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Master Thesis

Improving the productivity of the SubStation5.1ing process using discrete-event simulation

This is a public version. If needed, company names, employee names, product names and types are replaced by fictive names. In some cases, sections are completely removed.

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Management summary

Motivation and research question

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Company X experiences a serious loss due to a high cycle time at this pressing process, especially at their indication press, which is Machine X. At this press, only the small A. Product A and Product B are produced. So, it is also known as a SubStation5.1. In total, Company X has five of these MachinesXYZ extra which are nearly identical. This means that the improvements on Machine X also could lead to the same improvements at all MachinesXYZ. Therefore, the following central research question is formulated:

"To what extent can the productivity of the pressing process, specifically at Machine X, within Company X be improved?"

Methods

In order to come to an answer to this central research question, we analyze the current situation and study the literature to find alternative solutions to the existing problem. The cycle time is analyzed over the year 2018 and the following performance is obtained:

Table 0-1. Performance of Machine X based on four KPIs measured over the period of September 2017 until October 2018.

KPI	Performance
Average cycle time	4.244 seconds
Minimal cycle time	4.413 seconds
Maximal cycle time	4.060 seconds
Products below target of 4.000 seconds	0%

Machine X consists of two tables, a Machine X.2 and the Machine X.1, where each station has their own cycle time. In the figure below, we can see both tables schematically and in the attached video we can see the press in action. The station with the highest cycle time defines the cycle time of the overall process because after each operation one wheel is produced. We analyze the process by looking at each station separately in order to determine which stations can be identified as bottlenecks within the pressing process.

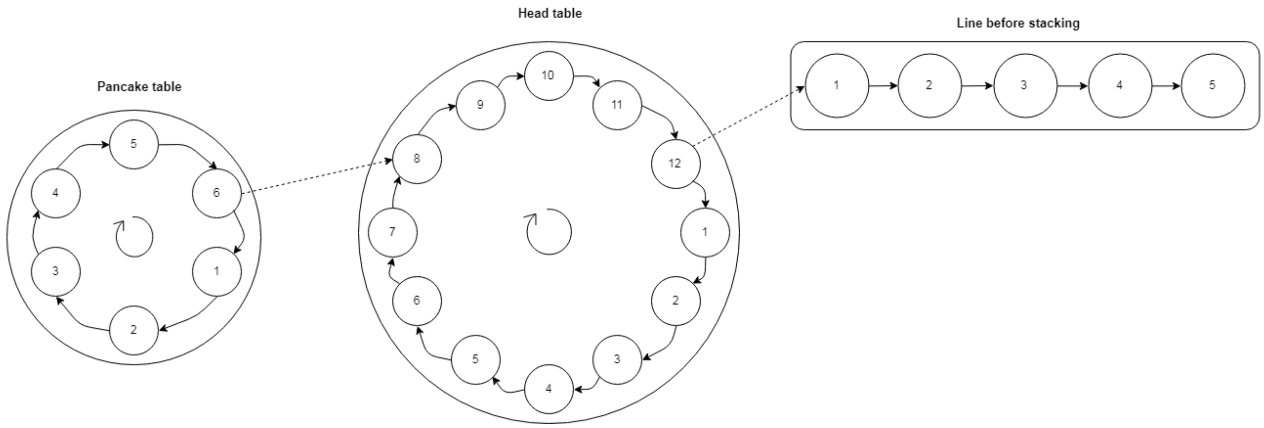

Figure 0.1. Schematic overview of the pressing process.

We identified the following bottlenecks:

- SubStation10.2 station (at the Machine X.2) (**station 10 of the Machine X.2 in the figure**)
- SubStation2.1 station (at the Machine X.1) (**station 2 of the Machine X.1**)
- Waiting time of inlay stations
- SubStation4.1 station (at the Machine X.1) (**station 4 of the Machine X.1**)

Since each station cycle time has a stochastic character, we decided to use a simulation model in order to evaluate several improvement options. The evaluated interventions can be found in the table below.

Table 0-2. Improvement options per bottleneck that could be tested in the simulation model.

Bottleneck (station)	Improvement option
SubStation10.2 station	• Time reduction of moving the plunger (Dutch: stamper) down • Distance reduction of crawl height (Dutch: kruiphoogte) • Reduction of press time
SubStation2.1 station	• Reduction of distance between mold and station
SubStation4.1 station	• Reduction of distance between inlayer and mold
Waiting time	• Better synchronization of the system in order to eliminate waiting time

Since some improvement options are quite technical, we explain them briefly. In the figure below, we can see schematically on the left side a simplified version of the SubStation10.2 station. With the plunger moving down we mean the time until it reaches the mold. The materials pressed together at this station are not that fragile, this moving time could be shortened by increasing the speed. For the crawl height, we also refer to the same left side of the figure where we can see an unscaled indication of height. A crawl height of 3 millimeters means that the plunger is slowed down 3 millimeters before reaching the mold. For the reduction of the SubStation2.1 station, we can see on the right side schematically the mold and the station. Since there is a difference in height of spreading the SubStation2.1 onto the mold, this time can also be shortened by reducing the distance.

