine. So a total of four interviews will be performed to get more knowledge about the manual moulding process. The interviews are used to gather more information that can be used to answer both sub-research questions **Q1** and **Q2**. Besides that the interviews are also useful to gather more information about the opinions and mood of specific persons inside the manual moulding process. But before conducting these interviews a list of interview questions should be composed that can be used to gather sufficient data. Now, with newly obtained information from the interviews, the first two sub-research questions should be solved.

1.5.5 Literature review

A part of the third sub-research question should be answered with the help of a literature study.

Q3: Which existing theories can be used to reduce the waiting times in the manual moulding process?

With the help of a literature study theories should be found that can be used to optimize a production process and mainly to reduce the waiting times in a production process. Possibly a lot of different theories will be found and some of these theories cannot even be applied to the manual moulding process of Eternit. Later on in this report only the theories that are chosen in the decision making process are explained. More about this decision making process is explained below in *paragraph 1.5.6*.

1.5.6 Decision making

To give a comprehensive answer to the third sub-research question the best theories should be filtered out after the literature study is done. This decision making process is done with the help of the systematic literature review, this can be found in ***Appendix F.1***. The chosen theories will then later on be explained in the third chapter to have a complete and comprehensive answer on the third sub-research question.

1.5.7 Implementation into a simulation model

With the help of the information gathered during the first three sub-research questions it should be possible to set up a simulation model with the help of Plant Simulation software. This simulation model can be used to simulate the manual moulding process and is therefore ideal to test certain solutions. With the help of the Plant Simulation model the implementation later on should be easier since crucial information can be gathered before implementing the solution in practice. So the Plant Simulation model can be really helpful to answer the fourth and last sub-research question:

Q4: How can the chosen solution(s) be implemented into the manual moulding process?

Besides the Plant Simulation model also the information from the first three sub-research questions is needed to give an answer to this sub-research question. With answering this question all four sub-research questions are answered, this will hopefully lead to a final solution to reduce the waiting times.

1.6 Research cycle

The first and second sub-research question are two typical questions that can only be solved by doing a lot of research and investigation into the process of the manual moulding process. Part of the research to come up with answers to these two sub-research questions will be observations and interviews. During these observations and interviews a lot of information will be collected about the manual moulding department, with most of the information not necessary or reliable. A proper research cycle can help with filtering out the necessary and reliable information that should be used to answer **Q1** and **Q2**. Therefore for these two sub-research questions a research cycle is made, this research cycle can be found in ***Appendix A.5*** The design of this research cycle is based on the book *Geen Probleem (Heerkens, 2012)*

2. Current situation

In this chapter the current situation inside the manual moulding department is discussed and various processes are further explained to the reader. During this chapter a lot of diagrams and maps are used to make it easier to visualize the process as a reader. The goal of the following chapter is to give a clear answer to the first two sub-research questions:

- **Q1:** What is the current situation inside the manual moulding department? (*§2.1, §2.2, §2.3)*
- **Q2:** How are fresh plates requested and what is the role of the G4 Line in this? (*§2.2)*

To come to a clear and comprehensive answer to both of these sub-research question this chapter is structured as follows:

§ 2.1 – General overview
§ 2.2 – Schedule
§ 2.3 – Requesting process
§ 2.4 – Moving process
§ 2.5 – Punching process
§ 2.6 – Moulding process
§ 2.7 – Observation
§ 2.8 – Spaghetti diagram

2.1 General overview

This paragraph will introduce the reader to the manual moulding process of Eternit. Since the manual moulding process can be quite complicated to understand first a general overview of the process will be given. Later on in this chapter a few processes will be explained in much more detail.

All the final products produced at Eternit in Goor are made from fiber cement plates. These fiber cement plates consist of over 90% fiber cement and some fillers. The fiber cement plates are produced on the large G4 Line with the help of various machines and techniques. During this process all 'standard' plates also get a few strengthening strips. The plates for the manual moulding process should not get these strengthening strips. Roughly spoken the first 30 minutes after this production process the fiber cement plates are still 'soft' and can be shaped to the desired form. If no fresh plates are needed at the manual moulding process then the fiber cement plates just progress on the G4 Line and become 'standard' corrugated sheets. If fresh plates are requested then some fiber cement plates will be produced especially for the manual moulding department. These plates will be taken apart and moved onto a cart. More will be explained about this requesting process in *paragraph 2.2*.

On the manual moulding department over 20 different special parts are produced from fiber cement plates. The manual moulding department uses job-shop manufacturing in the production process. All these special parts will be used to reach optimal and façade solutions. Each special part has its own 'specialism', for example the *k-nok* is used for closing the ridge while the *s-windveerstuk* is used as closing of the roof sides. Roughly spoken the manual moulding process consists of four different processes in *figure 1*:

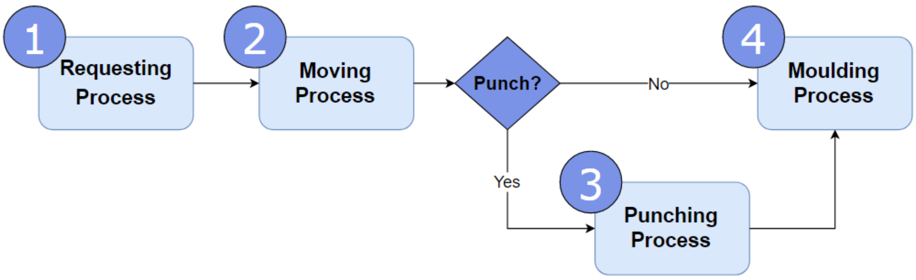


Figure 1: Diagram of manual moulding process

These four processes mentioned in the flow diagram on the last page will be explained in more depth below:

1. Requesting process

At the beginning of a process material is needed, so the first step in the manual moulding process is that the cart driver requests fresh plates at the G4 Line. If the operator of the G4 Line receives the request he/she will change the machine settings so that this machine starts producing plates without a strengthening strip for the manual moulding process. Each plate is put on the cart after production by the machine.

2. Moving process

When all plates are ready on the cart it is time for the cart driver to bring the fresh plates to the correct location. In total there are three different locations possible; the two punching machines and the tables. This location can differ every time and is dependent on which employees need the plates. Arrived at the correct location the plates are moved onto the punching machine or tables.

3. Punching process

When the plates were destined for the table, then this process is skipped.
With the fresh plates on the punching machine the punching process can start. Dependent on which special part is produced the employees grab a punching knife. The punching knife is placed on top of all the plates, then the plates plus punching knife are moved under the machine. Here pressure is put on the punching knife so that smaller plates are punched out of the large plate. All the punched out smaller plates are put on a driveable table to be moved later on. The remaining material is placed on a waste-cart and can be used again later on.

4. Moulding process

Each special part has its own place in the work floor where the moulding process takes place. During the moulding process the punched out plates from the previous process are put on a mould. Then an employee makes sure that the plate fits the mould correctly. Finally when the plate is placed on the mould correctly the mould plus plate are put away to harden.

Really simplified this are the four processes needed to come to a finished end product.
Of course all these processes are way more complicated than described above. Later on in this chapter these four processes will be described more in-depth. Then will also be explained further where the waiting times and bottlenecks in the production process occur.

In ***Appendix B.1*** a map of the work floor of the manual moulding department can be found. With the help of numbers is highlighted where each process that was mentioned above takes place. The punching process can take place on two different locations since there are two punching machines. The same goes for the moulding process, each special part has its own place where the moulding process takes place, that’s why there are multiple numbers 4 in the map. A further explanation of the schedule and the different processes will be given in the next paragraphs.

2.2 Schedule

Eternit uses a weekly schedule on their manual moulding department, the goal is to keep this schedule almost the same each week. On this schedule there is one cart driver, a driver who picks up the carts with waste and around 20-30 employees responsible for punching and moulding. Those employees work as much as possible in pairs, but this is not always possible. Both drivers are busy the whole day with driving with carts to deliver plates or to remove the waste from the work floor. The employees work in sessions of 1 hour (*k-nok* has sessions of 45 mins.), in this hour they punch the plates and put them on the moulds. After 1 hour they are finished with this and then they start over with punching again. So if an employee works from 7:00 till 15:30 he has 8 different sessions in which he produces special parts. (There is a break of 30 minutes)

The employee pairs are split up in two different groups, one group starts at 7:00 and the other at 7:30. This is because the cart driver has to deliver plates to all pairs, if they all start at the same time it's impossible for the cart driver to do this. The cart driver starts at 6:45 so that he can already start delivering plates for the pairs that start at 7:00. The waste driver can start later than the employees because there is no waste before they started. So the waste driver starts at 7:15. An example of a weekly schedule can be found in ***Appendix B.7***.

Even though the cart driver starts at 6:45 he is still unable to make sure that each pair has plates at 7:00 in the morning. As seen in the example schedule 7 pairs need plates at 7:00, and that is too much in 15 minutes. Besides that also some pairs need the same punching machine at the same time, which is of course not possible. So in reality some pairs may start 10 minutes later, these pairs also stop working 10 minutes later.

2.3 Requesting process

The requesting process of fresh plates is a process in which collaboration and communication are important since both the G4 Line and the manual moulding department are involved in it. If waiting times occur during this process that is mainly due to bad collaboration and communication. This paragraph will give a more in-depth explanation about this process and several issues that appear during this process.

The requesting process consists of various steps that should be performed by the cart driver or the G4 Line operator. To easily explain the requesting process the various steps are listed below in a chronological order. The employee (or machine) mentioned in parentheses performs the specific step. A visualisation of this process can be found in ***Appendix B.2*** in the form of a flow diagram.

1. Place an empty cart (*Driver*): Before requesting fresh plates there should be an empty cart next to the G4 Line, since the fresh plates will be loaded onto this cart. Most of the times the driver already placed an empty cart right after he removed a loaded cart. If he did not do that, then he should place an empty cart next to the G4 Line first. With an empty cart next to the G4 Line the request for new plates can be made.

2. Make request (*Driver*): Based on the schedule the cart driver can now make a request for a certain amount of fresh plates. Most of the times the amount of requested fresh plates is 8, but sometimes the amount is different. For each amount of plates requested the process stays the same. The request is made at a small computer next to the G4 Line and this request is then send to the G4 Line operator.

3. Complete the request (*Operator*): When the request is sent by the cart driver he is dependent on the operator and has to wait till all requested plates are produced. The operator gets a notification of the request on his control screen. Normally when the request is received the operator changes the machine settings and starts the production of the fresh plates and completes the request. However from time to time the operator doesn't start working on the request straight away because he's busy with something else or just doesn't notice the request. If the operator doesn't start working on the request straight away then the waiting time of the cart driver increases. So if the operator doesn't start working on the request in 1 or 2 minutes then the cart driver requests the operator again to start working on the request. This process is also showed with the help of timers in the flow diagram in ***Appendix B.2*** The production process of the fresh plates starts when the machine settings are changed by the operator.

4. Produce fresh plates (*Machine*): With the machine settings changed the requested amount of plates without strengthening strip are produced. Each plate is put on the empty cart next to the G4 Line. If all plates are on this empty cart then the cart driver gets a notification that the cart with plates can be moved away from the G4 Line.

5. Remove loaded cart (*Driver*): With the requested amount of plates ready on the cart the cart driver can remove the cart away from the G4 Line. After removing this loaded cart the requesting process is done and the loaded cart should be moved, which is explained in the next paragraph.

Since the driver has three different carts available, most of the times the he already places an empty cart next to the G4 Line and also hands in a request for fresh plates. This way step 3 and 4 of the next requesting process can take place while the driver is working on the moving process. So by already requesting new plates before starting the moving process some time can be saved.

2.4 Moving process

Now that the requesting process is done the fresh plates should be moved to their next location. This next location can be one of the two punching machines or to the table. To move the plates to their desired location the cart driver has three different carts available on which plates can be loaded.

The location where the fresh plates should go is, just like at the requesting process, based on the schedule of that day. This is quickly shown with the help of a flow diagram, this flow diagram can be found in ***Appendix B.6***. As soon as the moving process is in progress the driver is not dependent on other factors during this process, therefore no waiting times occur during the moving process. In ***Appendix B.3*** there is a map of the work floor with the driving routes of the cart driver pictured in yellow on the map. As shown on this map; when the driver is close to one of the punching machines he has to drive backwards to be able to deliver the plates. The fresh plates can be unloaded when the loaded cart is standing right in front of the punching machine. But unloading the fresh plates is part of the punching process and will be explained in the next paragraph.

2.5 Punching process

The next process to come to a proper end product is the punching process. In this process the larger plates are punched into smaller plates with the help of punching knifes. These smaller plates can then later on be used at the moulding process. In this process the 'regular' employees of the manual moulding department appear for the first time. As already mentioned in *paragraph 2.1* these employees are responsible for the punching process and moulding process of a specific special part that they get assigned to. In this process one or two employees are involved and the cart driver is partly involved as well. Since the employees are dependent on the cart and also the other way around the punching process is responsible for unnecessary waiting times. In the steps will be explained where and why these waiting times occur in the process.

Before explaining the step of the punching process in more detail it should be mentioned that there are two punching machines in the manual moulding process. Between those two punching machines there are some minor differences. The main and most important difference between the punching machines is that there are different punching knifes present at the punching machines. Each special part needs its own punching knife, so that means that each special part has its own desired punching machine on which it is produced. On punching machine 1 the *k-nok* special part is mainly produced, the other special parts will be produced on punching machine 2.

The place where the plates are put on the mould is different for each special part. In the example down below the employees produce the *k-nok.* This punching process consists of 6 different steps and these steps are described in chronological order. For each step a map of the work floor is made to visualize the movements made during the step. These maps are numbered and can be found in chronological order in ***Appendix B.4***. To make it easier to read the description of each step is also placed in the appendix.

1. Move to punching machine: As explained the employees are responsible for the punching process and moulding process of a specific special part. So when they are done with the moulding process they start with the punching process again with a fresh amount of plates. So in reality the first step in the punching process is the employees moving back to the punching machine with their driveable tables. In the map the movement of the cart driver is also shown. This is part of the moving process, but normally this movement takes place at the same time as the employee movement. So for a better understanding the cart driver is shown on the map as well.

2. Unload the plates: When the loaded cart is standing right in front of the punching machine the fresh plates are ready to be unloaded onto the punching machine. The fresh plates are unloaded by attaching an engine to the loaded cart, with help of this engine the conveyor belt on the loaded cart will be turned on. Then the fresh plates are transported onto the punching machine. With all plates on the belt of the punching machine the engine can be detached. During this step the waiting times occur in the punching process.

Most of the times the plates on the cart are unloaded by the employees, only in the early morning the driver unloads the plates himself. If the employees are not there yet when the driver arrives he has to wait for the employees and gets waiting time. But the driver can also decide to just leave the cart behind and move on. Then he has to go back later to return this empty cart to the G4 Line. It also works the other way around, the employees can be waiting at the punching machine till the cart driver arrives. Then these employees have waiting time.

3. Start punching: Now that the fresh plates are ready on the punching machine the actual punching can begin. The employees grab the correct punching knife they need for the special part that they want to produce. Then, with help of a conveyor belt, the punching plates with the punching knife are moved under the press. The press is then activated and the punching knife is punched through the layers of plates. The result are small plates that can be used for the moulding process. The waste that is not needed anymore will be thrown away in a special waste cart, the waste can then later on be recycled. This process of punching continues until the whole surface of the plates are punched out.

4. Move plates on table: The punching is done and all the smaller plates are ready to be moved to the moulding process. To move the smaller plates they should be loaded onto driveable tables. While loading the plates onto the table it's important that water is put between the plates so that the plates don't stick together.

5. Go to moulding place: Now that the smaller parts are ready and loaded onto the driveable tables the employees can move the place where they can put the plates onto the mould. This place is dependent on the specific special part that is produced, in this example the employees produce a *k-nok* so they go to one of the *k-nok* machines.

6. Arrive at moulding place: The last step of the punching process is that the employees arrive at the *k-nok* machine with the smaller plates. From then on the moulding process starts.

2.6 Moulding process

The last process that is done on the manual moulding department to get to the end product is the moulding process. During this process the smaller plates from the punching process are placed on a mould. Then the moulds are put away to harden for about a day and then the special part is done and ready to get a coating. As mentioned before this moulding process can take place at different places on the work floor. This is also visualised in ***Appendix B.1***. The moulding process is fairly easy and no waiting times occur during this process. That's why the moulding process will not be explained in more detail since it doesn't affect the research.

2.7 Observation

A large part of the information mentioned above in this chapter is based on the observation that was done during the research. Here the process behind this observation is shortly explained and some major findings of this observation will be mentioned. Some of these findings might be already mentioned earlier in this chapter, but for a more understandable research these findings are mentioned again shortly.

The observation was done in the morning when the start-up of the day is done. The transport driver starts around 6:30/6:45 with requesting and delivering fresh plates so that the employees can start around 7:00. During this observation the cart driver is followed for about an hour during the process in the early morning. The timeline of this observation is found in the ***Appendix B.8***.

During this observation there were a few findings that were interesting for the rest of the research, these findings will be explained below:

- Most of the employees that start at 7:00 already start a little earlier. Because of this the driver is able to deliver the plate much quicker in the morning, since the employees can help unloading the carts. When some employees start a little earlier this is also helpful for the rest of the day. For example, normally all employees need plates at 7:00, 8:00, 9:00 etc. since they work in shifts of an hour. So each hour the driver will have problems to deliver all plates at once. However if these employees start a bit earlier they need plates at, for example, 6:50, 7:50, 8:50 etc. This makes it easier for the driver to deliver plates the rest of the day.

- Driving with the cart is quite difficult, especially at the punching machines and the G4 Line since driving backwards is necessary there. Sometimes multiple attempts are necessary to get the cart precisely in front of the punching machine. So this driving takes some unnecessary extra time.
- Manually unrolling the plates at the table can only be done with two people. So if the driver arrives at the tables with no employees nearby then he can't unroll the plates. This might for example happen early in the morning before 7:00, when most employees are not working yet. However the driver told me that most of the times someone is available to help him with unrolling. Besides that the manually unrolling also takes a lot of time since each plates has to be unrolled individually, some plates even need to be split before unrolling.

Next to the above findings there was another main thing that was noticed during the observation. The cart driver is dependent on a lot of different factors he has no influence on. For example the schedule, the G4 Line, other employees etc. All these different factors have influence on the work of the driver, this also make the problem more difficult to solve. If the driver doesn't arrives on time this can be influenced by various different factors. So to solve the problem of the driver not arriving on the right time all these factors should be looked into. Making the problem more complicated to solve since each factor needs to be addressed on its own.

2.8 Spaghetti diagram

With the help of the observations and interviews it was possible to create a spaghetti diagram of the manual moulding department. This spaghetti diagram helps to get an even better understanding of the manual moulding process and can therefore help later on while building the simulation model. Pictured in the spaghetti diagram are all employees that start at 7:00 in the morning based on the schedule in ***Appendix B.7*****.** Also pictured in the spaghetti diagram is the transporter that delivers the plates to both punching machines and the different tables. The employee movement is pictured with help of green lines and the transporter movements are pictured with yellow lines. This spaghetti diagram can be found in ***Appendix B.5***.

3. Theoretical framework

During this chapter of the research the third sub-research question should be answered with the help of a literature review.

Q3: Which existing theories can be used to reduce the waiting times in the manual moulding process?

The optimal goal when answering this sub-research question is to find a applicable theory that can be used to reduce the waiting times in the manual moulding department. In this chapter two interesting theories will be explained and an answer to the sub-research question will be given, therefore this chapter is structured as follows:

§ 3.1 – Introduction
§ 3.2 – Theory of Constraints
§ 3.3 – Drum Buffer Rope theory
§ 3.4 – Apply theory on Eternit
§ 3.5 – Possible solutions based on the theory

3.1 Introduction

To answer the sub-research question above a literature review has been done in various databases. Goal of this literature review was to find theories that could give an answer to at least one, and hopefully two, of the following questions:

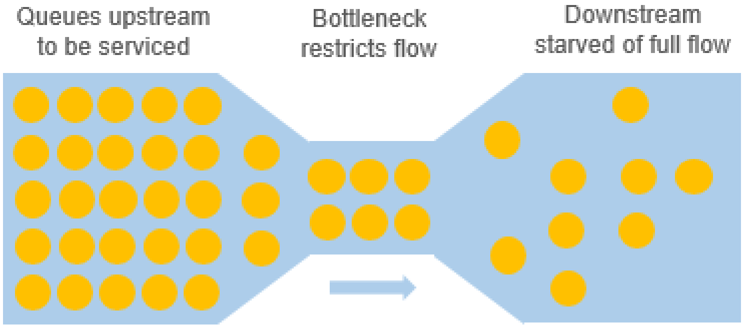
- How to reduce waiting times in a production process?
- How to deal with a bottleneck in a production process?

With the help of a systematic literature review (***Appendix F.1***) a multiple theories were found that can help solving one or two of the above questions. Finding theories to answer those two questions should also help with answering the sub-research question (**Q3**). Not all theories found are applicable equally well to the manual moulding process, so of all these theories a selection is made. Since reducing the waiting times in the manual moulding department is a complex problem multiple theories were being considered to improve the process. But in the end two theories were chosen that could help with optimizing the manual moulding process. More about these chosen theories in *paragraphs 4.1 and 4.2*. The sub-research question will be answered in *paragraph 4.3* and the theories will then also be applied to the manual moulding department of Eternit.

Before going to the multiple theories it's important to shortly address the definition of waiting time. The definition of waiting time, according to *The Law Dictionary,* is the period where an employee is unable to work because of factors he has no control over. So at the manual moulding department waiting occurs when the driver has to wait for the G4 Line or for the 'regular' employees. For the 'regular' employees waiting times occurs when they need to wait for the cart driver. This theory of waiting time will be used during this research.

3.2 Theory of constraints

A commonly used method to optimize production processes and therefore reduce waiting time is the *Theory of Constraints (TOC)* created by Eliyahu Goldratt in 1990. Like the name says this theory focusses on constraints/bottlenecks inside a production process. According to Goldratt each production process is limited in its outcome because it has one or more bottlenecks. Goldratt refers to these bottlenecks as constraints, the performance of the system's constraint will determine the performance of the entire system. The constraint will have an effect on the flow of the whole production process and will therefore reduce the performance of the process, this is also visualized in the image below.



Process flow is affected by a bottleneck and/or constraint.

Figure 2: Bottleneck impacts the flow (Theory of Constraints)

Most managements look into a production process with a profit focus, they want to make as much profit from their production process as possible (Goldratt, 1990). As a result of this profit focus each process is looked into individually, so everyone is busy with their own little process in the whole production process. Each little process tries to get their production rate as high as possible while keeping costs low to contribute as much as possible to the profit. Downside of this profit focus is that there is less collaboration between these processes, everyone is busy cleaning their own problems and getting profit. This lack of collaboration most of the times leads to constraints and/or bottlenecks since there is no clear communication between the different processes. In the end these bottlenecks lead to less profit.

In the *TOC* Goldratt uses a production focus to optimize the production process. With the production focus it's not that much about profit or about the production rate of a single process. The production focus is about the throughput of the entire production process. According to this production focus a good throughput of the entire production process is only reachable if all the different processes collaborate and communicate together. So optimizing the production process during *TOC* is done by letting the entire process work together. Most important in optimizing this entire production process then is to solve and/or optimize the constraint.

So to optimize the whole production process a production focus is needed and then the constraint should be solved and/or optimized. In *TOC* Goldratt describes five focussing steps that should be used to increase the flow through the constraint and therefore the flow through the whole production process.

1. Identify the constraint in the process
- *Find the constraint/weakest link in the production process by observing this process. Most of the times the constraint is the process that is running at maximum capacity.*

2. Determine the most effective means to exploit it
- *Research the most effective way to exploit the constraint. Exploitation of the constraint seeks to achieve the highest rate of throughput possible using the current resources of the organisation. TOC aims to use current resources more efficient instead of adding more capacity.*

3. Subordinate everything else to the above decision
- The other steps in the process should be made subordinate, since the constraint determines the performance of the whole production process. Improving other processes is a waste of time and costs.

4. Elevate the constraint
- Elevate the capacity of the constraint by adding new resources. This step is only done if step 2 and 3 didn't increase the capacity enough to break the constraint.

5. If in the previous the constraint has moved, go back to step 1.
- If during the process another constraint appears then go back to step 1 to also improve the throughput of this constraint.

According to Goldratt it's important to first pinpoint the core problems during these steps before coming up with solutions to the constraints. Solving these core problems will have far more effect on the constraint than hopping from one small problem to another. When the core problems are identified it's important to firstly clarify to *what the problem should be changed to*. When it's clear what the end goal of the problem is the solution generation can start according to Goldratt. A possible solution to solve a constraint is the *Drum Buffer Rope* theory that will be discussed during the next paragraph. But all options need to be considered during the solution generation to come to a sufficient solution.

If, and only if, the required solution is found men should think about the implementation of this solution. Possible implementation of a solution may not be an issue during the solutions generation. When this is an issue someone might hold back their solutions during this step, because he thinks the solution is too difficult to implement. But according to Goldratt this solution implementation is even as important as the solution generation. For a solution to get accepted by most and for the solution to work on the long term this solutions implementation is an important step and should be take seriously according to Goldratt.

3.3 Drum Buffer Rope theory

A theory that can be used to optimize a production process and to improve the throughput of a bottleneck/constraint is the *Drum Buffer Rope* theory as described by Watson et al. (2006). The *Drum Buffer Rope* theory is used to improve a weak chain in a production process, the so called bottleneck or constraint. The *Drum Buffer Rope* theory can also be used during the Theory of Constraints, however it's not the same. That's why the *Drum Buffer Rope* theory is introduced as a separate theory during this report.

The *Drum Buffer Rope* theory compares a production process with a chain; each resource and function are linked. So like a chain, the whole production process is as strong as the weakest link, again called a constraint. In this theory the constraint is called the drum and this drum determines the pace of the whole production process. So in order to improve the production process the weakest link, the drum, should be optimized. According to the theory the drum can be optimized by doing the following things:

1. <u>Develop a detailed schedule for the drum.</u>

First create a detailed schedule for the drum that is reachable, so that the maximum capacity is not transcended. This schedule is important since this schedule determines the working speed of the drum and therefore also determines the pace of the rest of the production process.

2. <u>Add buffers to protect the performance of that resource.</u>

Buffers can be placed in front or behind the drum to compensate for process variation, these buffers make the *Drum Buffer Rope* theory very stable and flexible. Since the drum determines the pace of the process it's important that the drum can work/produce at its maximum speed, this is only possible if the drum always has material to work with. So the buffer in front of the drum can compensate for variation earlier in the process and therefore keep the drum running at its maximum speed. With a buffer behind the drum it can be assured that processes behind the drum can always continue, even if the drum has some problems. So both buffers can compensate for variations in the process and make the production process more stable against possible problems.

3. <u>Synchronize the schedule of all other resources to the drum schedule.</u>

The other parts in the production process should be synchronized with the schedule of the drum. So resources should be released at the same rate as the drum can consume it, this is done by the rope. The rope gives a sign to the start of the process as soon as the drum consumed a resource, then the production of a new resource starts. Also the processes behind the drum should be scheduled to work at the speed of the drum.

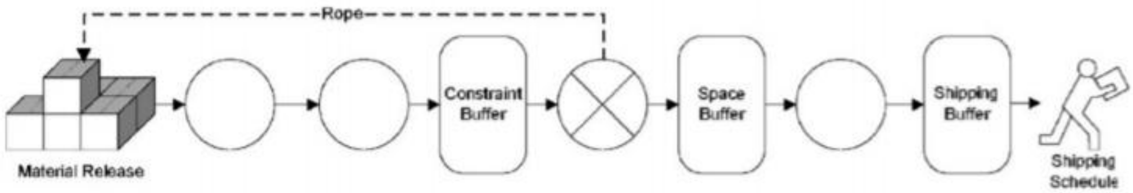


Figure 3: Drum Buffer Rope technique (Watson et al, 2006)

The image above gives a visualisation of the *Drum Buffer Rope* technique. In this particular image the circle with the cross in it is the drum or constraint of the process. This drum determines the pace of the whole production process. In this particular case there is a buffer both before and after the drum to deal with variations in the process. The buffer before the drum makes sure that the drum always has resources and can therefore produce at its maximum speed. The buffer behind the drum makes sure that the output of the drum stays steady, even if problems occur. If the drum almost runs out of resources then the first processes should start producing at the same pace as the drum. This is communicated by the rope, also visualized in this image. The rope is basically used for communication between the drum and the other processes. With help of this rope is made sure that other processes are synchronized with the drum.

3.4 Apply theory on Eternit

Now that the *Theory of Constraints* theory and the *Drum Buffer Rope* theory are all explained and set out it's the right moment to apply these theories to the manual moulding department of Eternit. This paragraph will apply both theories to the manual moulding department and will explain how this theory can help with optimizing the manual moulding process. In the end also an introduction will be given how the *Drum Buffer Rope* theory can help with a solution to reduce the waiting times.

3.4.1 Theory of Constraints

Right now inside of Eternit there is kind of a profit focus, the manual moulding department and especially the G4 Line are mainly focussed on their own production rate and profit. The same goes a bit for the manual moulding department itself. Here all the little processes also mainly focus on themselves instead of collaborating with the other little processes. In the manual moulding process the G4 Line is mostly busy with producing the 'regular' corrugated sheets and not so much with producing plates for the cart driver. The 'regular' employees who are responsible for the punching and moulding are mainly interested in reaching their target for the day. The cart driver on the other hand is more willing to collaborate since he is dependent on both the G4 Line and the 'regular' employees. But at the end of the day the driver is also mainly focussed on his own process. So right now inside of Eternit and inside of the manual moulding department there is kind of a profit focus. Each different process is really busy with its own production rate and profit instead of working together. To solve the constraints inside the manual moulding process there should be more of a production focus. This research will be solved with a production focus to optimize and/or solve the constraint to make sure that the entire production process is optimized and the waiting times are reduced.

The five focusing steps from Goldratt can be followed to optimize the manual moulding process with the help of the *Theory of Constraints*:

The first step is to identify the constraint, this is mainly done by observations and the information from chapter 2 is used. The constraint in the manual moulding process of Eternit is the plate delivery process, the process in which the cart driver delivers plates at various locations. This plate delivery process is a combination of the requesting process and the moving process mentioned before in chapter 2. So together these processes together lead to problems and are the constraint. The cart driver most of the time has difficulties to deliver new fresh plates on time to the 'regular' employees. Which then leads to problems later on in the manual moulding process since the 'regular' employees have no fresh plates available to work with.

On the same day as the observation took place a total of 12 measurements were done to support the claim that the plate delivery process is mainly responsible for the waiting times and therefore is also the constraint. Six of these measurements took place on the waiting time of the transporter. The waiting time of the transporter is the time between his arrival at the G4 Line to get new plates and his departure. Also six measurements were done on the waiting time of the employees. This waiting time is the time between the arrival of the employees at the punching machine, based on the schedule, and the moment they can start with punching the plates. Besides the transporter and the punching employees there are no other places in the manual moulding process where waiting time occurs, so based on these measurements the bottleneck can be determined. The outcomes of these measurements can be found in ***Appendix C.1***.

Five out of the six times the plate transporter had to wait at the G4 Line because the plates were still being produced, so quite a lot of waiting time occurred in those situations. Only one time the plates were already produced and ready at the G4 Line, this time the transporter only had some loading time that is also counted as waiting time. For the employees the plate transporter was too late at the punching machine two out of the six times because there were some problems with the plate delivery process. One time the waiting time occurred because the punching machine was still being used and therefore the punching employees had to wait for a little until the previous punching job was finished. The other three times the transporter was at the punching machine at the desired time, these times there was only some unloading time that was measured as waiting time. As said the measurements are in ***Appendix C.1***, there also a legend can be found that explains the measurements.

Based on these measurements the conclusion can be drawn that the plate delivery process is the constraint/bottleneck in the manual moulding process. Out of the 12 measurements there were four situations in which no specific waiting time occurred, only (un)loading times were counted as waiting time. In seven out of the 12 measurements waiting time occurred because of the plate delivery process. Only one time the waiting time that occurred was caused by the punching process. This is also shown in the chart in ***Appendix C.2***, in this chart can be seen that seven from the eight times the plate delivery process is responsible for the waiting time that occurred. So based on this chart and the measurements the conclusion is quite clear that this plate delivery process is the constraint/bottleneck in the manual moulding process.

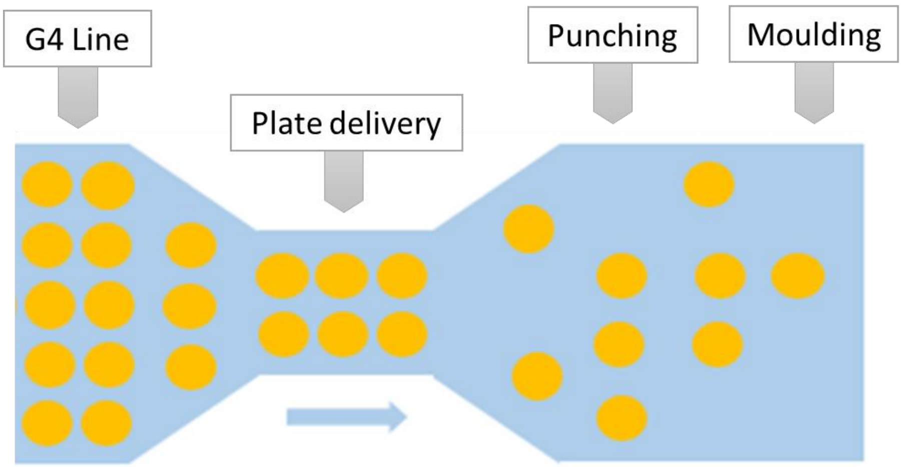


Figure 4: Bottleneck inside the manual moulding process

In the image above the manual moulding process is visualized in a very simple way. This image is already earlier used during this chapter to visualize the *TOC*. In this image the constraint of the manual moulding process can be seen easily. In this image the plates are represented by the yellow dots. Entirely on the left is the G4 Line that can produce a lot of plates in a short period, in an optimal scenario these plates flow through the process smoothly and they arrive without problems at the other processes like punching and moulding. But in the manual moulding process problems occur during the requesting and moving process, in this image these processes are put together into the plate delivery process. Because of problems during this plate delivery process the flow of the rest of the process gets affected. This has influence on the entire throughput of the manual moulding process. Therefore this plate delivery process is the constraint in the process that should be solved and/or optimized. Now that the constraint of the manual moulding process is clearly defined the following four focusing steps of Goldratt should be followed to be able to optimize this constraint. This will be done during the experiments later on in the research.

3.4.2 Drum buffer rope

As mentioned earlier in this chapter the *Drum Buffer Rope* theory can help with finding a good solution to solve and/or optimize the constraint that was noticed when applying the *Theory of Constraints*. In this part of the paragraph the *Drum Buffer Rope* will be applied to the manual moulding department and there will be an explanation how this theory can help with reducing the waiting times.

In the last paragraph the constraint of the manual moulding process was already identified, the delivery of the plates is where the problems occur. As mentioned and visualized earlier these problems affect the flow and throughput of the entire production process. To come up with solutions towards this constraint the *Drum Buffer Rope* theory will be used. According to this theory the constraint/bottleneck of the process should determine the pace, this is called the drum. So in the manual moulding process the plate delivery process is the drum, this plate delivery process consists of the requesting process and the moving process. So simply speaking the cart driver determines the pace of the whole process. But of course the cart driver is also dependent on other processes. From now on the plate delivery process and the cart driver are mentioned to as the drum, the process that should set the pace.

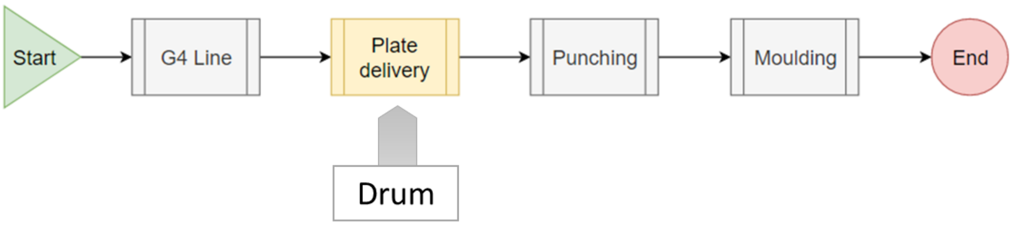


Figure 5: Place of the drum inside manual moulding process

In the image above the manual moulding process is simplified and the drum is shown. Now with the drum of the manual moulding process being clear it's time to follow the theory of the *Drum Buffer Rope* as described by Watson. Following this theory hopefully leads to a better throughput of the entire production process and leads to less waiting times. The *Drum Buffer Rope* steps mentioned earlier in this chapter will be followed in this paragraph. The perfect solutions will not be given in this paragraph, only how these steps can help with coming to a perfect solution.

1. Develop a detailed schedule for the drum.

Based on the schedule of that week the drum should deliver a certain amount of plates at different locations before certain times. This schedule is made based on the current ongoing orders, so there is not a lot of flexibility in this schedule. But the schedule is not really strict, this will be explained with an example. In the schedule are for example four different locations that need plates before 7:00, the cart driver starts with delivering these plates around 30 minutes earlier. An example of this schedule can be found in ***Appendix B.7***. Beforehand there is no strict order in which the cart driver has to deliver plates to these four locations, so the order in which these plates are delivered can be changed. To make sure that the drum works on the best way possible a detailed schedule for this order should be made. This order should be made with the help of calculations so that the best order is chosen, ensuring that the drum works at its maximum pace.

2. Add buffers to protect the performance of that resource.

As mentioned earlier buffers can be used to deal with process variations and to ensure a steady throughput of the process. In the manual moulding process a buffer can be placed in front of the drum, so after the G4 Line. With this buffer the cart driver should always have plates available to deliver, instead of sometimes waiting for new plates. This buffer might help with drastically reducing the waiting times. Next to that buffers can be placed at the different locations where the punching process takes place. With the help of this buffer the 'regular' employees always have plates available for their punching process. This buffer leads to less variation after the drum, which might help reducing waiting times.

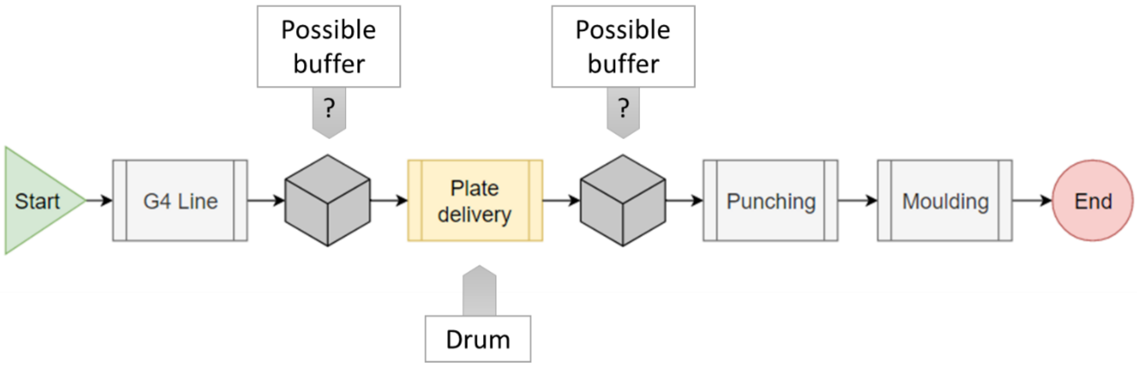


Figure 6: Possible buffer locations inside manual moulding process

The image above shows the possible locations of the buffers. The ideal locations of these buffers will be later on decided based on calculations and simulations. Then will also be decided what the buffers should look like.

3. Synchronize the schedule of all other resources to the drum schedule.

The next and last step according to the *Drum Buffer Rope* theory of Watson is to synchronize the schedules of all other processes to the schedule of the drum. Most important in this synchronization is the collaboration and communication between the different processes. This communication between processes are mentioned as 'ropes' by Watson. These ropes help making sure that the other processes work on the pace of the drum. In the manual moulding process a rope should be placed between the cart driver and the G4 Line since good collaboration and communication between these processes is necessary. This can be done by for example purchasing a radio telephone/headphones for both the plate transporter as well for the G4 Line operator so that they can communicate with each other all the times. A better communication can make sure that the G4 Line can produces resources at the same pace as the cart driver needs them. This way the cart driver never needs to wait for new plates and therefore the waiting time can be reduced. The possible place of this rope is

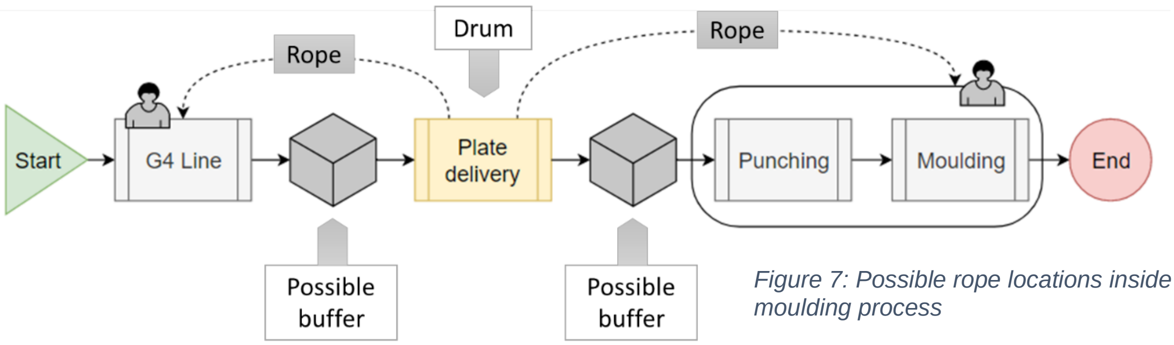


Figure 7: Possible rope locations inside manual moulding process

visualized in the image above. The possibilities and benefits of this rope should be more thoroughly researched later in the research.

Another possible place for a rope is between the plate delivery and the ‘regular’ employees that are responsible for the punching and moulding process. A better communication between the cart driver and the ‘regular’ employees might help with reducing waiting times. The ‘regular’ employees are dependent on the cart driver for fresh plates, with better communication it becomes easier for the cart driver to deliver fresh plates on the right time. The possible place of this rope is also shown in the image, this image can be found on the previous page. Just like the last rope, the possibilities and benefits of this rope should be researched later on in this research.

3.5 Possible solutions based on the theory

Based on these existing theories there are a few possible solutions that should be tested with the help of a simulation model. This can be done be implementing these solutions in the basic simulation model that will be discussed in chapter four. After that experiments can be performed with the newly created simulation models to see if these existing theories may improve the manual moulding department. The theories that should be tested with experiments are mentioned shortly below:

Solution 1: Make the transporter the leading factor *(Theory of Constraints)*

Mentioned during the *Theory of Constraints* is that each process has its own constraint that holds back the performance of the whole process. As mentioned earlier during this chapter the plate delivery/requesting process is the constraint inside the manual moulding department. According to the *Theory of Constraints* this constraint can be solved by giving this problem the highest priority. Right now the plate transporter has to request new plates to an operator of the G4 Line, so the plate transporter and the plate requesting process do not have the highest priority. So to follow the *Theory of Constraints* it should be tested what happens when the plate transporter becomes the leading factor and the operator is removed from the process.

Solutions 2: Place an (extra) buffer next to punching machines *(Drum Buffer Rope)*

The punching process inside the manual moulding department is fully dependent on the plate delivery process. According to the *Drum Buffer Rope* theory this plate delivery process is the drum and therefore the part that causes problems inside the process. To solve this, according to *Drum Buffer Rope*, buffers should be placed on strategical places to deal with process variations of the drum. So in this case a (extra) buffer can be placed in front of the punching process so that the punching process always has a steady throughput of fresh plates despite variations at the plate delivery process. So it should be tested if placing a (extra) buffer before the punching process leads to a decrease in the waiting times.

4. Simulation model

For this research a simulation model is built in the Plant Simulation software, this will be a 'basic' simulation model that represents the current situation inside the manual moulding department. This simulation model can then be used to measure the various waiting times inside the manual moulding department. The waiting times from this 'basic' simulation model will be used as the baseline measurement. Besides this 'basic' simulation model there are five more system configurations of the existing simulation model that will be built with a possible solution implemented. Later on the experimental results of the 'basic' simulation model and the five other simulation models will be compared with each other. But first in this chapter there will be more information on the simulation model. Therefore, this chapter is structure as follows:

§ 4.1 – Theory on simulation model design
§ 4.2 – Conceptual model of the manual moulding department
§ 4.3 – The interface of the simulation model
§ 4.4 – Logic behind the simulation model
` **§ 4.5** – Validation of the simulation model

4.1 Theory on simulation model design

All the simulation models in this research rely on the simulation theory mentioned by Robinson (2014) and Law (2015) in their simulation books. According to both Law and Robinson simulation is about achieving results in a simplified computer model, the results of this simplified model are later on used to improve a real world system. In the model down below the setup of a simulation study is shown in a simplified manner:

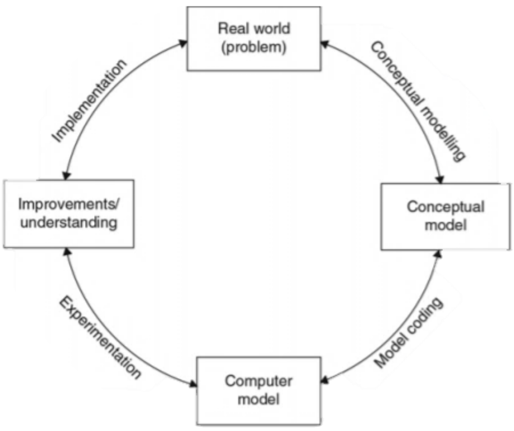


Figure 8: Setup of a simulation study

Most of the times when a simulation model is used this is because there is a problem in a real world system, a simulation study can then help to get more knowledge about the problem. For the simulation study the real world should be simplified and put into a computer model. So basically the first task during a simulation study is to understand the real world system and to put this system into a simpler simulation model. To come up with an appropriate simulation model the level of abstraction at which to work should be determined. Abstracting a model from the real world is done with the help of a process known as conceptual modelling.

A conceptual model is a specific description of a simulation model that will be developed later on. This conceptual model should describe the objectives, inputs of the model, outputs of the model, assumptions and simplifications of the simulation model. Especially the simplifications that take place are important since, as said before, a real world system is way too complex to put into a simulation model. So simplifications are crucial to be able to even develop a simulation model in the first place. But on the other hand there shouldn't be too much simplifications because then the simulation model will no longer be a representation of the real world system. If the difference between the model and the real world is too big than the results of the simulation model will be meaningless for the real world. So simplifications are crucial when developing a simulation model but they should only be used when necessary.

Before explaining the conceptual model used for this research in the next paragraph there is one more thing that should be discussed. There are a lot of different software programs that can be used to build a simulation model, Plant Simulation is only one of them. For all these programs there are, simply speaking, two different options they can use to run a simulation. The first one used by quite a few software programs is *Time-Oriented Simulation, TOS* from now on. With TOS the time passes continuously, just like it happens in the real world. For instance, when a product moves along a conveyor line in the simulation there will be no leaps in time. As said before, the time is continuous so the product will simply move on the conveyor line while time keeps ticking away at the same time.

The other way to run simulations is with help of the so called *Discrete Event Simulation* way*, DES* from now on. A DES program only takes into consideration the points in time where something happens that is important for the rest of the simulation. For example a product entering a certain machine or products being unloaded into a storage. Any movements between the important points in time are simply skipped by the simulation since these movements are of less interest for the simulation. This is also immediately the main advantage of DES in comparison with TOS. A DES program can simply skip the less interesting points during a simulation, this makes the performance of DES way better than TOS. So with the help of a DES program simulating a few months in real life only takes a couple of minutes.

The simulation software used during this research, Plant Simulation, is a DES program. So only the most interesting points, called events by Plant Simulation, will be taken into account during the simulation runs performed later in the research. Since a DES program has such a good performance it is quite simple to do a lot of replications when running a certain simulation model. With the help of the replications and the good performance it is possible to run the same day over and over again in a matter of minutes. Each replications will have different values because of the probabilities used in the simulation model. Therefore each replication will have a slightly different result. The average of all these results will be the final outcome, this outcome will be a lot more trustworthy because of the multiple replications. So the Plant Simulation software will really fit this research well.

4.2 Conceptual model of the manual moulding department

As mentioned in the last paragraph the conceptual model is a specific description about a simulation model that will be developed later on. A conceptual model contains the objectives, inputs, outputs, simplifications and assumptions of the model (Robinson, 2014). During development of the simulation model this conceptual model serves as a guideline.

Objectives

The first objective is to build a simulation model that represents the actual manual moulding department as far as possible. After the development of this simulation model also five more models/experiments should be developed with possible solutions correctly implemented in these simulation models. With the help of all these simulation models experiments can be performed. The results of all these different experiments will hopefully lead to new insights that can help with decreasing the waiting times in the manual moulding department.

The inputs of the model are all the values that are put into the model after the completion of the model. These values can easily be changed without destroying the logic behind the simulation model. Therefore the model's inputs are the experimental factors, the factors that can be experimented with.

Inputs

- A schedule that contains information when and where certain plates should be delivered. Each simulation model uses the same standard weekly schedule.
- The normal distribution of the processing time of *Punching1, Punching2, SpecialPart* and *PlateProduction.*
- The normal distribution of the response time of the operator of the G4 Line.
- The capacity of the buffers in front of the punching machines, so the capacity of *BufferPM1* and *BufferPM2*. (Standard capacity of these buffers is 1)
- The working hours of both the plate transporter and the waste transporter.

The tasks that have to be performed during the *Punching1, Punching2, SpecialPart* and the *PlateProduction* processes are most of the time the same standard tasks. Each plate goes through the *PlateProduction* and through one of *Punching1, Punching2* or the *SpecialPart.* There may be some fluctuations, but most of the time these standard tasks have almost the same processing time. A process in which the same standard tasks take place each time can be modelled with the help of a normal distribution. For each of the four processes mentioned above 20 different measurements have been performed towards the processing times of these processes. With the help of these measurements and the *Minitab* software it is possible to perform tests to proof that the assumption is correct that the dataset of the measurements follows a normal distribution. This is explained for the *Punching1* process below:
The dataset of *Punching1* is imported into the *Minitab* software. With the help of this software a probability plot is created to test if the dataset can be modelled as a normal distribution. This probability plot created for *Punching1* can be viewed in *figure 10* below. The middle red straight line perfectly follows a normal distribution, so if all datapoints are on this line then the dataset is perfectly normally distributed. For the dataset of *Punching1* this is not the case. However if the datapoints are all inside the other two curved red lines than the dataset can also be modelled as a normal distribution with 95% confidence.. This is the case for this dataset, so the processing time of *Punching1* can be modelled as a normal distribution in the Plant Simulation software.

In the table next to the probability plot the input data for the simulation model is shown. This data will be the input for the processing time of *Punching1.* With the help of these probability plots was also proven that the other three processes follow a normal distribution. The probability plots of the other three processes can be found in ***Appendix D.2***.

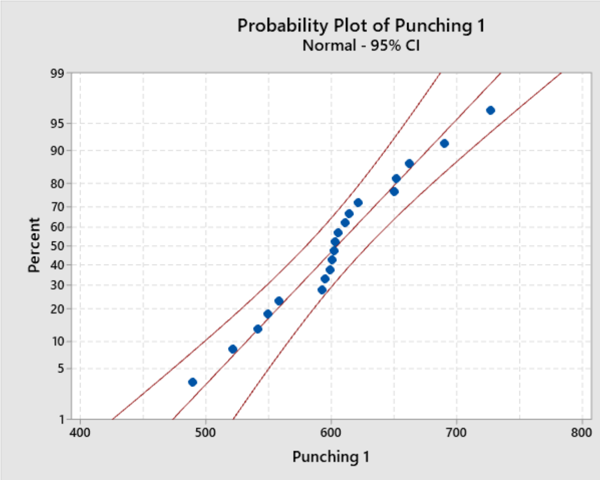


Figure 10: Probability plot for Punching1 processing time

Simulation data for *Punching1* process.	
Mean:	**10:04** *(604s)*
St. Dev:	**0:56** *(56s)*
Lower bound:	**8:09** *(489s)*
Upper bound:	**12:07** *(727s)*

Figure 9: Simulation data for Punching1

Outputs

The outputs are all the KPI's (*Key Performance Indicator*) on which the different simulation models can be compared after running the experiments. So each of the simulation models will have values for all of the outputs mentioned below. The Plant Simulation model should give a lot of different waiting times as output, but they are not all even important. For the experiments only four waiting times are really important, these are the KPI's and are listed below. The *TotAvgWT* gives the best insight into the average performance of a certain solution, so this KPI will be used the most during the comparison later on.

- AvgWT: This is the average waiting time for the plate transporter per plate. So this is the time the plate transporter has to wait on average at the G4 Line plus the time the plate transporter has to wait on average during unloading the plates on one of the punching machines or the tables.
- AvgWT-Emp: This is the average waiting time the punching employees have per plate. This waiting time occurs when a plate arrives later than the scheduled time at one of the punching machines or the tables.
- TotAvgWT: The *AvgWT* plus the *AvgWT-Emp* together is the *TotAvgWT*. So in fact this is the total average waiting time that occurs per plate.
- AvgWasteTime: This is the average time it takes before the waste is picked up and recycled. Measurement of this time starts as soon as the waste is 'created' next to one of the punching machines or the tables. This *AvgWasteTime* should be below the 15 minutes, otherwise the waste got too stiff and can no longer be recycled.

Assumptions

- All the processing times of the processes inside the simulation model are based on several measurements. Based on these measurements the processing times are assumed to be normally distributed. These processing times stay the same in all the simulation models.
- The driving speed of both the plate transporter and the waste transporter is based on the average driving time. This average driving time is based on several measurements inside of the actual manual moulding process.
- After the plate transporter received fresh plates he immediately request new plates at the G4 Line. Of course the transporter will only request plates if there are still more employees that need fresh plates.
- The waste transporter always priorities the waste that is waiting for the longest time.

Simplifications

- A set of multiple plates in the real world is represented by a single plate in the simulation model.
- In the model there is a buffer at both *Punching1* and *Punching2* where the plate transporter can leave a cart with plates behind when the actual punching machine is occupied. In the actual manual moulding department this is also possible, but then the plate transporter also has to pick up the empty cart afterwards. In the simulation model the plate transporter does <u>not</u> pick up this empty cart.
- In the simulation model both the plate transporter and the waste transporter have their own lane in which they drive both forward and backwards. In real life there is only one wide lane in which both drivers can drive at the same time easily. However this will not work in the simulation model since there will be collisions.
- During the requesting process a plate gets a certain desired location where it needs to go, for instance *Punching1*. Just like in real-life, in the model the plate will always go to that desired location and cannot deviate from the path to that location.
- There are no actual punching employees present in the simulation model. There is only a special chart that checks for each plate if its delivered on the scheduled time. When the plate is on time then there is no waiting time. If the plate is overtime than this overtime will be the time the employees had to wait for that certain plate.

4.3 The interface of the simulation model

In this paragraph the interface of the model will be explained, the interface is the part of the model that is visible when opening the model and during the experiments/simulations. Together with the logic behind the model a good understanding of this interface is crucial to understand the working of the simulation model. All the separate parts of this interface will be shortly explained below. For this explanation it comes in handy when one already understand at least the basic concepts of the Plant Simulation software. In ***Appendix D.3*** there is a short introduction to the basic concepts of Plant Simulation. If one is already familiar with at least the basic concepts of Plant Simulation than this introduction in the appendix can be skipped.

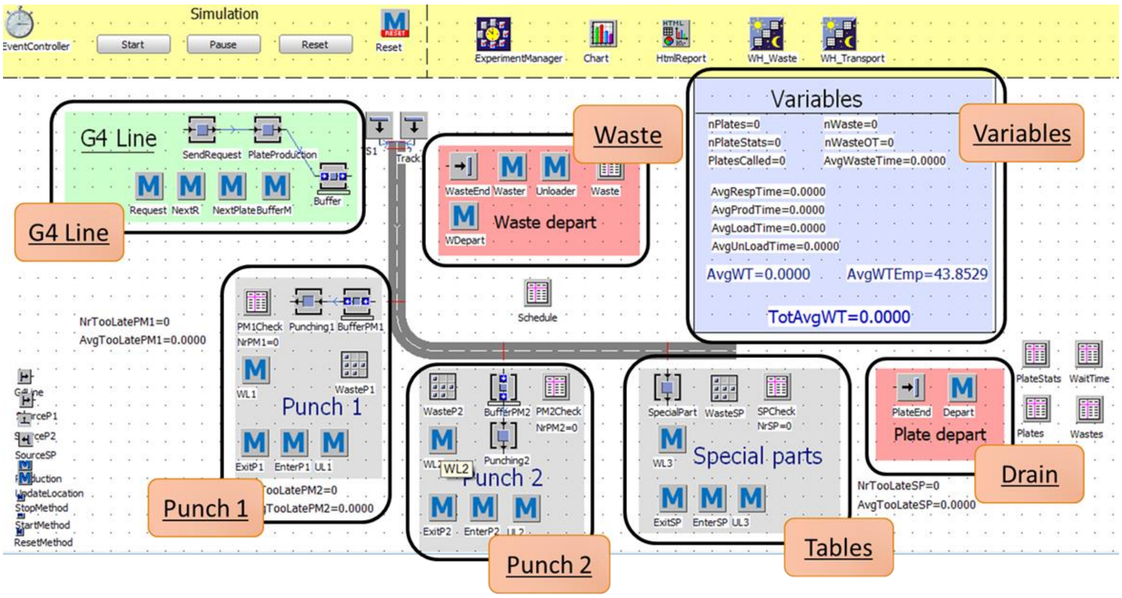


Figure 11: Interface of the simulation model

Now that the core concepts of the Plant Simulation software are hopefully clear it is time to start with explaining the interface of the simulation model. With the help of the conceptual model this interface tries to represent the manual moulding department as good as possible. Above and also in large in ***Appendix D.4*** an image of the interface can be found. On this image a few parts of the interface are highlighted with the help of black squares. For each of the highlighted parts there will be a short introduction and an explanation what happens in these parts. In the image below there is also a *Variables* part where all the data is stored, more information about this part is found in ***Appendix D.5***.

4.4 Logic behind the simulation model

The aim of this paragraph is to give a better insight in the way the simulation model works. For this purpose there will be a flow diagram that should give an idea of the logic that is used during development of the simulation model. Besides that this paragraph will also discuss a few lines of code from the actual simulation model.

4.4.1 Flow diagram of the plate movement

Earlier in this research models of both the requesting process and the moving process were discussed and explained. This requesting process and moving process are also the main processes of the simulation model. These models however are a bit too difficult to implement immediately into the simulation software. Therefore some simplifications were made during implementation into the simulation model.

To get a better idea of the logic behind the requesting and moving process in the simulation model a flow diagram of the movement of a plate can be found in ***Appendix D.1*** This flow diagram gives a perfect insight in the way the simulation model works and how the plate moves through the model. This will hopefully help to better understand the simulation model. If a rectangle has a blue colour this means that the plate is in a process and has to wait for a while until that process is finished. For instance if the plate is at the *SendRequest* process then the plate has to wait until the operator responds before moving on. The green coloured rectangle indicates the start of a new plate requesting and moving process.

4.4.2 The code behind the simulation model

In the Plant Simulation software lines of code play a crucial part in letting the simulation model work. The lines of code in Plant Simulation are placed in so called *methods*, check ***Appendix D.3*** for more information on a *method*. Since these lines of code play such an important role in the simulation model a few lines of code should be shortly discussed. In ***Appendix D.6*** there is a picture with a few lines of code from the simulation model in it. These lines of code are from the *UL1* method, which is a part of the *Punch1* process. Next to these lines of code there are a few lines of so called pseudo code. This pseudo code is the green text on the right and this part of the code will be ignored by the Plant Simulation software. The aim of the pseudo code is to provide information about the real lines of code in the *method*. So the pseudo code in the image will hopefully help with the understanding of the lines of code.

The image in the appendix only contains a small part of all the code that is used in the simulation model. However this part is shown in this report to give a little more insight into the code behind the simulation model. The rest of the code can of course always be viewed in the Plant Simulation model.

4.5 Validation of the simulation model

Another important step during a simulation study is that the simulation model should be validated. With the validation of the simulation model it is checked if the simulation model correctly represents the real-life situation. So for this research should be checked if the simulation model introduced during this chapter correctly represents the manual moulding process. In this research the simulation model is validated in two different ways. The first one is checking together with a supervisor of the manual moulding process if all the assumptions made in the model are correct. The other one is comparing the data of the simulation model with the real-life data. For the real-life data the 12 measurements mentioned earlier during this research could be used.

4.5.1 Validation of the assumptions

For this part of the validation a walkthrough of the simulation model was performed together with the supervisor. During this walkthrough all parts of the simulation model are explained including the assumptions that were made to come up with this simulation model. Each of the assumptions made in the simulation model were understandable and correct from the perspective of the supervisor. During this walkthrough the logic behind the simulation model was also partly explained towards the supervisor. This was also clear and correct according to the supervisor.

4.5.2 Validation of the measurements

Out of the 12 measurements that are found in ***Appendix C.1*** the waiting times of the transporter, the punching employees and the total waiting time can be retrieved with the help of some calculations. These three real-life different waiting times can then be compared to the output of the simulation model.

The waiting times of both the real-life situation as for the simulation model that will be used for the comparison can be found in ***Appendix D.7*** and **D.8** For each waiting time in real-life six different measures were done, the average of these measurements will be compared with the average of the *AvgWT*, *AvgWTEmp* and the *TotAvgWT* that is output of the simulation model. The graph below shows the comparison between the real-life waiting time measured and the waiting time retrieved from the simulation model.

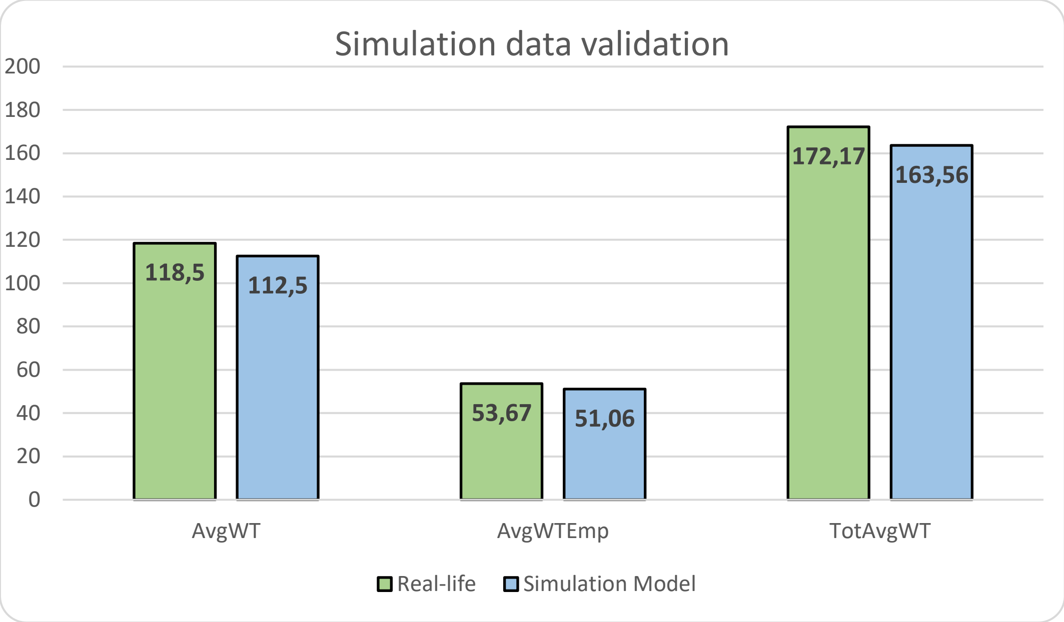


Figure 12: Comparison of waiting times in real-life and simulation model

From this graph can be quickly seen that the real-life waiting time is relatively close to the waiting time that was retrieved with the help of the simulation model. Although the waiting times in real-life are a bit higher in real-life then in the simulation model. But this is probably because only six measurements are done in real-life, when more measurements are done the average will probably go closer to the average of the simulation model. In the table below the percentual difference between the all the average waiting times is shown.

	AvgWT *(s)*	AvgWTEmp *(s)*	TotAvgWT *(s)*
Real-life (base)	118,50	53,67	172,17
Simulation Model	112,50	51,06	163,56
Difference	**+5,33 %**	**+5,11 %**	**+5,26 %**

Figure 13: Difference between real-life and simulation model in percentages

As shown in the table above the waiting times measured in real-life are only around 5% higher then the waiting times that are retrieved from the simulation model. So based on this data, the chart and the table the Plant Simulation model can be validated since the difference between the actual waiting time and the waiting time of the model is minimal. Besides that the assumptions made during the development of the simulation were also correct as mentioned before. Now that the simulation model is validated it could be used for experiments in the next chapter.

5. Results

As already mentioned in the last chapter there will be a total of six different simulation models, each of these models is a bit different and represents another possible solution. Experiments will be performed with all six of these simulation models to find out what is the best possible way to optimize the manual moulding process and therefore reduce the waiting times. In this chapter the different simulation models and results of these experiments will be discussed. But before discussing the results there should also be a short introduction to the concept of experiments in the Plant Simulation software. Therefore this chapter is structured as follows:

§ 5.1 – The simulation configuration
§ 5.2 – Results of the experiments
§ 5.3 – The basic simulation model
§ 5.4 – Plate transporter is leading factor
§ 5.5 – Extra buffer added at punching machines
§ 5.6 – Buffers removed at the punching machines
§ 5.7 – Both transporters are responsible for one punching machine
§ 5.8 – Transporters are leading factor and responsible for one punching machine

5.1 The simulation configuration

In the real world the time needed for certain processes can often not be predicted with absolute certainty. For example the exact time needed for punching a certain amount of plates is difficult to correctly predict. Also for the simulation model there is no way to correctly predict the exact time needed for certain processes. However in both the real world as in the simulation model it is possible to estimate the average time needed for a certain process with the help of a probability function. All the processing times and other times in the simulation model are also handled this way, they are estimations with the help of probability functions.

Running simulation with the help of chances based on probability functions does not seem to be the most confident way to obtain output results on which the six simulation model can be compared. To be able to compare the six different simulation models an accurate estimate (mean) of the KPI's should be obtained. To get to an accurate estimate (mean) of the KPI's of a simulation model according to Robinson (2014) there are two different topics that should be dealt with. The first one is to determine the number of *replications* that should be made while performing the experiments. The other topic is about dealing with the warm-up period in which the KPI data might not be too reliable.

5.1.1 The number of replications

The number of replications that are made during the experiments should be correctly determined to make sure that enough data is obtained to get an accurate average of each KPI. But also after a certain number of replications each extra replication does not affect the average of a KPI anymore. Since each extra replication takes more time no more replications than needed should be performed. According to Robinson (2014) there are two different methods to determine the number of replications that should be made: the confidence interval method and the graphical method. Determining the number of replications in this research is done with the help of the graphical method.

In the graphical method a series of replications is carried out and the cumulative mean of a chosen KPI is plotted against the number of replications, *n*. For this research $n = 1..15$. So with the graphical method a graph will be created in which the cumulative mean of a KPI is plotted against the number of replications. A specific graph will be created for each of the three main KPI's of this research. Then in each graph the number of replications should be selected where the graph becomes flat.

In this research there are three main KPI's, so the number of replications selected should also be based on all the three different graphs. For instance the graph of the first KPI can already become flat after only four replications, but if the graph of the third KPI only becomes flat after eight replications then the experiments should be performed with eight replications. All three graphs from the KPI's used in this research are found below in ***Appendix E.1***.

As can be seen in the appendix the graph of both the *TotAvgWT* and the *AvgWT* become flat after the eight replication. This means that for both the *TotAvgWT* and the *AvgWT* at least eight replications are needed to obtain enough data to get an accurate average of those KPI's. An extra replication does not affect the average of this KPI anymore. The graph of the *AvgWTEmp* already becomes flat after the seventh replication. So for the *AvgWTEmp* only seven replications need to be performed to make sure that enough data is obtained to get an accurate average of this KPI. For the *AvgWTEmp* also applies that an extra replication does not affect the average of this KPI anymore.

Summarizing; both the *TotAvgWT* and the *AvgWT* need eight replications to make sure that an accurate average is obtained. The *AvgWTEmp* only needs seven replications to be able to gain enough data to get an accurate average. Therefore, the number of replications that will be performed during the experiments will be eight. This number of eight replications is ideal for both the *TotAvgWT* and the *AvgWT* since this is the exact number where the graphs of those KPI's become flat. For the *AvgWTEmp* seven replications are ideal, but as already mentioned before an extra eight replication does not affect the average of the *AvgWTEmp* KPI anymore.

5.1.2 Warm-up period

During the start of a simulation run the data is most of the times not really reliable since the simulation only just started. The same goes for real-life, if one wants to collect data about a certain process then the data will not be collected during the start-up of the process since this data is not too reliable. Therefore most simulation studies will use a warm-up period in which the retrieved data is not stored and will not be taken into account. However in the manual moulding process the start-up period is quite important and also a large cause of the waiting times. Therefore some of the 12 measurements that were done earlier for chapter two and three were also done during the start-up period. Also during the simulation study and the experiments the data collected during this start-up period is important for the outcome of the research. Therefore the simulation model will not have a warm-up period while running the experiments since its important to collect data during the start-up period as well.

5.1.2 Experiment run length

Each experiment has a pre-determined run length, when the run length is reached the simulation model stops running. Only during this run length data is collected for the experiments. In this simulation study the run length is exactly one day, only during this day data will be collected. The run length is only one day since the manual moulding process is not a continuous process. So when the day is done nothing happens until the next day begins and the start-up of the process starts again. Therefore running the simulation model for more than one day does not add anything. During the experiments however this one day will be run multiple times with different random variables so that the collected average data is more reliable.

5.2 Results of the experiments

In the table below are the results of the six experiments that are performed in this chapter. The first experiment is performed with the basic simulation model that exactly represents the manual moulding process. Therefore this first experiment will be used as the baseline measurement. This table already gives a good overview of the results of the different experiments, later on in this chapter each different experiment and its results will be further explained. This table can also be found in ***Appendix E.7***.

Experiment	Total Waiting Time	Transporter Waiting Time	Employee Waiting Time
Experiment 1: *(Baseline measurement)*	2:43.5636	1:52.4992	0:51.0644
Experiment 2:	**2:00.4479**	**1:19.7700**	**0:40.6779**
Experiment 3:	2:42.7400	1:52.0001	0:50.7399
Experiment 4:	7:58.6662	3:35.0174	4:23.6488
Experiment 5:	9:23.9216	6:05.7713	3:18.1503
Experiment 6:	8:24.3518	5:05.6198	3:18.7320

Figure 14: Table with the six experiments results

5.3 The basic simulation model

The first experiment will be performed with the 'basic' Plant Simulation model. Everything about this simulation model is already explained in chapter five, next to that an image of the interface of this model can be found in ***Appendix D.4***. Basically this simulation model represents the current situation inside the manual moulding department. Therefore the results of this first experiment will be used as the baseline measurement. So the results of the other experiments will be compared with this experiment to see if the waiting times were reduced. From the experiment came forward that there is an average waiting time of *2:43* minutes per plate. At the moment this result does not tell us anything since there is no other experiment to compare this with. However the results of this experiment are in the table below, these results will be used as the baseline measurement.

Figure 15: Results of experiment 1

Experiment 1

Variable	Waiting time	St. Dev	Minimum	Maximum	Left Interval	Right Interval
AvgWT	1:52.4992	*0:05.8563*	*1:46.2940*	*2:02.4160*	*1:47.5973*	*1:57.4012*
AvgWTEmp	0:51.0644	*0:32.2203*	*0:26.4590*	*1:51.8000*	*0:24.0948*	*1:18.0339*
TotAvgWT	**2:43.5636**	*0:37.4672*	*2:15.0589*	*3:51.4964*	*2:12.2022*	*3:14.9250*

5.4 Plate transporter is leading factor

For the following five experiments the basic simulation model will be adjusted a bit so that a solution is implemented into the newly created simulation model. The first possible solution that will be tested is the one in which the plate transporter is the leading factor. This means that there is no longer an operator with a response time, instead the plate production starts when the plate transporter requests new plates. In other words the plate transporter can now immediately start the plate production whenever he wants. In the simulation model this solution is implemented by simply setting the processing time of the *SendRequest* process to 0,0 seconds. This is simply shown in ***Appendix E.2***.

Figure 16: Results of experiment 2

Experiment 2						
Variable	**Waiting time**	**St. Dev**	**Minimum**	**Maximum**	**Left Interval**	**Right Interval**
AvgWT	1:19.7700	*0:02.4632*	*1:16.0285*	*1:24.1751*	*1:17.7082*	*1:21.8317*
AvgWTEmp	0:40.6779	*0:22.4742*	*0:19.5931*	*1:20.0745*	*0:21.8662*	*0:59.4897*
TotAvgWT	**2:00.4479**	*0:24.0128*	*1:37.8574*	*2:44.2495*	*1:40.3483*	*2:20.5475*

The table above shows the results of the experiment. What becomes clear from these results is that the *TotAvgWT* is reduced drastically compared to the first experiment with the basic simulation model. For a large part this is due to the fact that *AvgWT*, the waiting time of the transporter, has been reduced. Without the operator the plate transporter no longer has to wait until this operator responses, this is one reason for the decrease of the *AvgWT*. Next to that the plate transporter can now requests plates whenever he wants and can therefore make sure that plates are ready when he arrives back at the G4 Line. This is the other reason for the decrease of *AvgWT*. Besides that it is also noticeable that the standard deviation of the *AvgWT* has reduced quite a lot relatively. This can be dedicated to the fact that the plate transporter now is no longer dependent on the operator who has a lot of deviation in his response time. But making the plate transporter the leading factor is a good possible solution since the waiting times are drastically reduced.

5.5 Extra buffer added at punching machines

The next solution that will be tested is based on the *Drum Buffer Rope* theory about placing extra buffers at certain locations to help the bottleneck in the process. So for this experiment the buffer capacity is increased from one to two, this is also portrayed in ***Appendix E.3***. The results of this experiment are not much different from the first experiment, the values of the KPI's are almost equal. The main reason behind this is that the extra second place in the buffer was barely used during the experiments. This way there is not much difference between the basic simulation model and the model used in this experiment. Therefore the waiting times will be almost equal. But there is still a small decrease in waiting times.

Figure 17: Results of experiment 3

Experiment 3						
Variable	**Waiting time**	**St. Dev**	**Minimum**	**Maximum**	**Left Interval**	**Right Interval**
AvgWT	1:52.0001	*5.2665*	*1:47.9732*	*2:00.6783*	*1:47.5919*	*1:56.4083*
AvgWTEmp	50.7399	*33.1807*	*25.9661*	*1:51.8188*	*22.9664*	*1:18.5133*
TotAvgWT	**2:42.7400**	*38.3152*	*2:14.8832*	*3:52.0769*	*2:10.6687*	*3:14.8112*

5.6 Buffers removed at punching machines

As mentioned in the last paragraph adding an extra buffer place does not change too much to the waiting times. Knowing this the single buffer place in the actual manual moulding department might also not be too useful as well. In this experiment the buffers in front of the *Punching1* and *Punching2* are removed, this is shown in ***Appendix E.4***. This experiment gave the following results:

Figure 18: Results of experiment 4

Experiment 4						
Variable	**Waiting time**	**St. Dev**	**Minimum**	**Maximum**	**Left Interval**	**Right Interval**
AvgWT	3:35.0174	*30.4481*	*2:59.6195*	*4:26.9804*	*3:09.5313*	*4:00.5036*
AvgWTEmp	4:23.6488	*2:30.4994*	*2:37.5261*	*8:49.2985*	*2:17.6752*	*6:29.6224*
TotAvgWT	**7:58.6662**	*2:59.4122*	*5:44.0989*	*13:16.2790*	*5:28.4915*	*10:28.8410*

The results of this experiment are a bit surprising but also quite clear. The waiting times for all three KPI's increase drastically when the buffer is removed at *Punching1* and *Punching2*. Besides that this is the first experiment in which *the AvgWTEmp* has a higher value then the *AvgWT*. In other words; without a buffer mainly the employee waiting time increases a lot. The main advantage of the buffer is that fresh plates can already be waiting in the buffer, then the employees will immediately have fresh plates to start punching. Without a buffer the employees have to wait for the transporter most of the times. So these buffers are really important for the manual moulding department. This was also suggested earlier by the *Drum Buffer Rope* theory that stated that the bottlenecks in a process should be supported with the help of buffers.

5.7 Both transporters responsible for a punching machine

The next solution that will be tested is that both the plate transporter and the waste transporter are responsible for one of the punching machines. So the transporter is responsible for both delivering the plates to this punching machine but also for recycling the waste of the same punching machine. One of the transporters will be responsible for the first punching machine and the other transporter will be responsible for the second punching machine and the tables where the special parts are made. All of this is portrayed in ***Appendix E.5***.

Figure 19: Results of experiment 5

Experiment 5						
Variable	**Waiting time**	**St. Dev**	**Minimum**	**Maximum**	**Left Interval**	**Right Interval**
AvgWT	6:05.7713	*0:39.3656*	*5:20.3491*	*7:04.2985*	*5:32.8208*	*6:38.7217*
AvgWTEmp	3:18.1503	*1:10.2663*	*2:22.5510*	*5:11.5217*	*2:19.3348*	*4:16.9659*
TotAvgWT	**9:23.9216**	*1:44.3282*	*8:05.8068*	*12:15.8203*	*7:56.5950*	*10:51.2482*

For this experiment the results are, just like the last experiment, really clear. The average waiting time per plate, *TotAvgWT*, increased drastically to more than *9:23* minutes per plate on average. Compared with the basic simulation model, the baseline measurement, the *TotAvgWT* has tripled with this solution. The main reason for the drastic increase in waiting time is that both transporters will sometimes need plates at around the same moment in time. Since the G4 Line can only produce plates for one transporter at a time this means that the other transporter has to wait for quite a while. This is leading to more waiting time for the transporters, so *AvgWT* increases. On the other hand this also means that the transporters are more likely to arrive too late at the punching machines, therefore also the *AvgWTEmp* increases. This increase of waiting times for both the transporters and the employees means that it is quite logic that the *TotAvgWT* increases drastically with this solution.

5.8 Transporters are leading factor and responsible for one machine

The sixth and final solution is based on the solution used in the fifth experiment from the last paragraph. Both transporters will once again have their own punching machine which they are responsible for. This means that they have to deliver plates but also recycle the waste. But besides that there will no longer be an operator at the G4 Line, once again the transporters are the leading factor. The G4 Line will immediately start producing fresh plates when requested to, given that the G4 Line is not busy with another request. The interface of the simulation model that will be used is almost the same as the one in the previous experiment. However for this solution the processing time of *SendRequest* is set 0,0 seconds, this is portrayed in ***Appendix E.6***.

Figure 20: Results of experiment 6

Experiment 6						
Variable	**Waiting time**	**St. Dev**	**Minimum**	**Maximum**	**Left Interval**	**Right Interval**
AvgWT	5:05.6198	*0:38.4168*	*4:43.7494*	*6:39.4811*	*4:33.4635*	*5:37.7760*
AvgWTEmp	3:18.7320	*0:17.3467*	*2:56.0912*	*3:42.6139*	*3:04.2121*	*3:33.2519*
TotAvgWT	**8:24.3518**	*0:38.4659*	*7:39.8406*	*9:45.8642*	*7:52.1544*	*8:56.5492*

This experiment is quite similar to the fifth experiment and also with this experiment the *TotAvgWT* increased drastically compared with the baseline measurement. The fact that both that both transporters will sometimes need plates at around the same moment in time is once again the main reason of this drastic increase. However compared to the fifth experiment the *AvgWT* decreased with almost one minute while the *AvgWTEmp* stayed around the same value. The main reason for this is most likely that there is no longer an operator. The transporters now no longer have to wait for nothing until the operator responses to their request. So just like in the second experiment making the transporter the leading factor had a positive effect on reducing the waiting times.

6. Conclusion and advice

In this final chapter the conclusions of the simulation study from the last chapter will be presented. Based on these conclusions an advice will be given to the company. This conclusion and advice together should contribute to an answer to the main research question that was presented at the beginning of this report. Therfore this chapter has the following structure:

§ 6.1 – Conclusion
§ 6.2 – Advice and recommendations

6.1 Conclusion

In this paragraph the conclusions of the research will be explained. However, before doing so, there will be a short recap on the main research question and the approach used to solve this main research question.

The goal of this research was to investigate the waiting times in the manual moulding department of Eternit and to try to reduce these waiting times. This goal also came forward in the main research question that was presented at the beginning of the research:

How can the waiting times at the manual moulding department of Eternit be reduced?

The first step to solving the above research question was to list all the problems that were present in the manual moulding department. Of all these problems the core problem was that fresh plates do not arrive at the right time. Based on this the conclusion was made that there was a problem in the plate requesting and delivery process, so the main focus would be on these processes from now on. With the help of observations and interviews both of these processes were mapped out further to gather more information that could be used in the simulation study later on.

With all the information gathered at the beginning of the research a simulation model was developed. The initial built of this simulation model represented the current situation inside the manual moulding department. Tests were performed with this simulation model to get an idea about the current waiting times in the manual moulding department, the results of this test were later on used as a baseline measurement. Later on some possible solutions were implemented into this simulation model. These solutions were partly based on already existing theories on process optimization. Each of the adjusted simulation models was used to perform new tests. The results of these tests were compared to the baseline measurement to see if the solution had been helpful towards reducing the waiting times. The results of all these tests were already shown and discussed earlier in this report. In this paragraph the conclusion will be presented that was drawn on the basis of the results.

Looking at the results of the tests in ***Appendix E.7*** the first conclusion that can be drawn is that there are only two experiments that managed to reduce the waiting times compared to the baseline measurement. Experiment 2 is one of these experiments, in this experiment priority was given to the plate transporter so that the plate transporter became the leading factor. This meant that the operator of the G4 Line was removed from the process and that there is no longer a response time since the transporter can start the plate production himself. From the experiment came forward that this solution will lead to a decrease in the *TotAvgWT*, *AvgWT* and the *AvgWTEmp*. The percentual decrease of these KPI's can be find in the figure below in this paragraph.

The other experiment that managed to reduce the waiting times was the third experiment. Based on the *Drum Buffer Rope* theory extra buffers were placed at a strategic location inside the manual moulding department to support the bottleneck of the process. As mentioned this experiment managed to reduce the values of the three main KPI's, although only minimally. The decrease in value of the *TotAvgWT*, *AvgWT* and the *AvgWTEmp* was below the 1%. So the solution used in this third experiment will not be that useful when reducing the waiting times. In the figure below the baseline measurement is shown together with the two experiments that managed to reduce the waiting times. Of both those experiments the percentual decrease compared to the baseline measurement is pictured.

	TotAvgWt	Decrease (%)	AvgWT	Decrease (%)	AvgWTEmp	Decrease (%)
Experiment 1: *(Baseline measurement)*	2:43.5636	-	1:52.4992	-	0:51.0644	-
Experiment 2:	2:00.4479	**-26,4 %**	1:19.7700	**-29,1 %**	0:40.6779	**-20,3 %**
Experiment 3:	2:42.7400	**-0,5 %**	1:52.0001	**-0,4 %**	0:50.7399	**-0,6 %**

Figure 21: Comparison between first three experiments

The other three experiments that were performed only resulted in a increase in the waiting times, so the solution of these experiments were not helpful. So in the end only the solution used in the second experiment will be helpful when reducing the waiting times. This solution was to remove the operator of the G4 Line and to give priority to the plate transporter, based on the *Theory of Constraints* of Goldratt.

Another lead that points towards this being the solution that should be used to reduce the waiting times is found when comparing experiment 5 and experiment 6. In both these experiments both transporters are responsible for their own punching machine for which they have to deliver plates and also recycle the waste. However there is one difference, in experiment 6 the transporter is prioritised, just like in the second experiment. Like mentioned before prioritising this transporter once again led to a decrease of the waiting times in experiment 6 compared to experiment 5. This is simply shown in the figure below. These results give another good lead that prioritising the transport may help with reducing the waiting times.

	TotAvgWt	Decrease (%)	AvgWT	Decrease (%)	AvgWTEmp	Decrease (%)
Experiment 5:	9:23.9216	-	6:05.7713	-	3:18.1503	-
Experiment 6: (Transporter prioritised)	8:24.3518	**-10,6 %**	5:05.6198	**-16,4 %**	3:18.7320	-

Figure 22: Comparison between last two experiments

Based on the results of the simulation study the conclusion can be drawn that prioritising the plate transport might be a good solution to reduce the waiting times. Prioritising the plate transporter means that the operator of the G4 Line is removed so that responses times are no longer there. This leads to a decrease in values of the three KPI's. For the other solutions that were tested the conclusion can be drawn that these solutions are not helpful when reducing the waiting times. So prioritising the plate transporter should be the way to go for Eternit when reducing the waiting times in the manual moulding department.

6.2 Advice

Based on the conclusion drawn in the last paragraph an advice should be given to Eternit. This given advice should help Eternit with reducing the waiting times inside their manual moulding department.

During the simulation study various solutions were tested that could contribute to reducing the waiting times. All these results were already discussed in the last paragraph. Based on these results the advice give to Eternit can be summarized as follows:

> "The response time of the operator leads to unnecessary waiting times for the plate transporter. Therefore the plate transporter inside the manual moulding department should be prioritised so that this transporter is less dependent on the operator of the G4 Line. In an ideal scenario the communication with this operator should be removed entirely so that the transporter himself can start the production of the plates."

Removing this operator from the process ensures that these unnecessary waiting times will be a thing of the past. Furthermore the process will have a more steady throughput when this operator is removed from the process. This steady throughput ensures that the plates will arrive at a more steady rate at the punching machines leading to less waiting times for the employees of these punching machines. So prioritising this plate transporter will reduce the total average waiting time, *TotAvgWT*, but also the waiting time for the transporter, *AvgWT*, and the waiting time for the employees, *AvgWTEmp*.

To be able to prioritise the plate transporter a change of mind inside of Eternit is needed. There should be way more collaboration and communication between the employees of the G4 Line and the manual moulding department. As mentioned it would be even better to entirely remove the plate transporter in the requesting process To do this Eternit should invest in their G4 Line machine so that the transporter will be able to start the plate production himself, so this will require some investment. But before investing the most important is that there is a better collaboration between the G4 Line and the manual moulding department, only by working together the waiting times can be removed effectively.

6.3 Research limitations

In this paragraph, a discussion will be made about the potential shortcomings of this thesis. In a simulation study it is very important to validate your simulation model with real world data. So that you can find out if the simulation model actually represents the real life situation. However in this research for all three KPI's used no data was yet available, so therefore there was no available data to validate the simulation model. To overcome this problem 12 different measurements were done to gather data on all the three KPI's. The data of these measurements was then used to validate the simulation model. This method worked for this research, however the validation of the model would be way more reliable if more data was already available beforehand.

The goal of this research was to reduce the waiting times inside the manual moulding department, which is quite a clear goal. However at the beginning of the research Eternit did not specify with how much, for example, percent the waiting time should be reduced. Eternit was unable to specify this since they had no data available about the current waiting times. Therefore it was of course difficult for Eternit to specify with how much the waiting time should be reduced.

6.4 Further research suggestions

After this research, the first task that should be fulfilled is the implementation of the research outcomes and the advice given. At the start of the research there was some data available, but this data was mainly focussed on the output of the entire manual moulding process. At the beginning not much data was available about the various smaller processes and waiting times inside the manual moulding department. Which made the research sometimes a bit slow and difficult since all relevant data had to be gathered. For future research and improvements towards the manual moulding department it would be good if Eternit starts gathering much more relevant data about their manual moulding process. If this is possible for Eternit, future research and data analysis will be more valuable and especially more reliable than it currently is. With all this data it will also be possible to validate the current simulation model, this validation will of course be way more reliable because more data is available.

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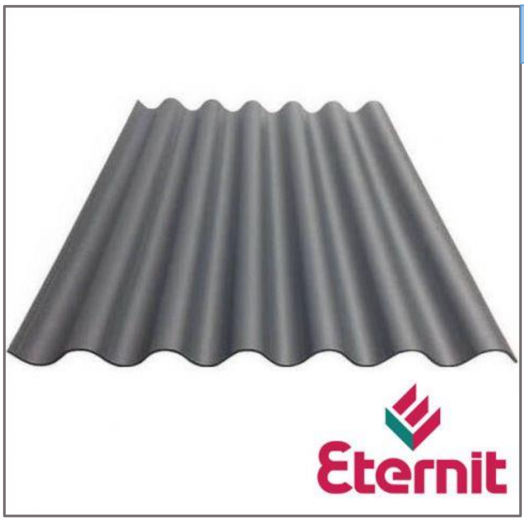
What is WAITING TIME? definition of WAITING TIME (Black's Law Dictionary). (2013, March 2). Retrieved April 17, 2019, from https://thelawdictionary.org/waiting-time/

Appendix A: Problem identification

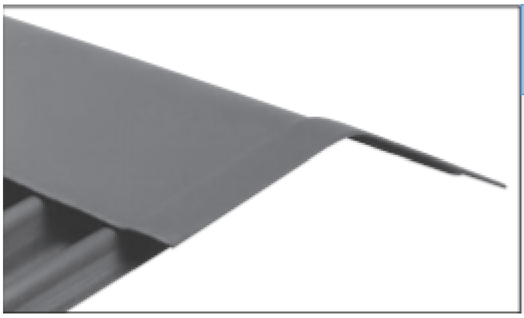
A.1: Product images

In this appendix an image of the standard corrugated sheets that Eternit produces can be found. Of course there will also be an image of two different products that are produced at the manual moulding department. At the end of this appendix there will be a link that refers to a folder of Eternit, this folder contains images of all the products Eternit produces.



Standard corrugated sheets produced by the G4 Line

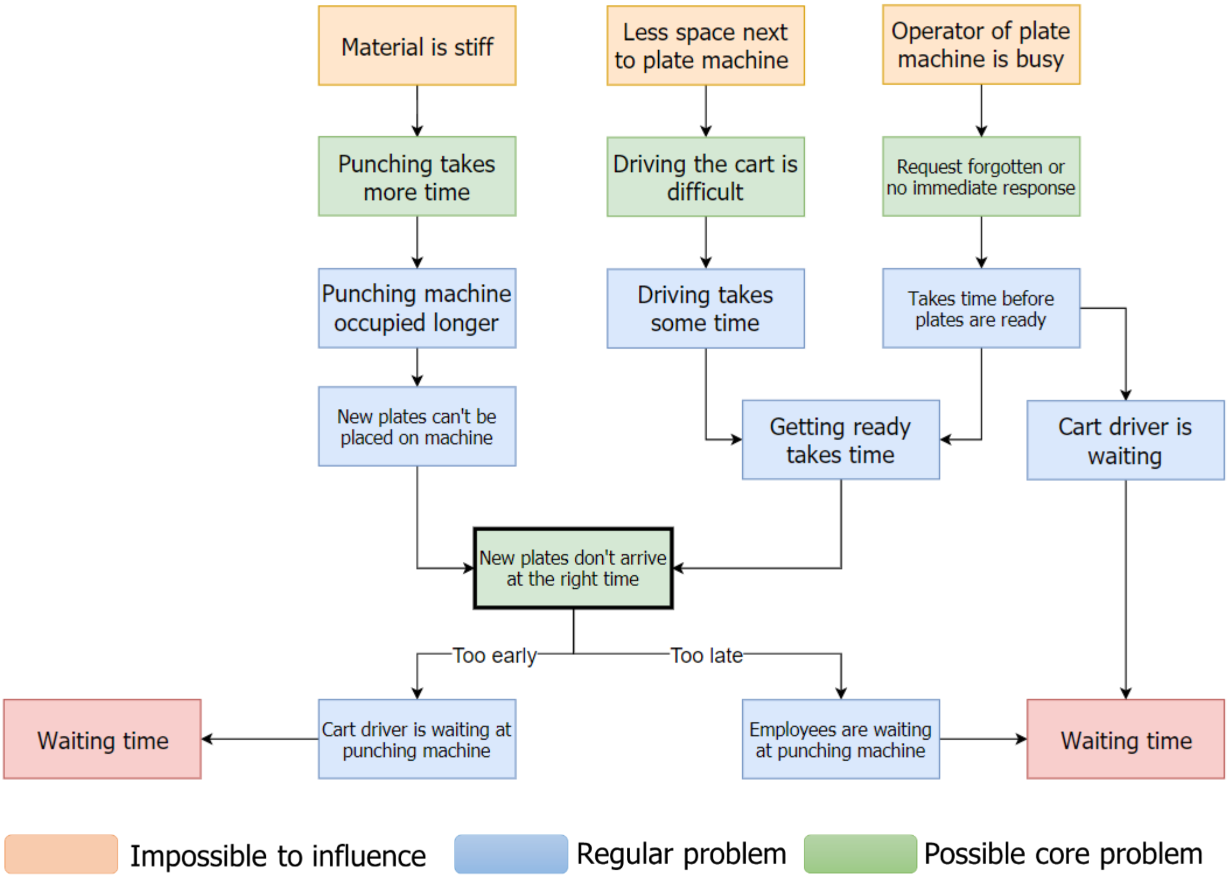
The '*k-nok' is* used to close of the roof. Produced by the manual moulding department



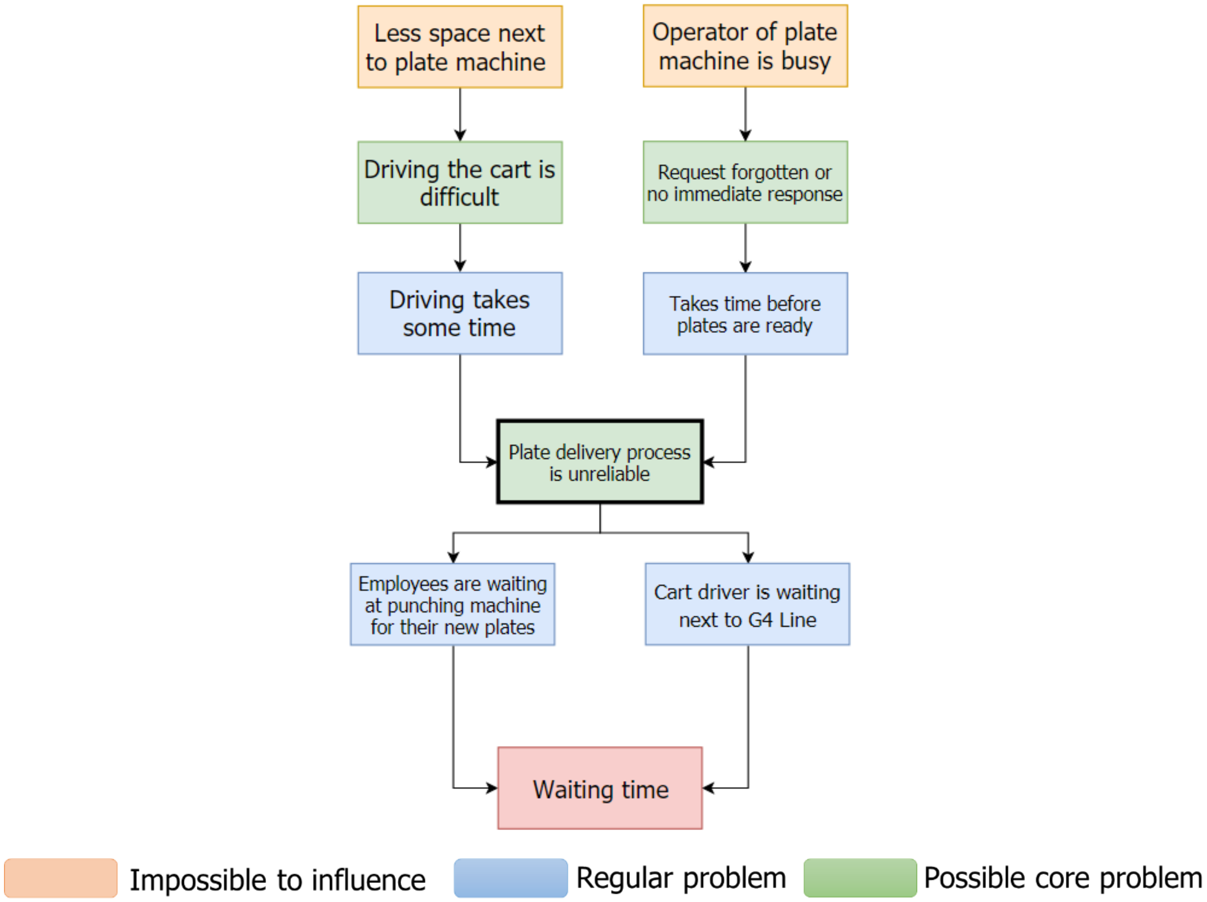
The '*v-nok'* that is also used to close of the roof. Produced by the manual moulding department.

More information about Eternit products can be found at their website (www.eternit.nl) under the tab '*Downloads*'.

A.2: Problem cluster

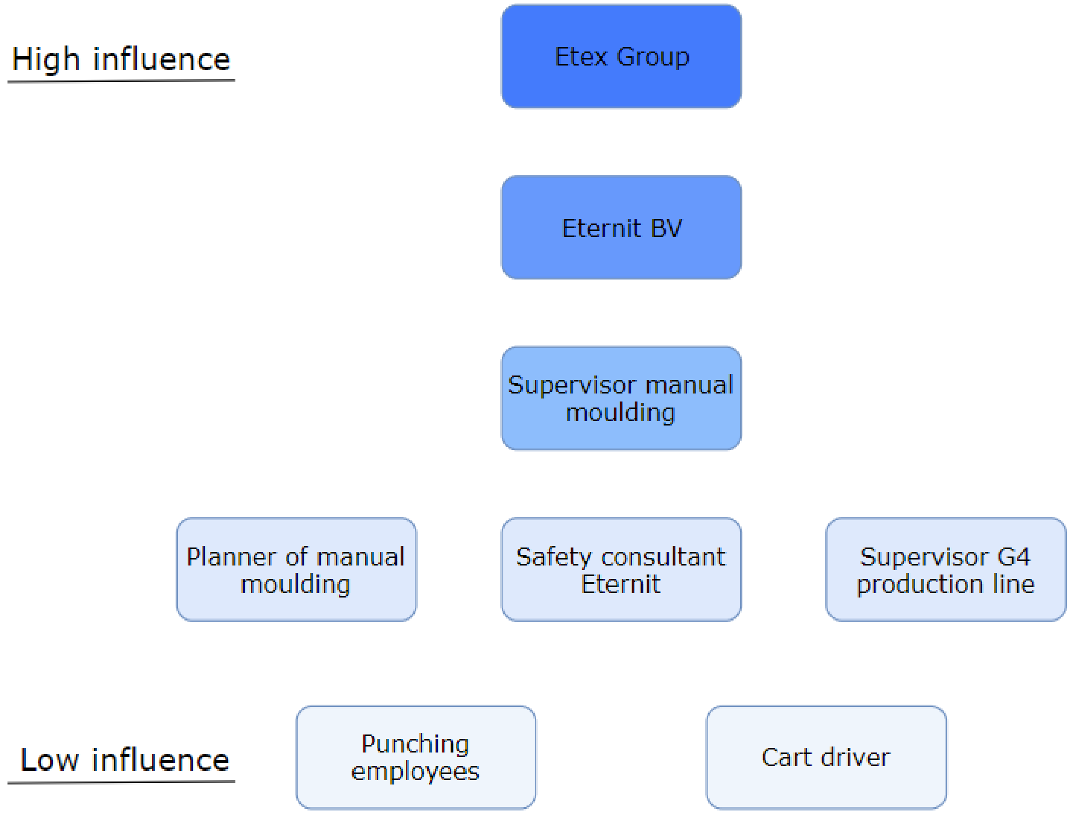


A.3: Updated problem cluster



The problem cluster above is the updated cluster after some more research and investigation was done during the project. Compared to the 'old' problem cluster the problems around the punching machine and punching employees are removed since the focus will now be only on the plate transporter and the plate delivery process. The new core problem is once again highlighted with a thick black outside border.

A.4: Stakeholder model



This model shows all the stakeholders concerned with the problem of this research. The most influential stakeholders are on top and the stakeholders with less influence can be found at the bottom of the model.

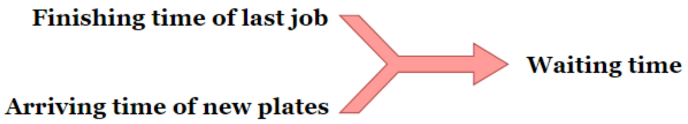
A.5: Research cycle for Q1 and Q2

To do proper research a research cycle can be used, in this research cycle the problem statement, research design and the validity of the research are discussed. The research cycle discussed in this paragraph will be used during both the interviews and the observations. So with the help of this research cycle reliable information should be gathered that can be used to answer **Q1** and **Q2**.

Problem statement

As stated gathering fresh information will be easier when a clear research design is set up. To set up a research design it is necessary to have a clear problem statement. The first important step of this problem statement is to explain what kind of research will be done. In this case an explanatory research will be done since relationships between different variables will be further investigated and explained. The variables for this problem statement will be (1) the waiting time, (2) the moment in time when the new plates arrive and (3) the moment in time when the last job is finished.

These variables have the following relationship; if the arriving time of the new plates is the same as the finishing time of the last job then this leads to no waiting time. If there is a difference between the arriving time and finishing time then there is waiting time, so in an ideal scenario the arriving time is always the same as the finishing time. If the arriving time is later than the finishing time then there is waiting time for the employees of the punching machine. The other way around, if the arriving time is earlier than the finishing time then there is waiting time for the cart driver. So in a model the variables have the following relationships:



The research subjects of this knowledge problem are all the employees of the manual moulding department that are involved with driving the cart or working at the punching machine. Since all factory employees of the manual moulding department should be able to do all tasks inside the process, all factory employees of the manual moulding department are part of the research subjects. The planner of the manual moulding department is also part of the process since planning is also a crucial part in this research. To end also the two punching machine should be research subjects since it's important to find out how they work exactly and how to possibly improve them.

To make the problem statement easier to be solved it should be split into different research questions. These research questions make it easier to gather reliable and sufficient information. The research questions used for this problem statement are listed below:

- How are plates requested and how is the request handled?
- How often does it occur that a job is already finished but that new plates are not yet available? What is the average waiting time when it happens?
- How often does it occur that the cart driver can't load the new plates onto the punching machine? And what is the average waiting time when it happens?
- How are the new fiber plates loaded onto the punching machine?
- Which factors have influence on the arriving time and/or the finishing time?

Research design

Now that the problem statement and research questions are known it's time to set up a research design. The research design is used to shortly describe the strategy that will be used when gathering data and performing the research. For the research design some important choices need to be made:

- As already mentioned during the problem approach, observations and interviews will be used to gather information.
- During both the observations as the interviews the variables will not be influenced since it's important for the research to gather data in the natural work environment.
- Since interviews and observations will be performed there will be contact with the research subjects multiple times during the research. During the interviews there will be direct contact with the interviewee. Before and after the observations the employees will be informed about the observation. However during the observations there will be no direct contact with the employees so that employees won't be influenced.
- The observation will just take place inside the Eternit factory at the manual moulding department. The circumstances of the manual moulding department will not be changed beforehand the observation.
- It will be a cross-sectional research, the multiple observations and interviews take place at roughly the same time.
- During the interviews data will most likely be collected in a qualitative way since these interviews are used to get information on how the employees feel and think about the current situation.
- During the observations the data will be collected mostly in a quantitative way since hard data is needed to set up a spaghetti diagram and a solid simulation model.

Validity:

There are a lot of threads to the validity of this research, in this part will be explained how these threats are handled during the research. Some possible threats are listed below with an explanation how the threats are handled.

Internal validity:

- One of the threads is *rivalry* between different groups of people of the sample group, since there are two different punching machines that will be observed there is a slight chance of rivalry between the employees of both machines. To cope with this thread the exact time of both observations won't be mentioned, in this way there will be no rivalry since the employees don't know when to perform better.
- Since the observation will be done at least two times a possible threat is that participants get more used to their specific tasks between the observations and this can make harm the validity of the results. However all employees that will participate in the observations already work at the manual moulding department for at least six months. So they are already used really well to their tasks, so *growth* is less of an issue.
- Sometimes there are some *extreme events* at the manual moulding department, those events have a large effect on the performance of the process. A possible extreme event is the presence of hard strips inside the fiber plates, when this happens the fiber plates can't be used. An event like that really affects waiting times and therefore the performance. So when an extreme event happens during an observation, the observation should be done over.

- During observation the processing time of certain tasks will be measured. To guarantee the validity of these results the observations will be recorded as well. By doing this the results of the measurements can easily be checked on the recordings, this way *good measurement types* are used.

Construct validity:

- Another possible threat to the research is an *inadequate use of definition*, so that the definition is not clear when the research is performed. This can be a threat when the concepts 'waiting time' and 'efficiency' are used, to cope with this threat the definitions used of both concepts are explained in the theoretical model. These definitions will be used during the observations and the definitions will also be explained to the interviewees before the interviews are conducted.

External validity:

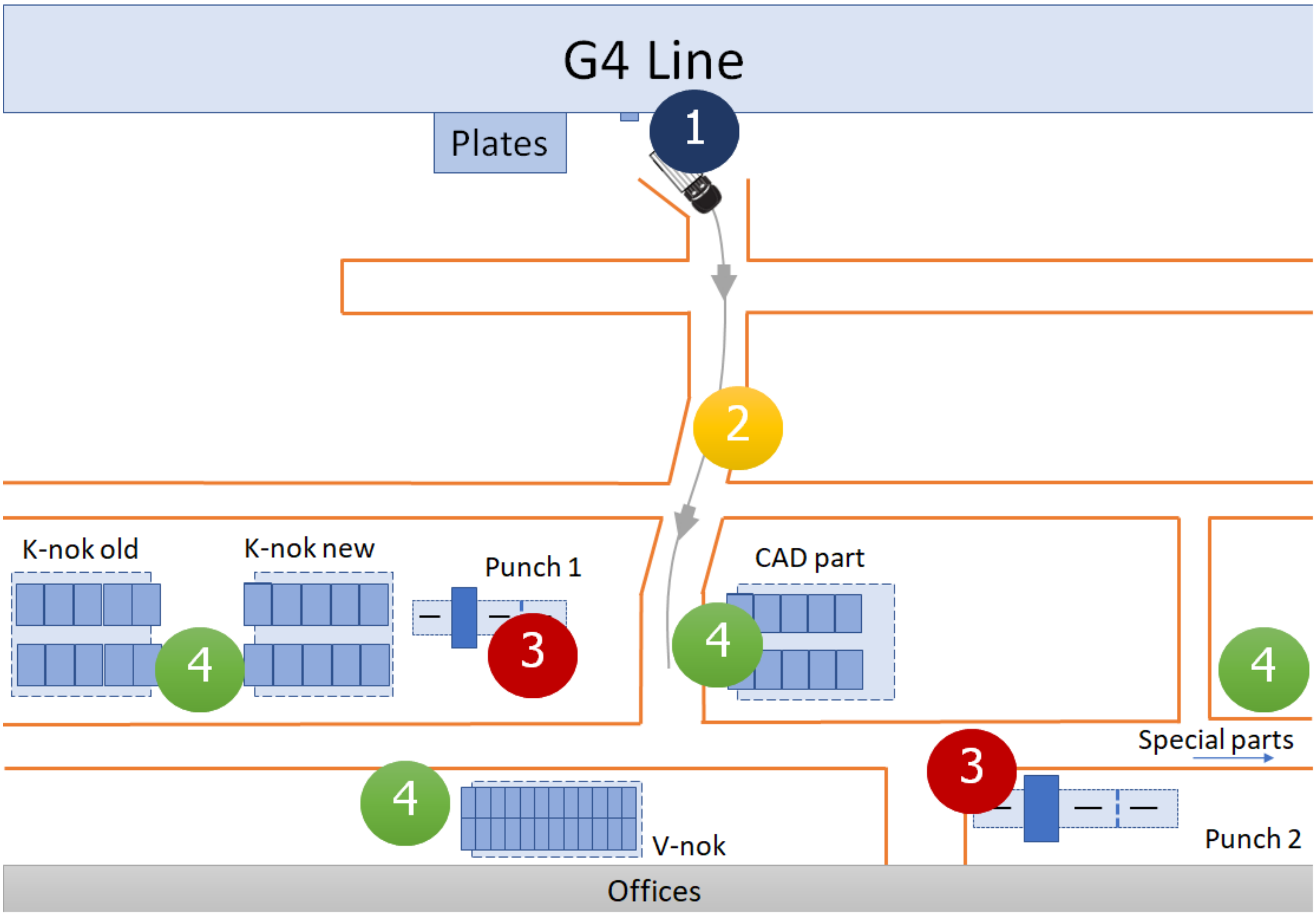
- The main question of external validity is if the results of the research can also be applied on other (partly) similar cases. Most researchers tend to generalise their research to make the research applicable on more cases, that is a threat. This research is really unique; the environment of this research is unique and will not be found anywhere else. Next to that the population of this research is also unique, most of the population is very used to the environment of the manual moulding department. So this research should not be generalised for another population or another environment. However if the punching machine is involved in the solution this might also be applicable to other cases where a punching machine is the problem.

Reliability:

To make sure that the results from the observation are reliable there will be a retest. So the observation will be done twice with the same subjects in one week. Retesting is extra important in this case since the observation is also used to do time measurements of certain activities. By doing a retest the reliability of the results can be confirmed. A possible threat when doing a retest is that there will be a time delay between the two different observations. In this time delay there might be a chance that the situational factors from the manual moulding process changed. However both observations will be done in the time span of one week, so there is not much time for situational factors to change. Besides that the supervisor of the manual moulding process also knows when the observations will take place and nothing will be changed in between the observations.

Appendix B: Current situation

B.1: Location of the process in the manual moulding department

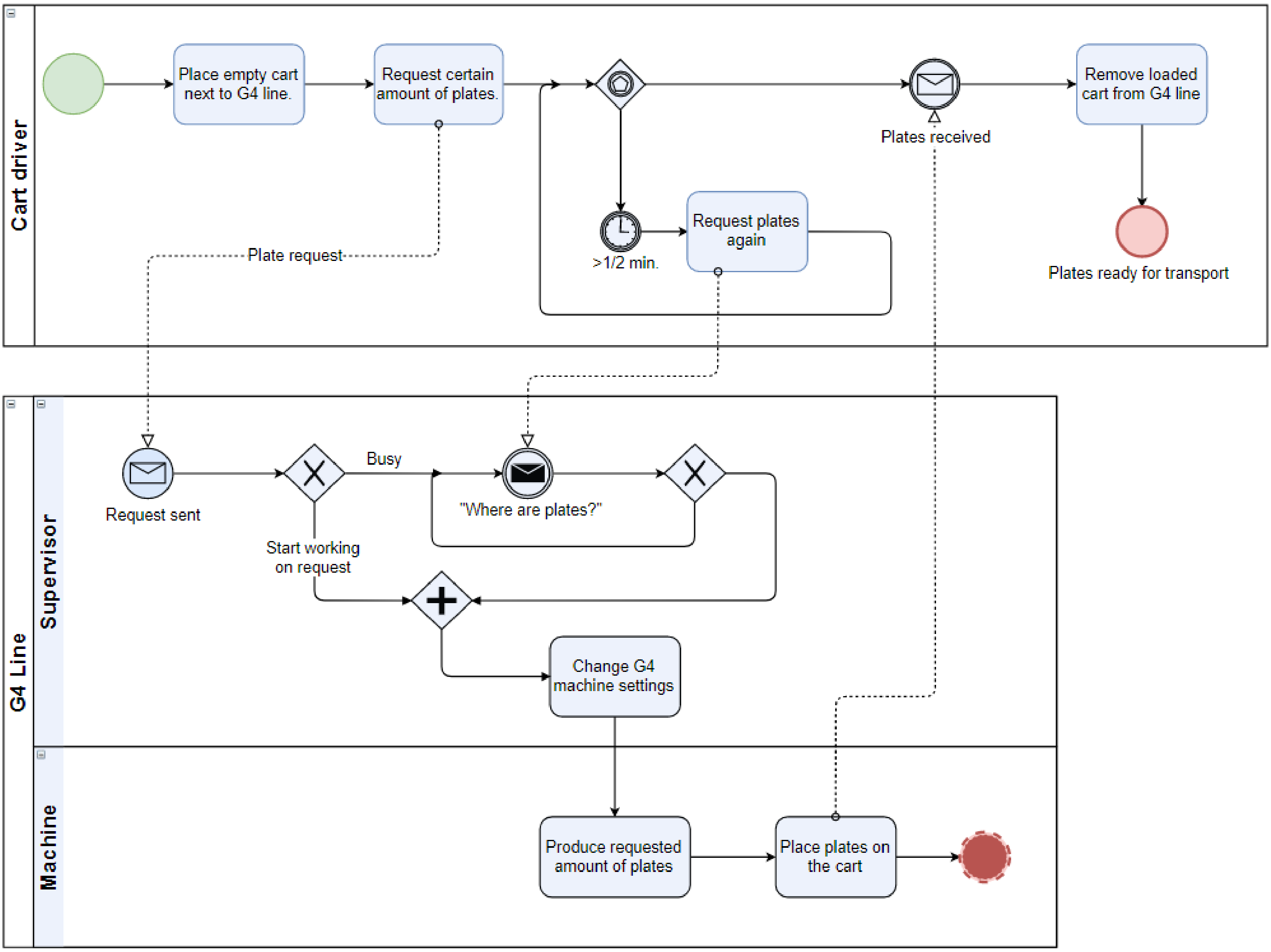


The map above shows where on the work floor each of the four processes mentioned in *paragraph 2.1* takes place. The legend of this map is found below:

1	- Requesting process	3	- Punching process
2	- Moving process	4	- Moulding process

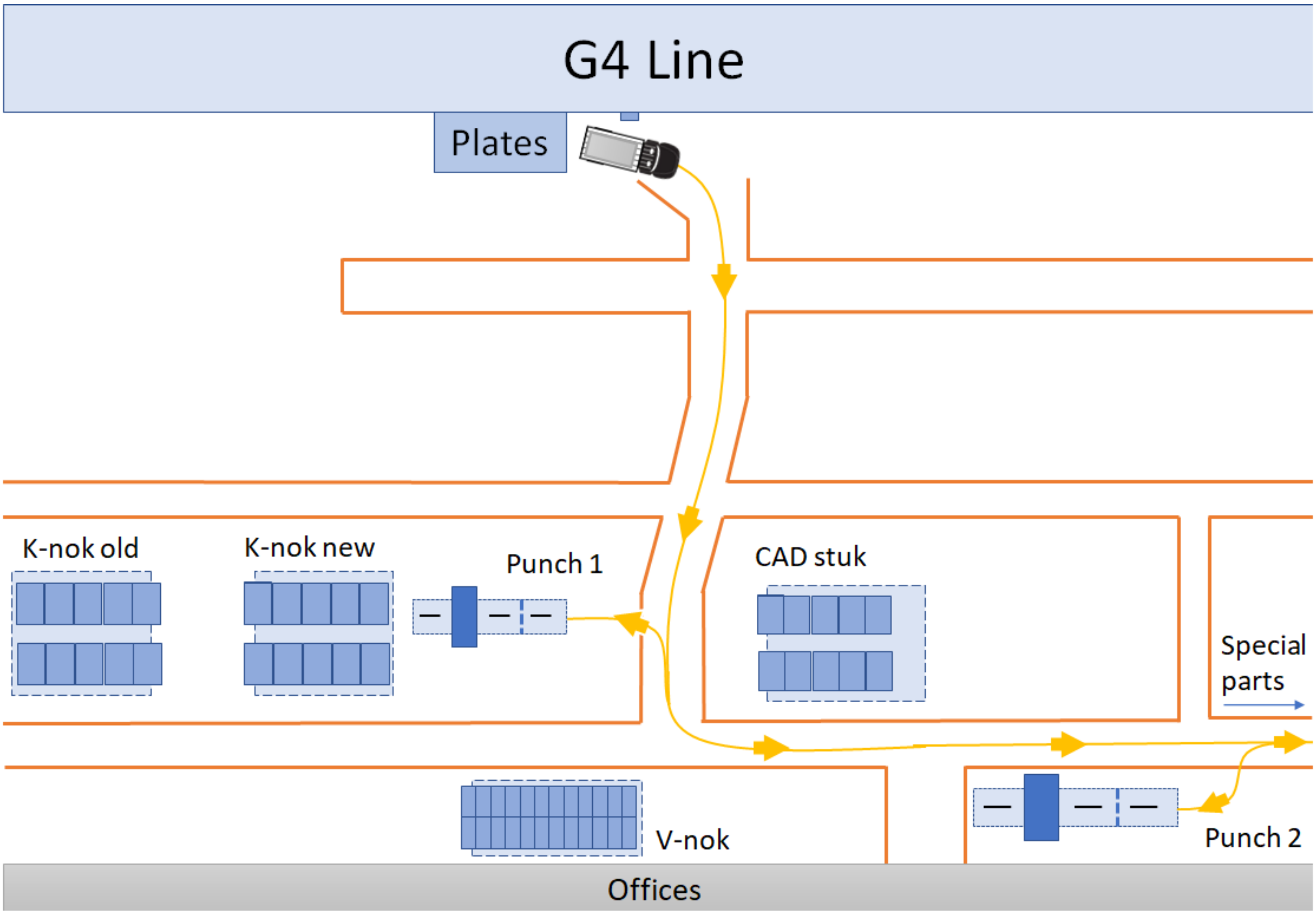
B.2: Flow diagram requesting process

The flow diagram that is referred to in *paragraph 2.2* is found below:



B.3: Routing map of the cart driver

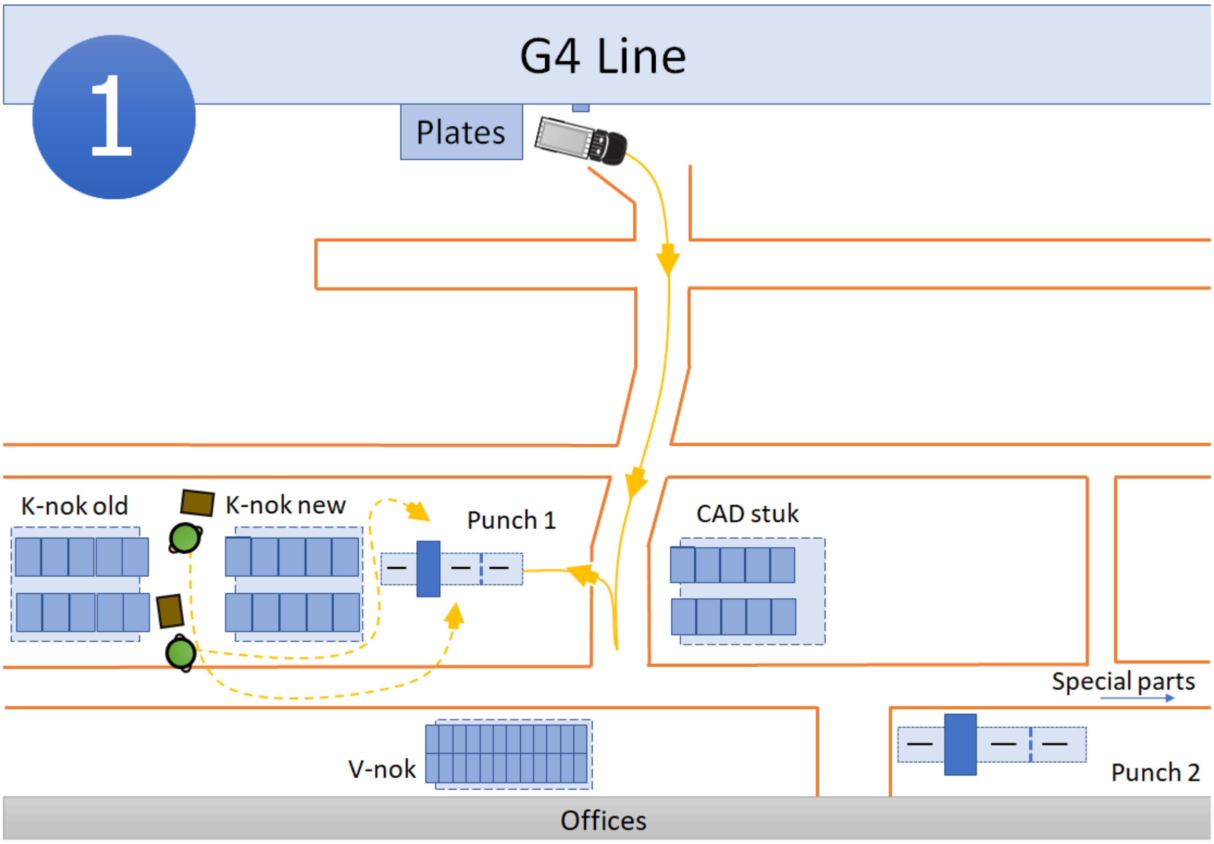
The map below shows the routes used by the cart driver in the manual moulding department.



B.4: Punching process

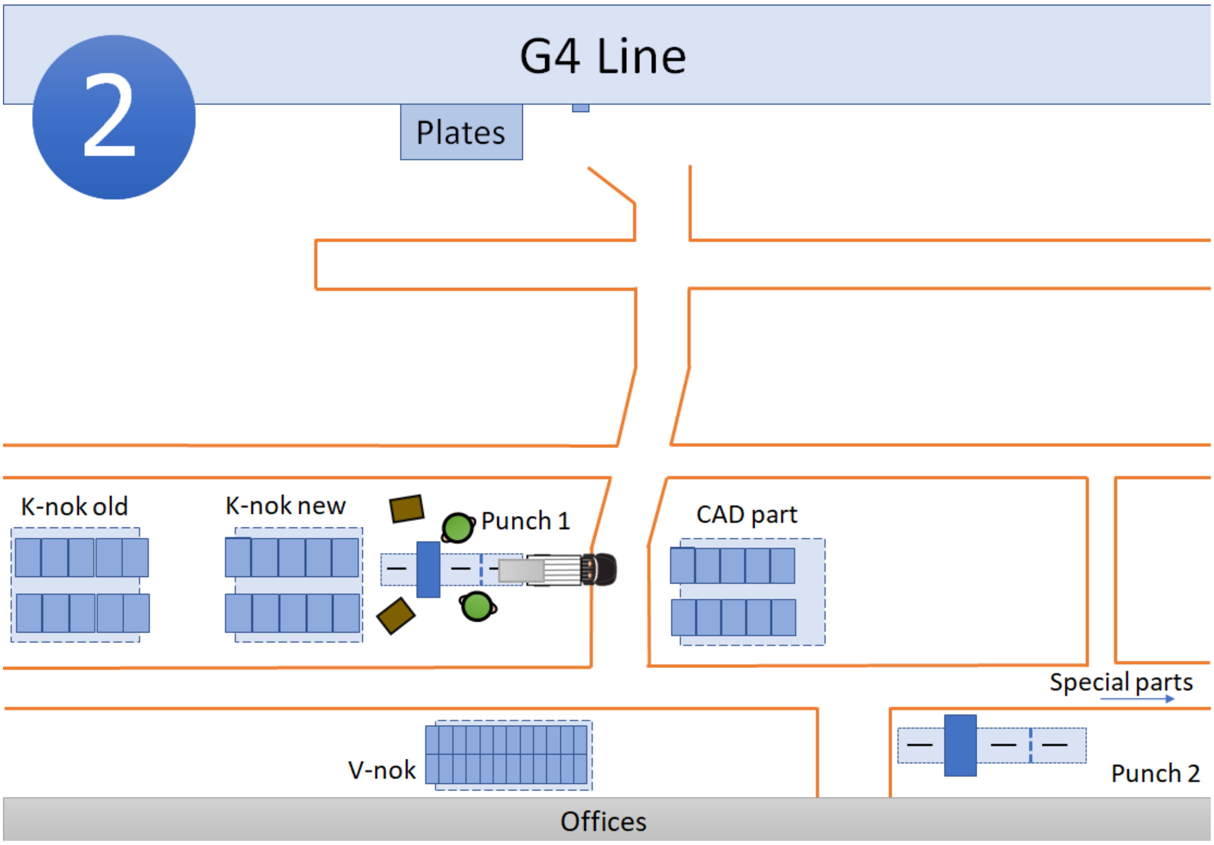
This part of the appendix contains the maps that are used to visualize each of the 6 steps that take place in the punching process.

B.4.1: Step 1



1. Move to punching machine: As explained the employees are responsible for the punching process and moulding process of a specific special part. So when they are done with the moulding process they start with the punching process again with a fresh amount of plates. So in reality the first step in the punching process is the employees moving back to the punching machine with their driveable tables. In the map the movement of the cart driver is also shown. This is part of the moving process, but normally this movement takes place at the same time as the employee movement. So for a better understanding the cart driver is shown on the map as well.

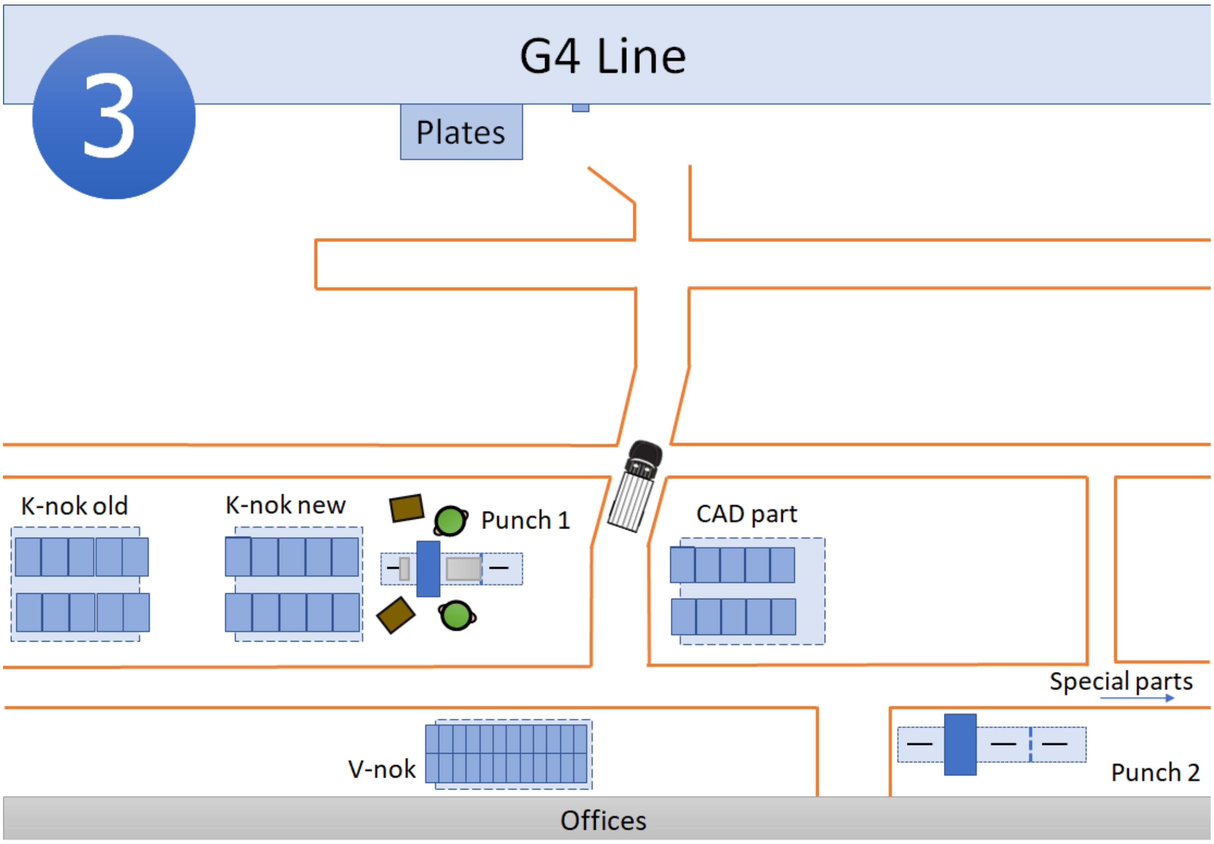
B.4.2: Step 2



2. Unload the plates: When the loaded cart is standing right in front of the punching machine the fresh plates are ready to be unloaded onto the punching machine. The fresh plates are unloaded by attaching an engine to the loaded cart, with help of this engine the conveyor belt on the loaded cart will be turned on. Then the fresh plates are transported onto the punching machine. With all plates on the belt of the punching machine the engine can be detached. During this step the waiting times occur in the punching process.

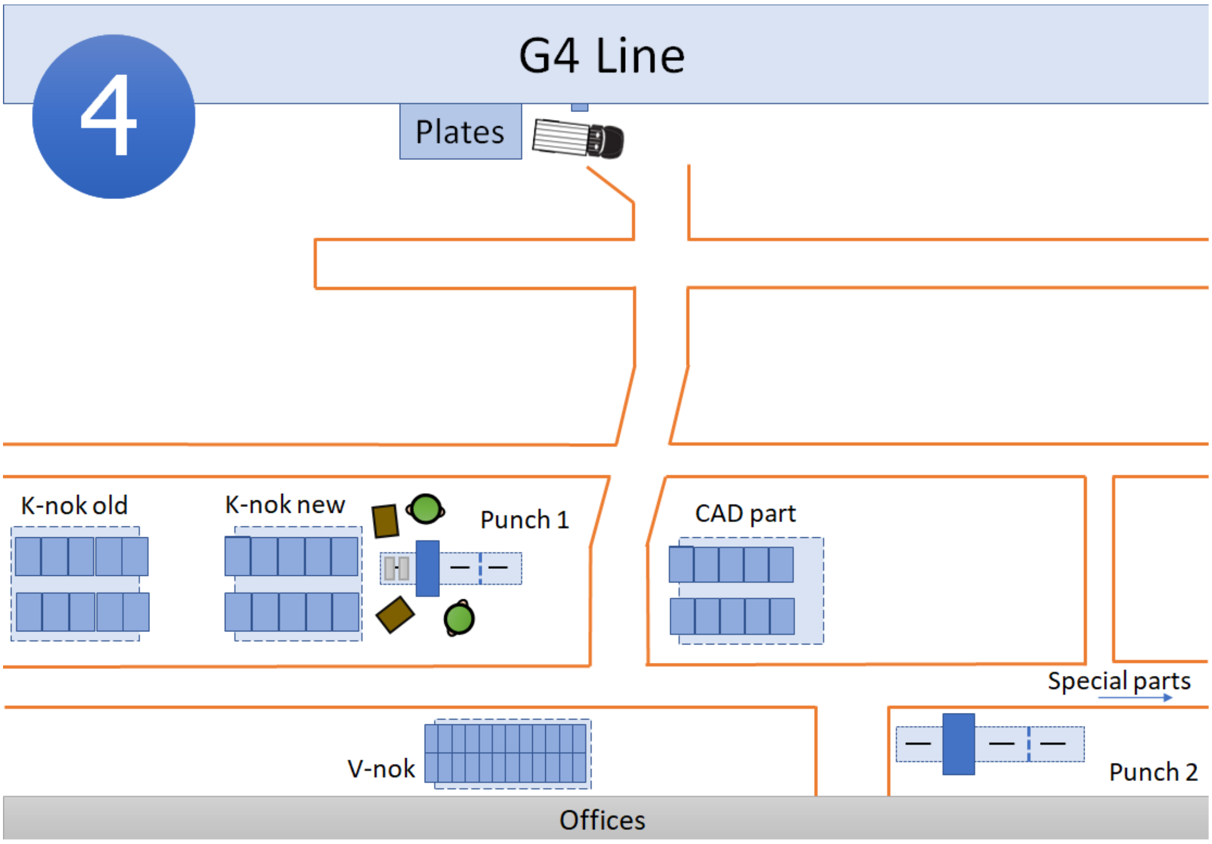
Most of the times the plates on the cart are unloaded by the employees, only in the early morning the driver unloads the plates himself. If the employees are not there yet when the driver arrives he has to wait for the employees and gets waiting time. But the driver can also decide to just leave the cart behind and move on. Then he has to go back later to return this empty cart to the G4 Line. It also works the other way around, the employees can be waiting at the punching machine till the cart driver arrives. Then these employees have waiting time.

B.4.3: Step 3



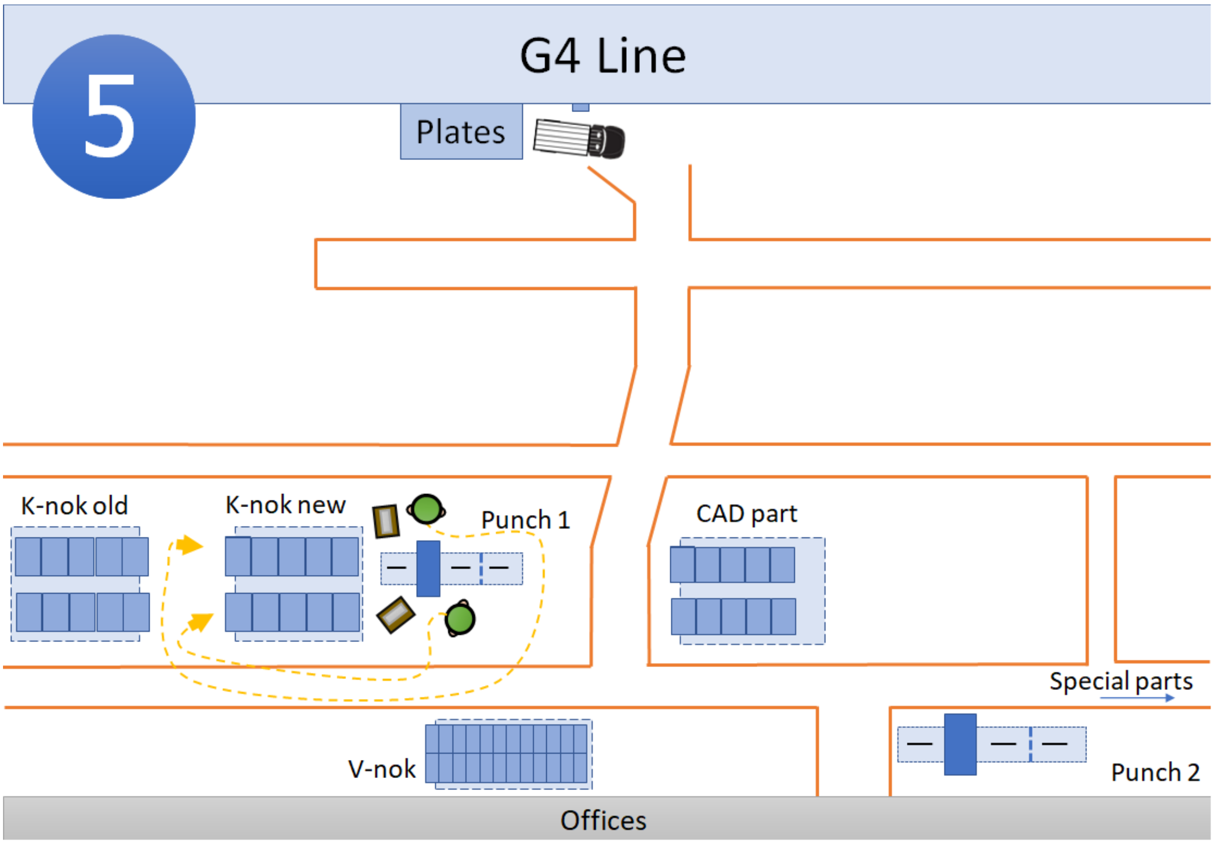
<u>3. Start punching:</u> Now that the fresh plates are ready on the punching machine the actual punching can begin. The employees grab the correct punching knife they need for the special part that they want to produce. Then, with help of a conveyor belt, the punching plates with the punching knife are moved under the press. The press is then activated and the punching knife is punched through the layers of plates. The result are small plates that can be used for the moulding process. The waste that is not needed anymore will be thrown away in a special waste cart, the waste can then later on be recycled. This process of punching continues until the whole surface of the plates are punched out.

B.4.4: Step 4



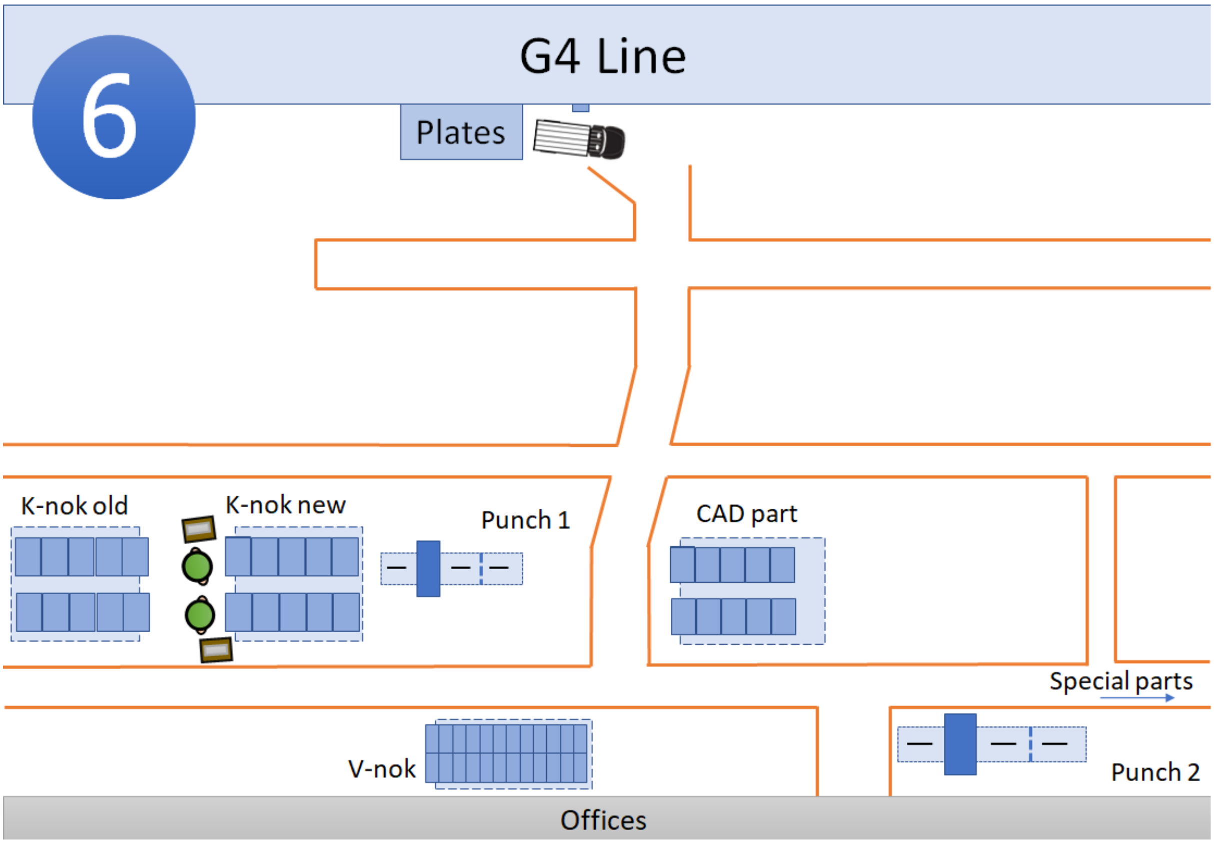
4. Move plates on table: The punching is done and all the smaller plates are ready to be moved to the moulding process. To move the smaller plates they should be loaded onto driveable tables. While loading the plates onto the table it's important that water is put between the plates so that the plates don't stick together.

B.4.5: Step 5



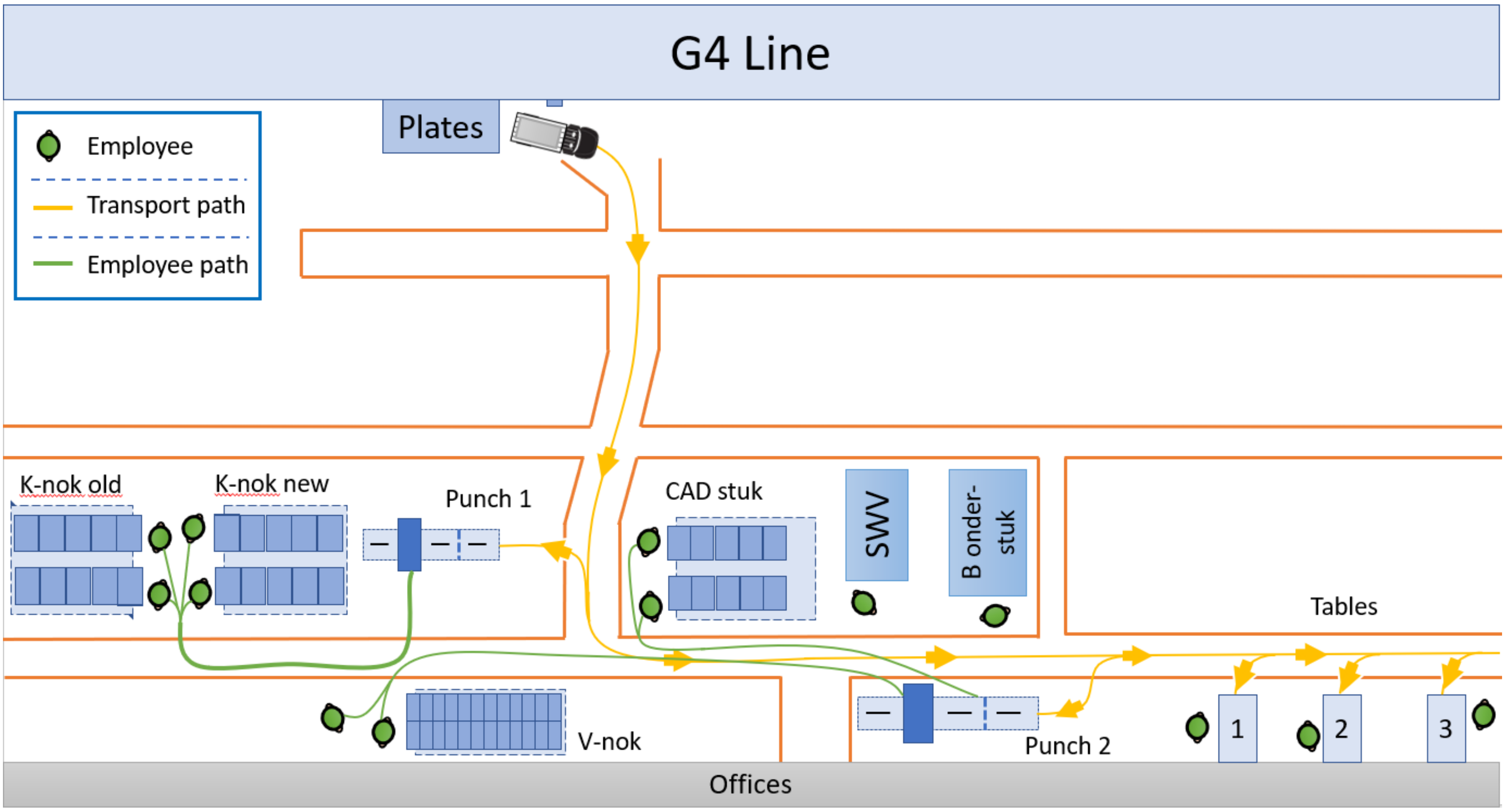
5. Go to moulding place: Now that the smaller parts are ready and loaded onto the driveable tables the employees can move the place where they can put the plates onto the mould. This place is dependent on the specific special part that is produced, in this example the employees produce a *k-nok* so they go to one of the *k-nok* machines.

B.4.6: Step 6



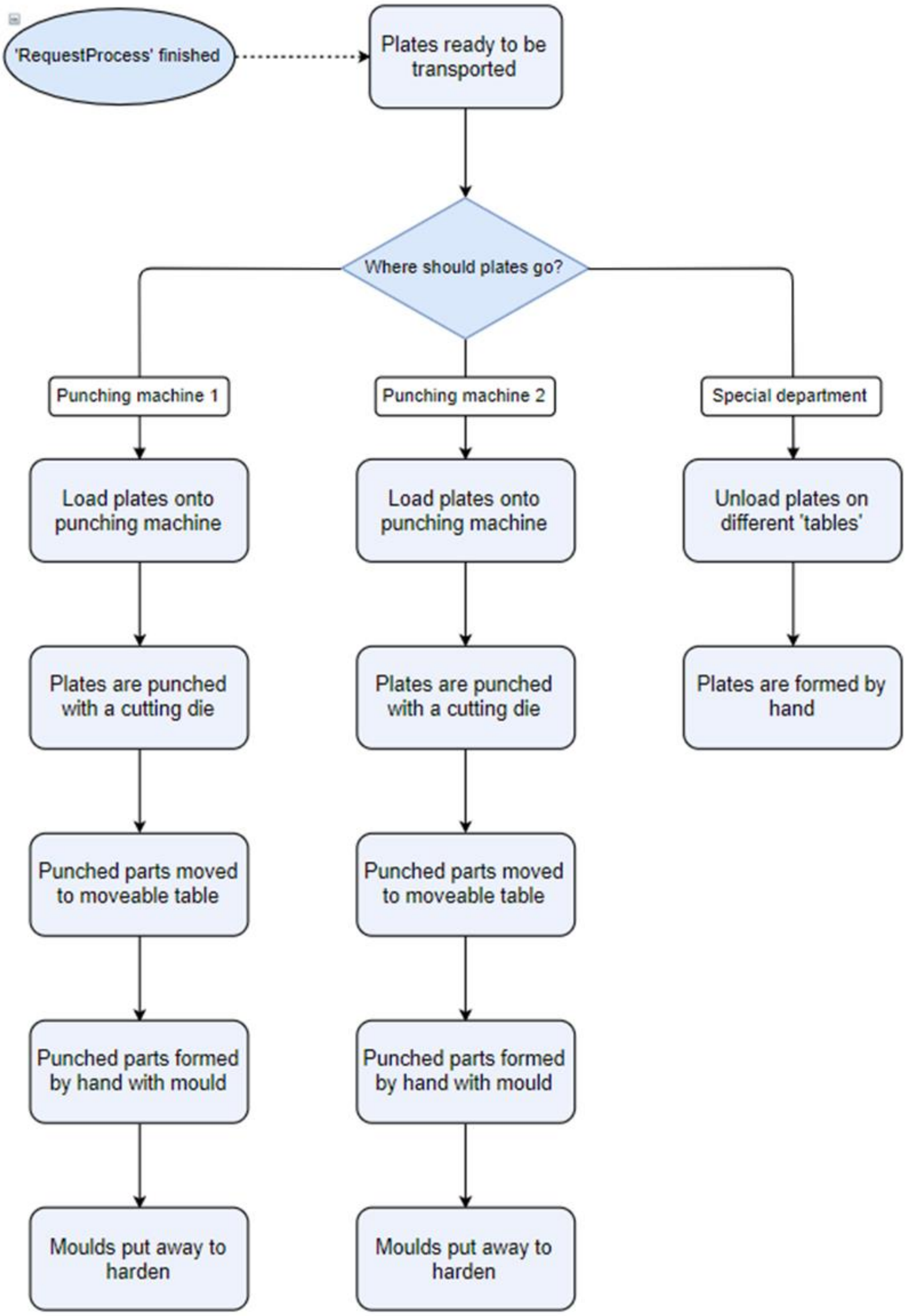
6. Arrive at moulding place: The last step of the punching process is that the employees arrive at the *k-nok* machine with the smaller plates. From then on the moulding process starts.

B.5: Spaghetti diagram



In the image above a basic spaghetti diagram from the manual moulding department can be viewed. In the top left of this image there is a legend that states what all the lines in the image represent.

B.6: Flow diagram of the moving process



B.7: Schedule

Week ..   7.00/15:30 and 7.30/16.00

Transport: *Employee* → 6.45 till 15:15 hrs

Waste: *Employee* → 7.15 till 15:45 hrs

7.00 hrs:

Employee 1 and Employee 2	K-nok machine old	7.00 hrs
Employee 1 and Employee 2	K-nok machine new	7.00 hrs
Employee 1 and Employee 2	Table (special parts)	7.00 hrs
Employee	SWV, Ardex	7.00 hrs
Employee	B-onderstuk	7.00 hrs
Employee 1 and Employee 2	V-nok, K-nok	7.00 hrs
Employee 1 and Employee 2	C.A.D machine	7.00 hrs
Employee	Table (special parts)	7.00 hrs

7.30 hrs:

Employee 1 and Employee 2	K-nok machine old	7.30 hrs
Employee 1 and Employee 2	K-nok machine new	7.30 hrs
Employee 1 and Employee 2	MWV, L-nok	7.30 hrs
Employee 1 and Employee 2	French K-nok	7.30 hrs
Employee	C.A.D machine	7.30 hrs
Employee	C-onderstuk	7.30 hrs

B.8: Observation

6:30 → The first empty cart is placed next to the G4 line and the first eight plates are requested by the driver. The desired location of this plates is punching machine 1 for the K-nok employees.

6:33 → After a few minutes the G4 Line now starts with producing the requested plates.

6:35 → The requested plates are produced and loaded onto the cart.

6:37 → Now that the plates are ready and loaded onto the cart, this cart is ready for transport and moved away from the G4 Line. After removing the loaded cart a new empty cart is placed next to the G4 Line.

6:38 → To save time new plates are already requested before transporting the loaded cart. These requested plates are meant for two different tables (special parts) and punching machine 2.

6:39 → The transport of the fresh plates to their desired location starts.

6:43 → The driver arrives with the fresh plates at punching machine 1, here the driver starts with unloading the plates. Normally the employees that do the punching unload the plates but the employees only start at 7:00, so now the driver has to unload the plates by himself. **(While driving to the punching machine he had to stop for about 2 minutes to answer some questions from another employee. Normally driving takes about 1 or 2 minutes.)*

6:45 → The fresh plates are loaded onto the punching machine and the driver leaves back to the G4 Line.

6:46 → The driver arrives at the G4 Line and notices that the earlier requested plates (*see 6:38*) are all loaded onto the cart. So this loaded cart is moved away from the G4 Line.

6:47 → Another empty cart is placed next to the G4 Line.

6:47 → With the empty cart ready a new request for plates can be made, these plates are meant for the production of C.A.D parts.

6:48 → The loaded cart (*see 6:46*) that was moved away earlier is now transported to the tables and punching machine 2.

6:51 → The driver arrives at the first table and here one plate is manually unrolled from the cart onto the table. At this table only one employee is working so the driver has to help with unrolling.

6:52 → After unrolling a plate the driver moves on to the next table.

6:53 → At the next table the driver needs to deliver 3 plates. Here are two employees present so they can do the unrolling and the driver waits on his cart. The unrolling at this table is also done manually.

6:54 → The plates are manually unrolled and the driver moves on to punching machine 2.

6:55 → The driver arrives at punching machine 2 and drives the cart in front of the punching machine. This takes quite some time because the plates are really width this morning, because of this the cart should be driven in front of the punching machine very precisely. When the plates are less width this driving is a bit easier and therefore quicker.

6:58 → Since it's still not 7:00 most employees didn't arrive yet. So the cart driver has to unload the plates onto the punching machine himself. After unloading the driver goes back to the G4 Line.

7:01 → The driver arrives at the G4 Line and notices that the earlier requested plates (*see 6:47*) are ready again and loaded onto the cart. So this loaded cart is moved away from the G4 Line.

7:02 → A new empty cart is placed next to the G4 Line.

7:03 → Again new fresh plates are now requested, the plates that are requested are meant for the employees that start around 7:30.
**On this day 3 different carts are enough to provide all the employees that start at 7:00 with plates. On another day with a different schedule also 4 or 5 carts can be needed.*

7:03 → The loaded cart moved away earlier (*see 7:01*) is now transported to punching machine 2.

7:05 → The cart driver arrives at punching machine 2 and places the cart in front of the punching machine. The employees that got their plates at *6:58* are still punching, so the fresh plates on the cart can't be loaded onto the punching machine. Therefore the cart driver leaves the loaded cart behind at the punching machine and goes on.
**There are 3 carts, so he can leave one behind. Later on this cart is picked up again.*

7:06 → Now that all employees that start at 7:00 are provided with plates it's time for a quick coffee break.

-- Break –

**From now on will no longer be mentioned that an empty cart is placed and new plates are requested. Every time a loaded cart is removed and transported also an empty cart is placed and new plates are requested.*

7:13 → The break is over and the driver goes back to remove the already loaded cart away from the G4 Line and this loaded cart is transported to punching machine 2.

7:16 → The driver arrives at punching machine 2 to deliver the plates that are used to produce V-nok later on. Since these plates are meant for employees that start at 7:30 the cart driver has to unload the plates by himself.

7:22 → The cart driver arrives back at the G4 Line and the next loaded cart is already fully loaded, so the driver connects this cart and drives to the punching machine 1. These plates are meant for k-nok production.

7:24 → The cart driver arrives at punching machine 1, here the employees are already present and they unload the plates onto the machine. The cart driver goes back to G4 Line

7:26 → The driver is back at the G4 Line but here the plates are not yet ready, the plates are still being produced. So the cart driver has to wait till the plates are ready.

7:28 → The plates are loaded onto the cart and the driver transports this loaded cart to punching machine 1. These plates will also be used for k-nok production.

7:31 → The cart driver arrives at punching machine 1, but the other employees are still punching. So the plates can't be loaded onto the punching machine so the driver leaves his cart behind at the punching machine and goes to G4 Line again.

**Since it's already past 7:30 the employees for who these plates are meant have to wait at the punching machine till the last punching job is done.*

7:33 → The driver arrives back at the G4 Line to get a new loaded cart. This loaded cart is not ready yet so the driver has to wait.

7:34 → The loaded cart is ready and the driver starts transporting this cart to punching machine 2.

7:37 → The cart driver arrives at punching machine 2 with the fresh plates, the plates are unloaded by the employees.

Now that all the employees that started at 7:30 have their plates and everything starts over again since the employees from 7:00 soon need plates again. But for now this observation is done.

Appendix C: Measurements

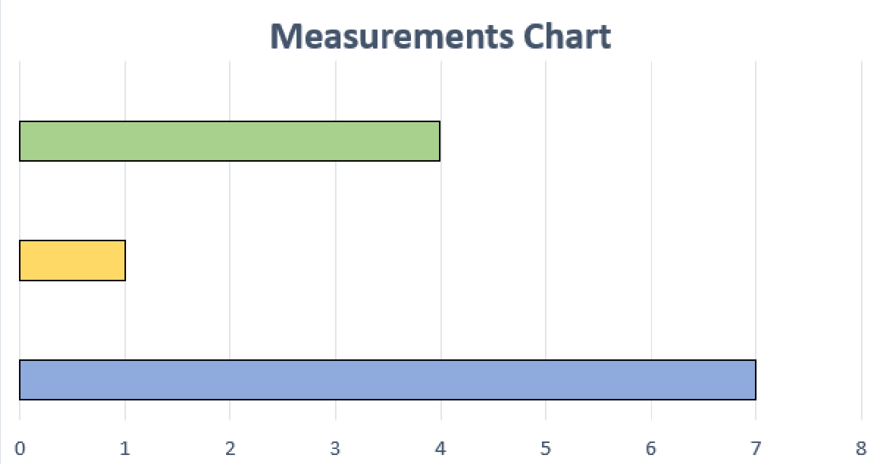
Appendix C.1: Real-life waiting time

WTT (s)	WTE (s)
184	93
12	14
41	21
91	66
177	111
121	17

	Waiting time caused by the plate delivery
	Waiting time caused by the punching process
	No waiting time, only (un)loading time

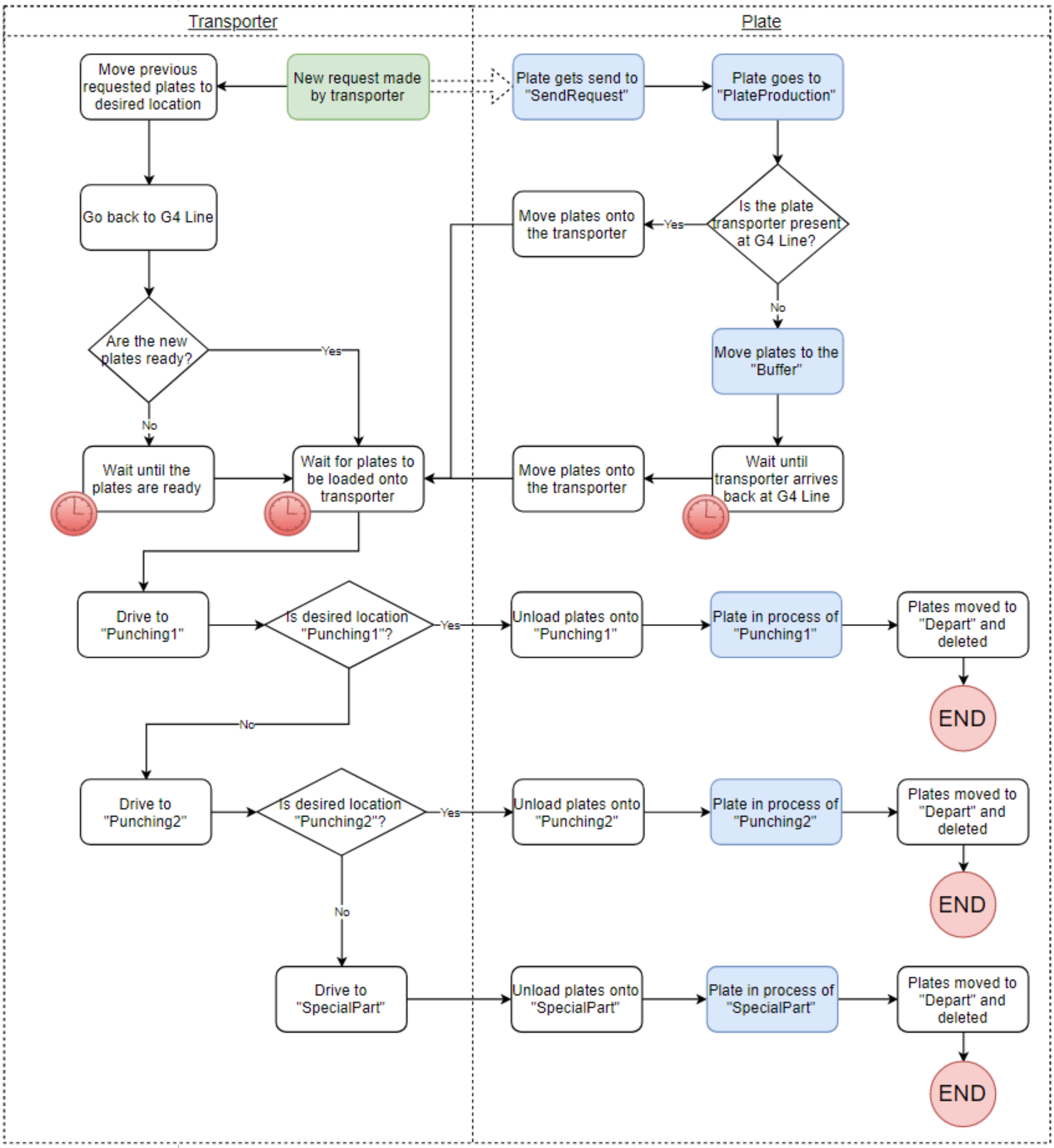
Appendix C.2: Measurement chart

	Waiting time caused by the plate delivery
	Waiting time caused by the punching process
	No waiting time, only (un)loading time



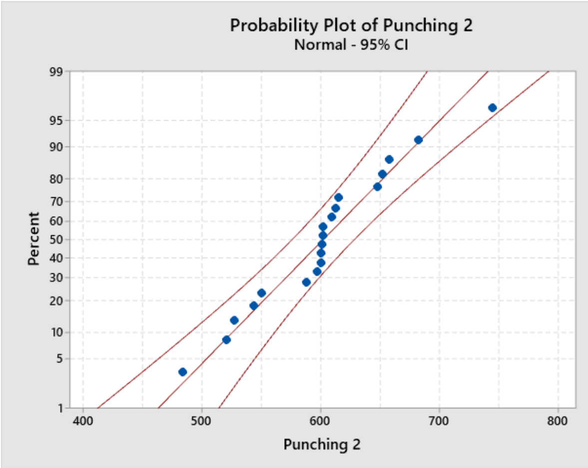
Appendix D: Simulation model

D.1: Diagram of logic behind the simulation model

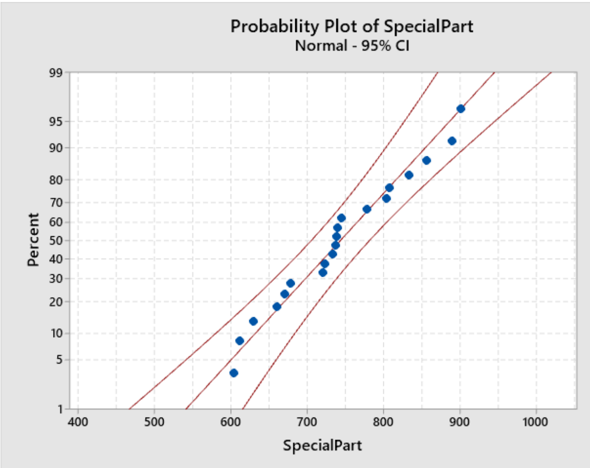


The flow diagram starts when the plate transporter requests new plates, the start of this flow diagram is also displayed with the green rectangle. Furthermore the blue rectangles indicate that the plate is in a certain Plant Simulation process, the plate leaves this process as soon as the processing time is over. For instance the plate will leave the *Punching1* as soon as the punching process is done. The red clock indicates that there is a waiting time for the transporter or the plate outside of a process. This happens when the transporter just stands still on the track waiting for plates to come. For the plates this happens when the are waiting in a buffer for the transporter to come or for a certain process to start.

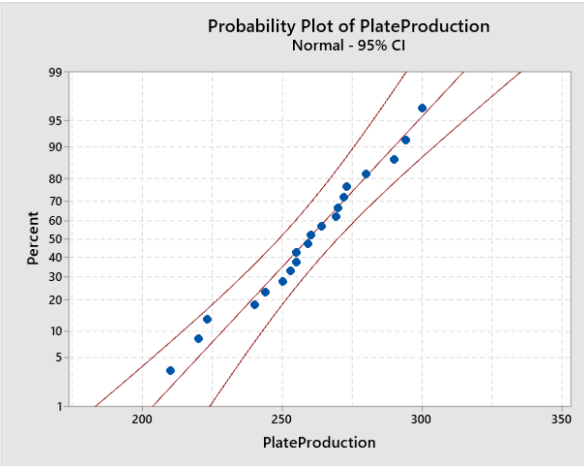
D.2: Probability plots



Simulation data for *Punching2* process.	
Mean:	**10:02** *(602s)*
St. Dev:	**1:00** *(60s)*
Lower bound:	**8:03** *(483s)*
Upper bound:	**12:25** *(745s)*



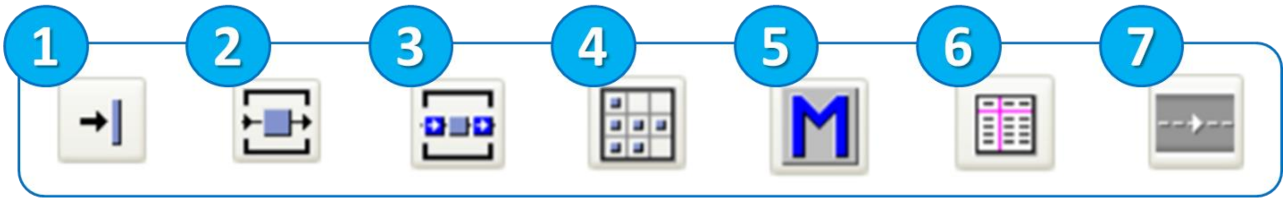
Simulation data for *SpecialPart* process.	
Mean:	**12:23** *(743s)*
St. Dev:	**1:27** *(87s)*
Lower bound:	**10:03** *(603s)*
Upper bound:	**15:01** *(901s)*



Simulation data for *PlateProduction* process.	
Mean:	**4:19** *(259s)*
St. Dev:	**0:24** *(24s)*
Lower bound:	**3:30** *(210s)*
Upper bound:	**5:00** *(300s)*

D.3: Introduction to Plant Simulation

This appendix is about shortly introducing and explaining some of the core concepts of the Plant Simulation software. If one is already familiar with Plant Simulation then this part can be skipped. In the image below seven core concepts of Plant Simulation can be seen, under the image each of the seven concepts will be explained shortly.



1 – Drain: After the plates went through all the different processes inside the manual moulding department they will be sent to the ‘drain’. This ‘drain’ then stores all the relevant data about the specific plates and deletes the plates from the simulation. This ‘drain’ will also store data about the waste and delete the waste from the simulation after that.

2 – Process: This object represents both punching machines and the tables where the special parts are made. The plates remain in this object during their processing time and are then moved to the next step. This processing time is a bit different each time and is determined with the help of a probability distribution.

3 – Buffer: The ‘buffer’ object represents the place next to the G4 Line where a cart can wait while the plates are loaded onto the cart. The ‘buffer’ also represents the spot in front of both punching machines where a loaded cart can wait until the punching machine is empty. The plates stay in the ‘buffer’ until an employee decides to move the plates.

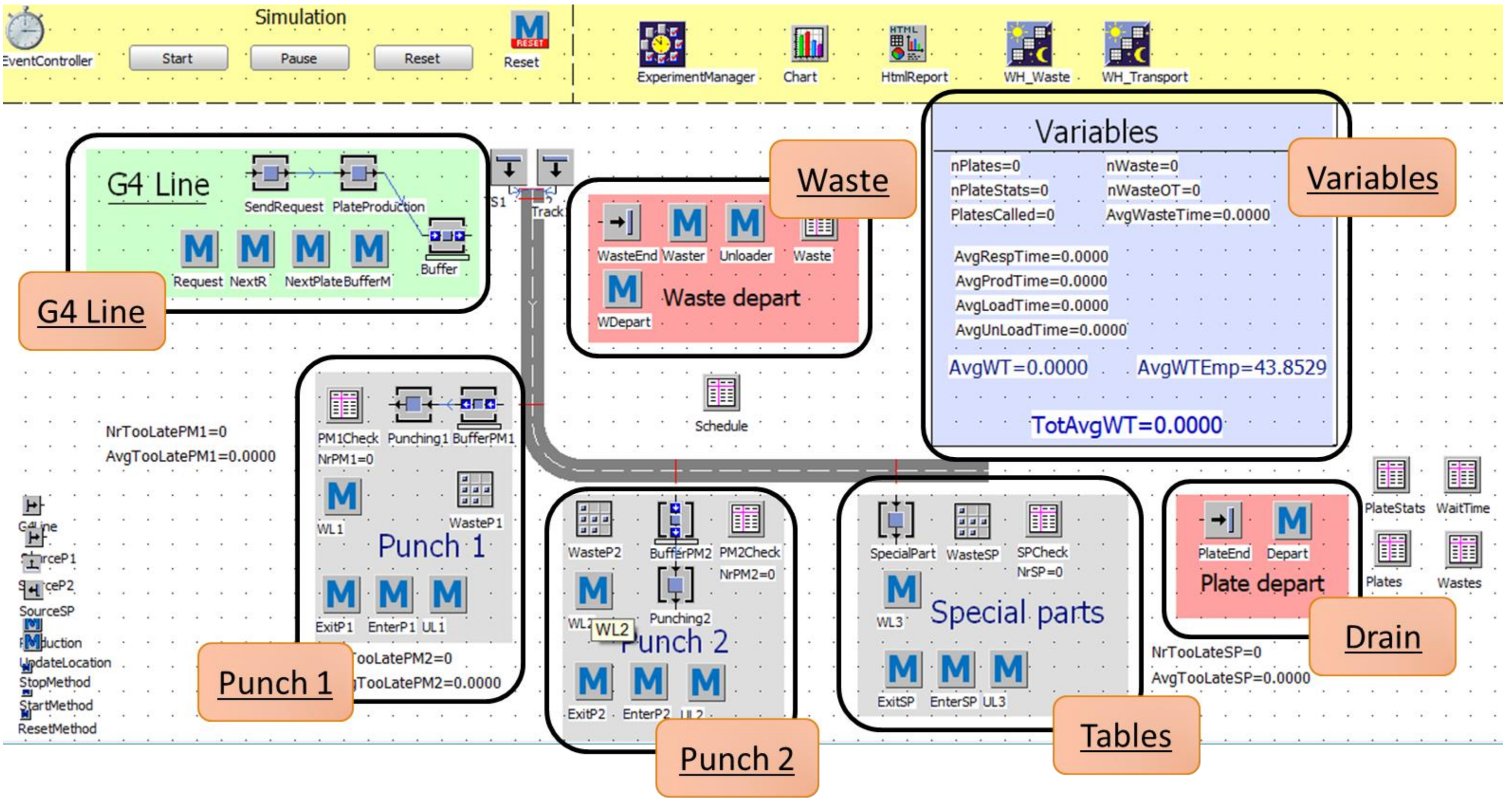
4 – Store: Both punching machines and the tables have a ‘store’, this is the place where the waste is stored until it is picked up by an employee.

5 – Method: Each ‘method’ object contains lines of code that are used to make the simulation model run. All these ‘methods’ are the core of the simulation model since they determine what will happen in the simulation model.

6 – Table: In the ‘table’ object relevant data can be stored during the simulation, this data can then be reviewed when the simulation is complete. A ‘table’ can also contain input data that is necessary to run the simulation model smoothly.

7 – Track: The ‘track’ object is an element that can be placed down in a simulation model on which transporters can drive. The track can be as long as needed and can even have corners in it. On a track sensors can be placed, these sensors are linked with ‘methods’. When the transporter on the track drives through a sensor then this sensor triggers the method. With help of the sensors the track can come in really handy when developing a simulation model of a process with a mode of transport in it.

D.4: Simulation model interface



Above is an image of the interface of the simulation model. On this image of the interface model certain part are highlighted with the help of black squares. Below there is some more explanation for each of those highlighted parts.

G4 Line: In the top left corner of the interface the G4 Line is situated, this is also where the G4 Line is actually located in the manual moulding department. When a request for new plates is done by the transporter, then this request is send to SendRequest. As soon as the operator gives a response to the request then this request is send to the *PlateProduction* where the production of the plates starts. The produced plates go to the 'Buffer' where the plates wait to be picked up by the transporter.

Punch 1: Close to the G4 Line the first punching machine is located, in the actual manual moulding department this punching machine is located at the same location. When the transporter has plates that are destined for punching machine 1 then the transporter stops at this punching machine. The transporter then unloads the plates onto *Punching1* or onto the *BufferPM1* when the punching machine is still occupied. During the *Punching1* process the plates are then punched, when the punching is complete the plates are moved to the drain to be deleted from the simulation model. The *WasteP1* is where the waste will be stored and picked up later. The tables and methods next to punching machine 1 are used to run the simulation model and to store relevant data.

Punch 2: In the manual moulding department the second punching machine is located a bit after the corner, so in the simulation model this is also where punching machine 2 is located. In the simulation model punching machine 2 works exactly the same as punching machine 1, so the working of *Punch 2* can be found above at *Punch 1*.

Tables: The tables where the special parts are produced are located all the way on the end of the track, just as in the actual manual moulding department. The tables work almost the same as *Punch 1* and *Punch 2*, the only difference is that the tables do not have a buffer. So the plates have to be unloaded onto *SpecialPart* straight away. If this *SpecialPart* process is occupied then the transporter has to wait until this process is unoccupied again. As soon as the process at the tables is done the plates will be moved to the drain to be deleted from the simulation model. Just as all other parts the tables also have a few methods and tables to run this part of the simulation and to store relevant data. For the tables the waste will be stored in the *WasteSP* where it will be later picked up by a cart.

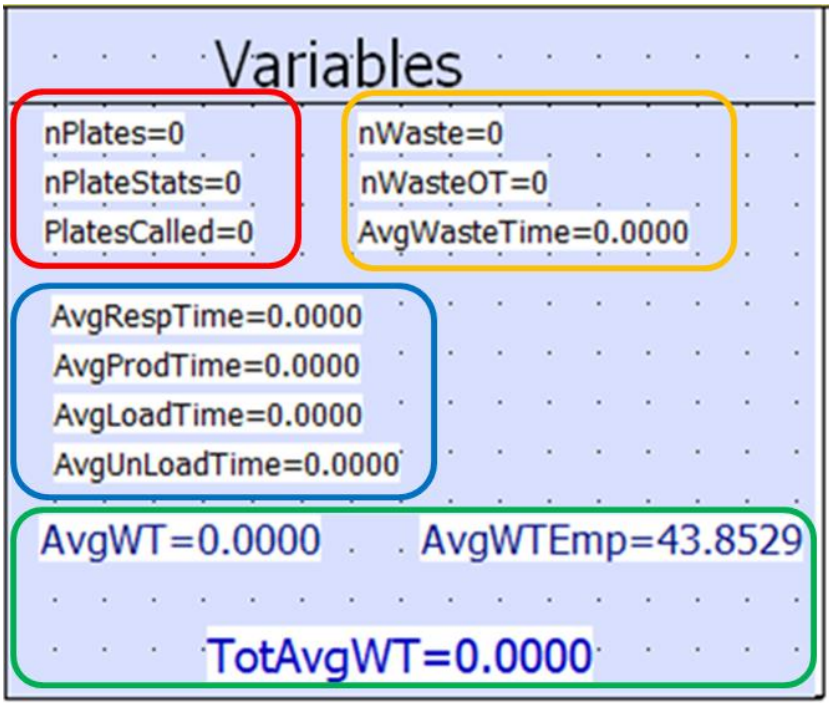
Waste: This represents the part of the manual moulding department where the waste will be transported to, to be recycled. In the simulation model the waste driver will have a list of all the waste that is present in the simulation model, with the help of a few methods the waste driver decides which waste needs the highest priority. The waste with the highest priority is then picked up first from either *Punch1,* *Punch 2* or the *Tables.* When the waste is picked up the driver drives back to the waste part where the waste is moved to the *WasteEnd*. The *WasteEnd* first stores all necessary data of the waste in a table and then deletes the waste from the simulation model.

Drain: In the simulation model the plates are sent to the *PlateEnd* in the drain part when they are finished, here the relevant and necessary data of these plates is stored. Then the plates are deleted from the simulation model. As soon as a plate enters the *PlateEnd* process the data will be stored by the *Depart* method. After that the plates leave the *PlateEnd* and will be deleted from the simulation model.

Track: In the middle of the interface a track can be seen, this track represents the lane at the manual moulding department where the carts with plates and/or waste can drive. In the simulation model both the transporter as the waste driver have their own lane in which they can drive both ways. This is difference from the actual manual moulding department, but for the simulation model it works better to give them both their own lane.

Variables: During the simulation the software is constantly calculating and storing all the different waiting times that occur during the simulation. Each of these different waiting times are important variables so they are constantly visible on the interface of the model. The waiting times visible on the interface are average waiting times so they can change from time to time and are constantly updated during the simulation. **Appendix D.5** contains a more detailed image of the *Variables* part of the interface.

D.5: Variables tab interface



This more detailed image is divided in four different parts with the help of coloured boxes. Down below is explained for each coloured box which type of variables are inside of these boxes.

Red box:

The red box contains extra variables that keep count of the number of plates in the process and the amount of plates that have already left the simulation model. These variables do not give much information but the model needs the information of these variables to perform certain tasks and calculations.

Orange box:

All three variables in this box are waste related. These variables keep track on the amount of wastes that have been recycled and checks how many of these wastes were recycled in time. Besides that it also has a variable that keeps track of the average time it takes for the waste transporter to recycle a plate.

Blue box:

A lot of tasks are performed in the simulation model for each plate that is processed. In the blue box are a few average times of some important tasks that take place in the simulation model when a plate is processed.

Green box:

This box contains the most important variables of the whole process, the KPI's. These variables were also mentioned in the conceptual model as the most important outputs of the simulation study. The variables in the green box contain information about the total average waiting time and about the average waiting times for both the punching employees and the plate transporter.

For each variable there is a short description on the next page so that it becomes clear what each variable represents.

nPlates: The number of plates that are present in the model.
nPlateStats: The number of plates that already got deleted from the simulation model.
PlatesCalled: This is the number of plates that are already requested by the transporter.

nWaste: Amount of wastes that are already recycled.
nWasteOT: The amount of wastes that were deleted on time, before it got stiff.
AvgWasteTime: The average time the waste transporter needs to recycle the waste.

AvgRespTime: The average time before the operator of the G4 Line responds.
AvgProdTime: Average time the production of the plates takes.
AvgLoadTime: The average time the plate transporter has to wait at the G4 Line
AvgUnLoadTime: The average time the plate transporter has to wait at one of the punching machines or the tables.

AvgWT: The total average waiting time of the plate transporter.
AvgWTEmp: The average waiting time of the punching employees.
TotAvgWT: Total average waiting time of the plate transporter and the punching employees combined. So this is the average waiting time that occurs in the model per plate.

D.6: Code behind the model

```
if @.cont /= VOID  -- Only run the rest of the code when the cart is loaded with plates

    if @.mu.DesLoc = "PM1"  -- Check if desired location of the plates is Punching Machine 1

        Plates["ArrivalAtP",@.mu] := EventController.simTime -- Current time is saved in a table
        @.stopped := true  -- The cart is stopped at the punching machine
        if Punching1.occupied = false   -- Before proceeding check if the punching machine is unoccupied

                wait z_uniform(6,8,20)
                Plates["UnloadTime",@.mu]   := EventController.SimTime
                Plates["WaitingTime2",@.mu] := Plates["UnloadTime",@.mu] - Plates["ArrivalAtP", @.mu]  -- Save more data in a table
                    v := nrPM1 + 1
                    nrPM1 := v
                PM1Check["ArrivalTime",NrPM1 ] := eventController.simTime
                Pm1Check["TimeDifference",NrPM1]    := pm1Check["ArrivalTime",nrPM1] - pm1Check["ExpectedTime",nrPM1]

                If Pm1Check["TimeDifference",nrPM1] < str_to_time("00:00") then -- Check if the plates were delivered on time
                        pm1Check["OnTime?",nrPM1] := true                     -- and store this data is a table
                    Else
                        pm1Check["OnTime?", nrPM1] := false
                    End

                @.mu.move(Punching1)    -- Load the plates onto the punching machine
                @.stopped := false      -- The cart should not be stopped at the punching machine anymore
                @.backwards := true     -- The cart has to go backwards to the G4 Line
```

The code in the picture above is part of the moving process of the plates in the model. This code can be found in the method named *UL1* which is a method in the *Punch 1* part of the model interface. The code above is triggered when the transporter drives through a sensor next to the first punching machine (*Punching1 in the model*).

D.7: Real-life waiting time data

	WT Transporter (s)	WT Employees (s)	Total WT (s)
	196	93	289
	26	14	40
	62	21	83
	103	66	169
	186	111	297
	138	17	155
Average:	**118,50**	**53,67**	**172,17**

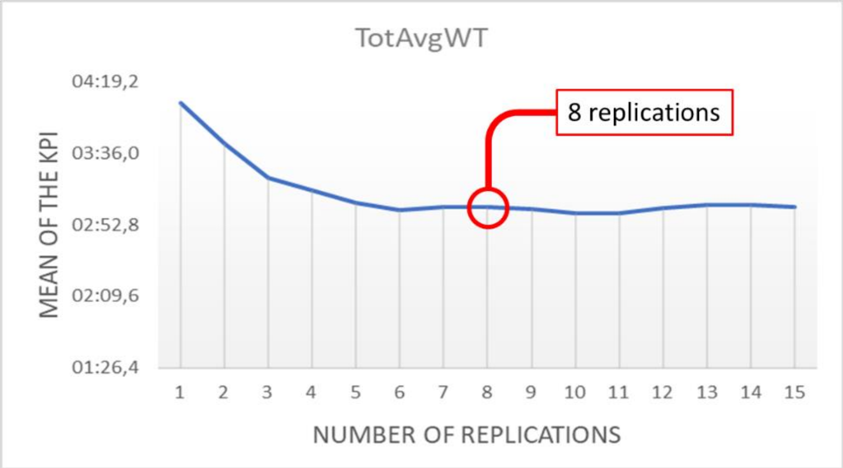
D.8: Simulation model waiting time data

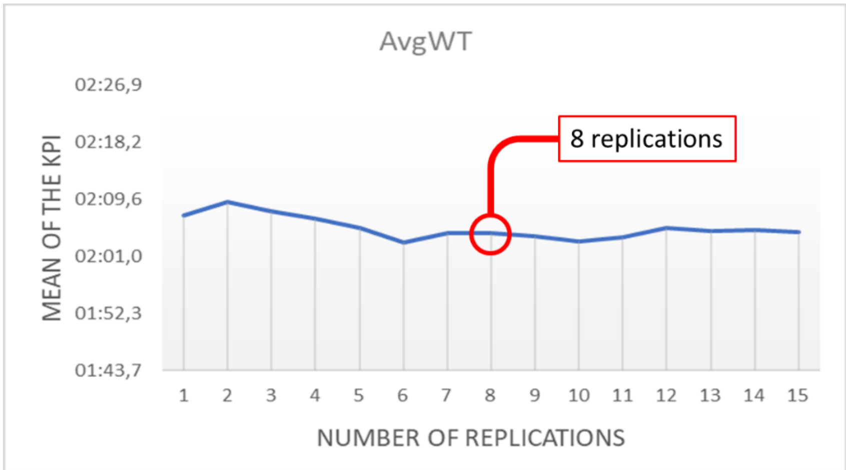
Simulation data	
Variable	**Waiting Time**
AvgWT:	112,50
AvgWTEmp:	51,06
TotAvgWT:	163,56

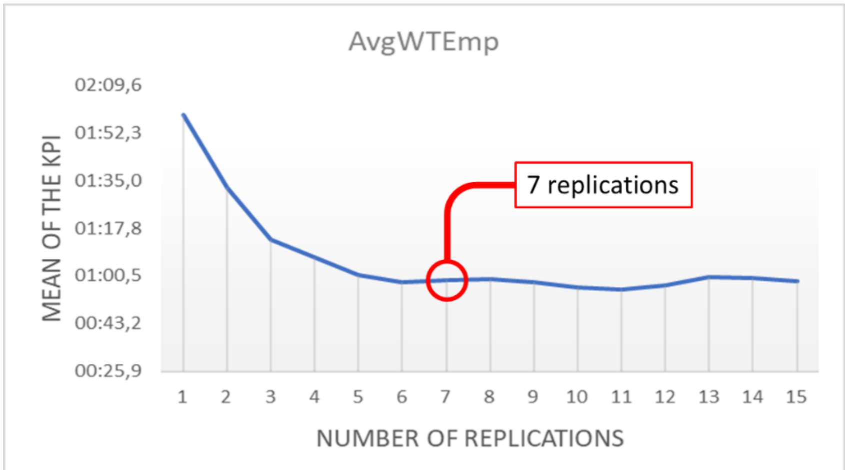
Appendix E: Experiments

E.1: Graphical method graphs

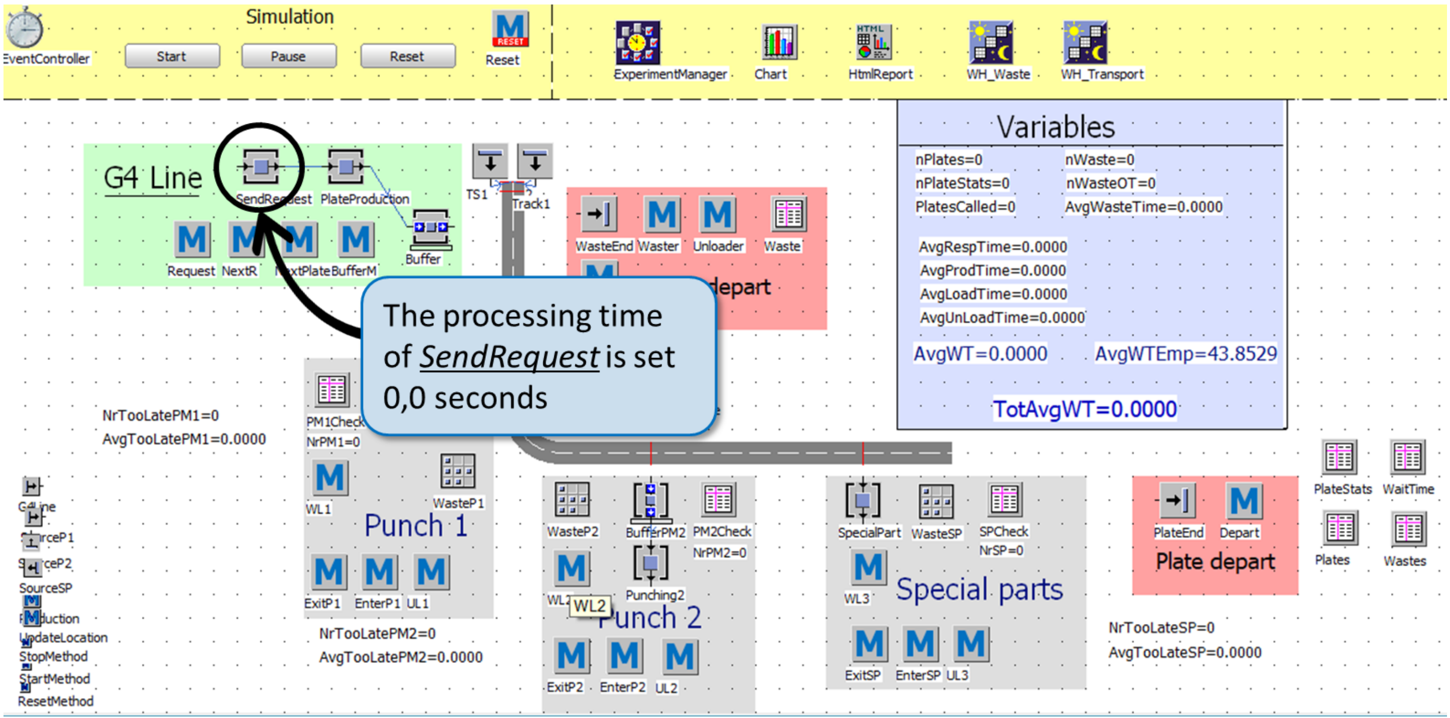
This appendix contains the three graphs that were created during the graphical method.



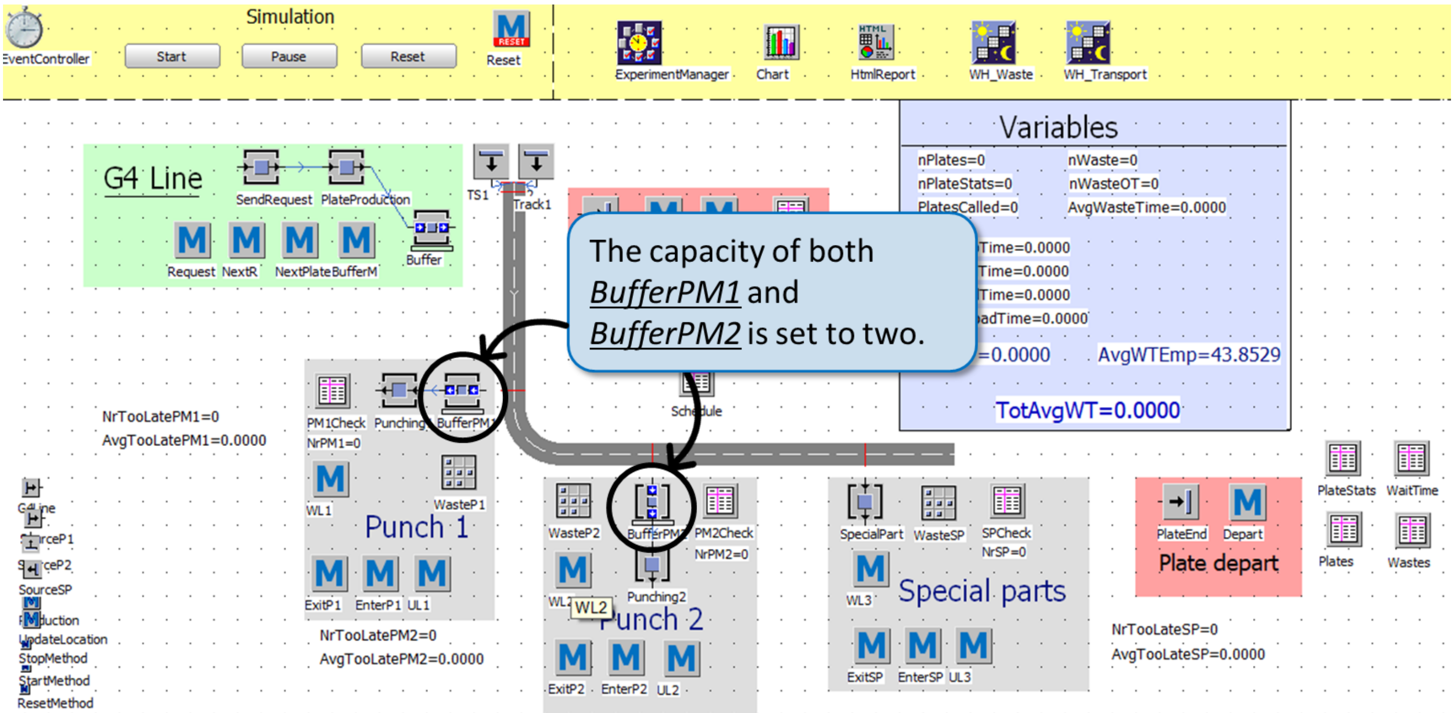




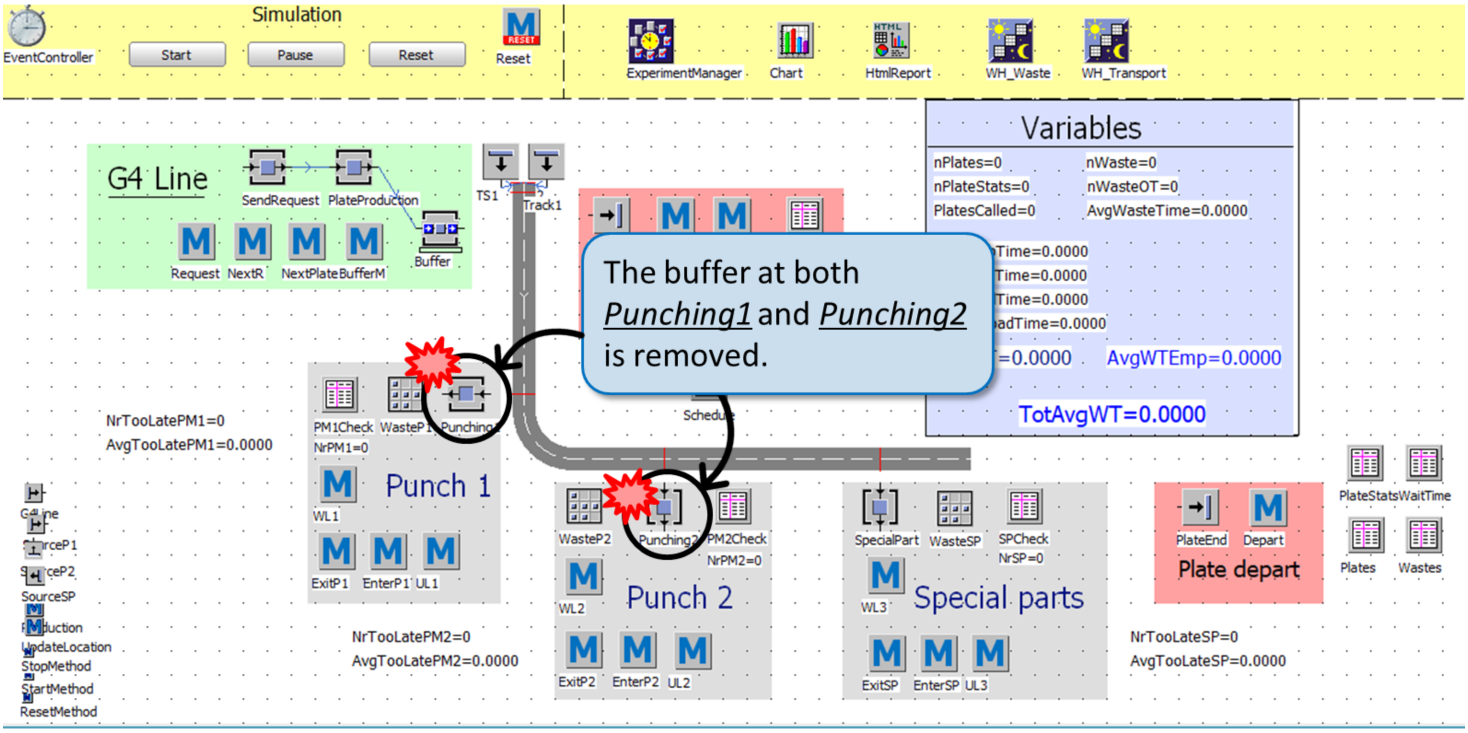
E.2: Transporter is the leading factor



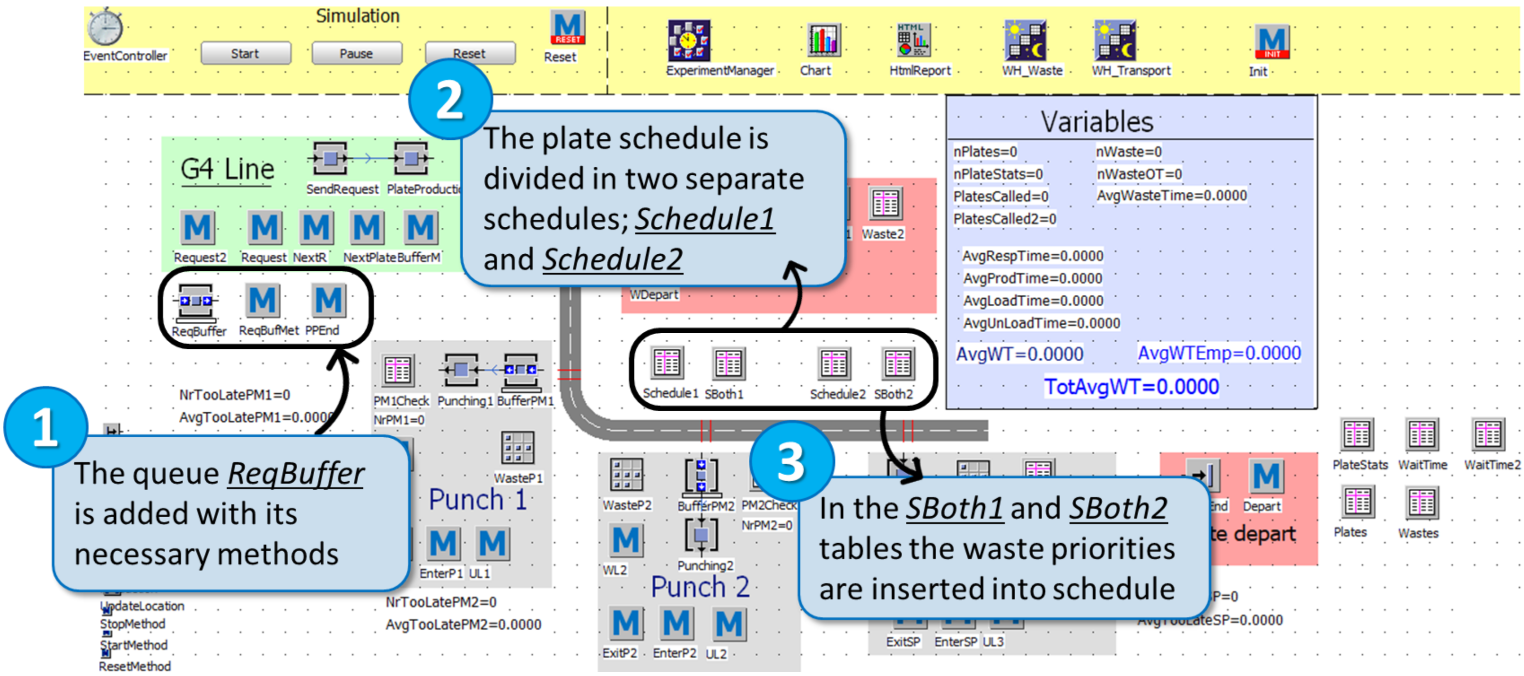
E.3: Extra buffer added at the punching machines



E.4: Buffers removed at punching machines

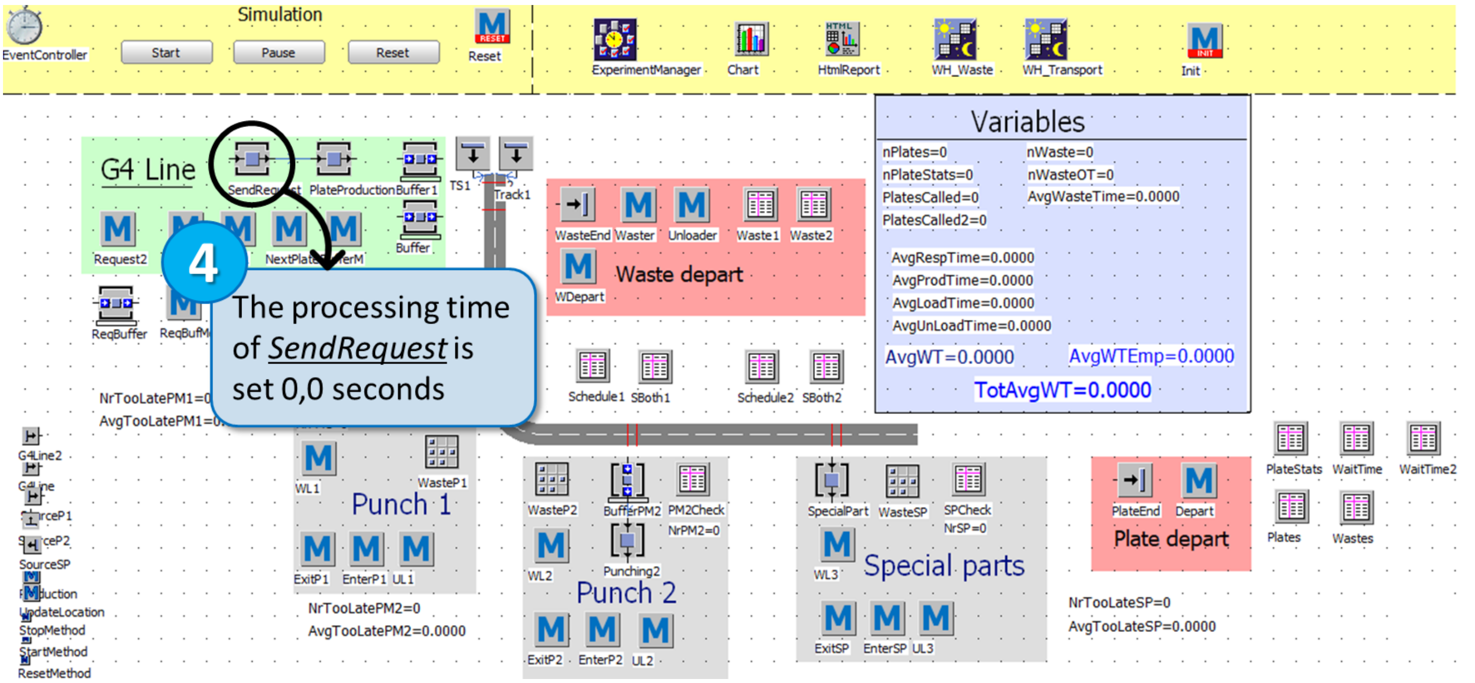


E.5: Cooperation between the two transporters



E.6: Cooperation and transporters the leading factor

The interface in the image below is from the simulation model in which the two transporters cooperate together and are both responsible for plate as well waste transport. This simulation model is almost the same as the one mentioned in **Appendix D.5** above. However in this simulation model the transporter is also the leading factor, so there is no longer a response time from an operator. Therefore the processing time of *SendRequest* is set 0,0 seconds as shown in the image below.



E.7: The results of all experiments

Experiment	Total Waiting Time	Transporter Waiting Time	Employee Waiting Time
Experiment 1: *(Baseline measurement)*	2:43.5636	1:52.4992	0:51.0644
Experiment 2:	**2:00.4479**	**1:19.7700**	**0:40.6779**
Experiment 3:	2:42.7400	1:52.0001	0:50.7399
Experiment 4:	7:58.6662	3:35.0174	4:23.6488
Experiment 5:	9:23.9216	6:05.7713	3:18.1503
Experiment 6:	8:24.3518	5:05.6198	3:18.7320

Appendix F

F.1: Systematic Literature Review

There are a lot of different theories/methods about how to optimize or improve a production process. It is also important to optimize the production process in a sustainable way, so this should also be researched. With the help of a literature research the following knowledge question should be answered:

Which methods are known in the literature to optimize the production process (in a sustainable way)?

Search term	Scope	Date	Period	# Results
Scopus:				
"Supply chain" *AND* method *AND* optimize	Article title, abstract, keywords	9-5-2019	1990-present	66
"Supply chain" *AND* theory *AND* optimize	Article title, abstract, keywords	9-5-2019	1990-present	18
"Improvement method" *AND* "supply chain"	Article title, abstract, keywords	9-5-2019	1990-present	3
Bottleneck *AND* "supply chain" *AND* improve	Article title, abstract, keywords	9-5-2019	1990-present	13
In total:				**100**
After inclusion and exclusion:				31
After reading the title and abstract:				8
After reading articles:				2
Adding extra articles:			**+2**	4
Total selected:				**4**

*Instead of production process the words supply chain are used since that is more general used when talking about a manufacturing process.

#	Criteria	Reason for exclusion
1	Article published before 1990.	Because of the technologization articles from before 1990 might be no longer relevant.
2	Article is not for free	I don't want to spend money to read expensive articles
3	Articles about service processes	The focus of the research is on manufacturing companies
4	Articles about setting up a new production process	Production process already exists, so article should focus on that
5	Articles in general about a production process.	Articles that describes a production process and its weaknesses are already known. Methods to improve the process are needed.

#	Criteria	Reason for inclusion
1	Full article should be available	If the full article is unavailable then I'm unable to read it.
2	Article should be Dutch or English	If the article is not in Dutch or in English then I'm unable to read the article.
3	Article about optimizing or improving.	Some articles are about controlling or managing the production process, that is not the subject needed.
4	"Optimize" and "Supply chain" should be in the keywords	If these two words are not in the keywords then the article is not about optimizing the supply chain.

5	Subject area should be engineering	All the other subject areas are too different from the project at Eternit and therefore not relevant.

Each of the four articles are analysed on three different concepts that will be needed for the research. In the conceptual matrix below the main findings of each article are described based on the three different concepts. The three concepts important for the research are:

1. Step-by-step action plan towards optimizing a production process. *(Concept 1)*
2. How to deal with a bottleneck in the production process. *(Concept 2)*
3. Sustainability taken into account. *(Concept 3)*

Article	Authors (year)	Concept 1	Concept 2	Concept 3
“What is this thing called THEORY OF CONSTRAINTS and how should it be implemented?”	Eliyahu M. Goldratt	1: Identify weak link 2: Exploit the weak link 3: Subordinate everything to the weak link 4: Improve the weak link by adding resources 5: Start over with the new weakest link.	First exploit the weak link as much as possible. Then subordinate all other processes towards this weak link. If that doesn’t help the weak link should be improved.	-
“Improving construction supply chain collaboration and performance: A lean construction pilot project”	Per Erik Eriksson (2010)	1: Identify which parts of the product add value for the customer 2: Make a Value Stream Map to identify which processes add value for the customer. 3: Remove ‘waste’ from the process as much as possible. Waste is everything that doesn’t add value for the customer, for example lead times or cleaning. 4: Focus on the flow of the product through the production process. Improve process where there is no continuous flow. 5: Keep improving the production process. Done by ‘kaizen’; everyone in the company should share knowledge and problems and learn from each other.	If the flow of the product is affected by the bottleneck then immediate action should be taken. The bottleneck should be improved with continuous improvement (kaizen)	During waste reduction unnecessary movements and processes will be removed. This leads to less gas, energy and utilities use.
“Sustainability optimization for global supply chain decision-making	Raunak Bhingea, Raphael Moserb, Emanuel Moserb, Gisela Lanzab and David Dornfelda (2015)	The supply chain is improved with the help of objective functions. (cost, social sustainability and environmental sustainability) 1: Identify the amount of manufacturing steps (w). 2: Put weightings on the three different objective functions. Highest waiting is most important.	-	This method focus’ is on improving the structure of the supply chain, while taking into account the economic, social and environmental sustainability.

		3: Define the upper and lower limits for the objectives, result of this is a vector-valued objective function. 4: Retrieve and fill in all necessary data into the objective functions. The formed maximization problem can now be solved.		One can choose how important sustainability should be during improving by changing the weights of the objective functions.
“An overview and evaluation of quality-improvement methods from the manufacturing and supply-chain perspective”	B. Radej, J. Drnovsek and G. Beges (2017)	With the help of seven basic quality tools 90% off all issues in the supply chain could be solved. Each tool looks towards the supply chain with a different perspective, therefore all tools should be used to optimize in the best possible way. The seven basis quality tools are: 1: Cause and effect diagram *List all causes and effects and the relationships between them.* 2: Flow chart *Make a workflow of the production process* 3: Control table *Create a table in which currently available data is shown.* 4: Control chart *Shows the trend of the KPI during the process. Should include upper and lower limits of the KPI.* 5: Histogram *Make histograms of different KPI’s. This makes it easy to understand data.* 6: Pareto analysis *Make a diagram with all causes and also their frequency. The focus can then be put on the main causes.* 7: Scatter plot *If unknown if certain data is interdependence, a scatter plot can help. The scatter plot can show positive or negative correlations.* To optimize the production process now different methods can be used, like Plan Do Act Check (PDCA),Failure Modes	The seven basis quality tools can be used to find weak spots/bottlenecks in your production process. By using all seven tools there is a lot of information about the bottleneck, making it easier to solve the bottleneck. However in this article no further explanation is given on how to solve the bottleneck.	The whole article is about optimizing the supply chain to get better KPI’s. If one of the KPI’s is for example sustainability then the method can be used to optimize the production process while also thinking about sustainability.

		and Effect Analysis (FMEA) and 5S		

Conclusion:

In the literature there are a lot of different methods known to optimize production processes, while also taking the sustainability into account. Although a lot of the methods in the literature are not really suited for general use, a lot of these methods can only be used in really specific cases or business. So all the articles with methods not suited for general use were removed. After adding two other articles that I used in earlier projects at the university there were four interesting articles left, consisting of different methods to optimize a supply chain. All four articles were analysed and read, after which the conceptual matrix was made up.

All four articles consist of fairly different optimizing methods, because of this I got a broad view on the different methods to optimize a production process. After analysing all articles and filling the conceptual framework a conclusion can be drawn on which method should be used. Based on the conceptual framework the Theory of Constraint (ToC) from Goldratt will be used.

So to answer the knowledge question; there are a lot of different methods to optimize a production process, some of them also sustainable. However not every method is a generic method and can therefore only be used on specific cases. The remaining four articles all added something to the three different concepts. But after careful analysing the Theory of Constraint (ToC) is assumed the best and most fitting method for this research. So this method is further investigated in the theoretical model.