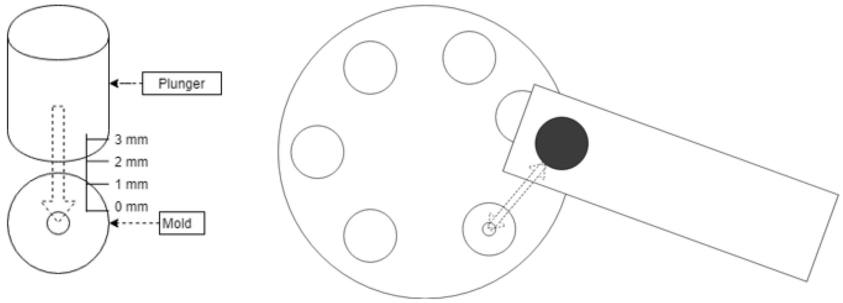

Figure 0.2. Schematic overview of crawl height principle (left) and SubStation2.1 station (right).

Results and recommendations

The experiments are evaluated with the KPIs as mentioned in Table 0-1. Since the outcomes of the best experiments were very close, we need to make some concessions. Since the result of reducing the distance at the SubStation4.1 station is only marginal, the following outcomes correspond with the best experiment:

- Reduce the SubStation10.2 time from 1.3 to 1.1 seconds after performing thorough research on reducing it on all different types of SubStation2.1 and pressure.
- Reduce the crawl height of the plunger of the SubStation10.2 from 3 to 0 mm.
- Adjust the moving time of the plunger of the SubStation10.2 from 80% to 90% of its maximum power.
- Reduce the distance between the mold and the SubStation2.1 station by inserting plugs.
- Synchronize the system in a way that no waiting time occurs.

Table 0-3. Performance based on the four KPIs as outcome of the simulation model.

KPI	Performance
Average cycle time	3.995 seconds
Minimal cycle time	3.921 seconds
Maximal cycle time	4.133 seconds
Products below target of 4.000 seconds	46.7% of total products

Besides this analysis based on the KPIs, we also look at the bottleneck contribution of the critical stations as mentioned. With the interventions as proposed above, a three-bottleneck situation originates with the SubStation2.1 station as the main bottleneck since its contribution is about 73%. The second major bottleneck is the SubStation10.2 station with about 20% contribution and thirdly the SubStation4.1 has a contribution of 7%. Furthermore, comparing the old situation with the new situation we can see that on a yearly basis 317,220 Product A extra can be produced. In terms of money, this would save Company X 12,255 euros on yearly basis. Let us see below what the savings for Machine X and for all MachinesXYZ are.

- **Only Machine X:**
    - Savings per year: *€12,255*
    - Extra Product A produced per year: *317,220*

- **All MachinesXYZ:**
    - Savings per year: *€73,533*
    - Extra Product A produced per year: *1,903,322*

In addition to the main goal of this research, we also performed a scenario analysis based on the average, minimal and maximal cycle time as respectively the average, best and worst case scenario. This analysis concerns the impact on the next steps in the overall production process, namely the curing process and the packing of the final products taking into account the need of help materials and the throughput time. We take the average case scenario as most realistic option. In terms of help materials, we can say that the improved productivity does not affect it negatively. However, within the total throughput time of 45.8 hours not all Product A can be handled. The main bottleneck in this system is the packing line, where the labor efficiency is too low, namely about 4 hours of backlog work that still needs to be done while a new batch of Product A arrives at the packaging line. Since this was also the case in the old situation, we think it can be of no harm to implement the proposed interventions with the remark that this packing line should be analyzed more deeply. Therefore, based on these results, we would recommend Company X the following:

- Implement the proposed improvement options in order to decrease the cycle time of Machine X with a special attention for pressing time that should be investigated more deeply. When obtaining good results, also implement adjustments to the similar MachinesXYZ.
- Focus on how to improve the SubStation2.1 station such that the cycle time could decrease further. Besides that, always continuously improve the pressing process.
- Keep track of the cycle time in the right way in order to analyze it correctly. Besides that, create an unambiguous way of performance measurement within the company.
- Reconsider the cycle time target of 4.000 seconds.

For further research, we would recommend Company X the following:

- Investigate how to improve the labor efficiency at the packing line to deal with the improved productivity.
- Investigate how to reduce stopping time of the machine like short stops, changeovers and set-ups in order to continuously improve the productivity of the pressing process.
- Investigate on how to improve the factory performance overall by doing research on several aspects like factory layout, warehouse improvements and logistical flows.

Implementation

In order to make sure that the improvements as suggested are maintained, we develop a roadmap. Within this roadmap, we formulate which actions need to be done by whom and within which time frame. By following this roadmap, employees are triggered to perform these actions such that it becomes and even more important stays profitable to implement the intervention. In addition to this roadmap, we also implement a part of the proposed interventions. The intermediate results of this testing phase are as follows:

- Reduction of average cycle time to 4.011 seconds.
- Almost 50% of the products produced in 4.000 or less seconds.
- No negative impact on the Overall Equipment Effectiveness.

- SubStation2.1 station to be the new serious bottleneck in the process.

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Figure 0.3. Roadmap for Company X in order to improve and control the production process.

Preface

The report in front of you is the result of my graduation assignment for the Master Industrial Engineering & Management with as specialization Production & Logistics Management at the University of Twente. The research is executed on the behalf of Company X located in Place X within the department of Research and Development. During this research, I investigated how they could improve their cycle time within the pressing process of the overall production process.

First of all, I would like to thank Company X to give me the opportunity to perform this research within their company. Further, a special thanks to my two supervisors dr. Person B and Person A for their help and guidance during this assignment. In addition, I would like to thank all employees of Company X that helped me with providing and gathering all information and data that I needed during my research.

Moreover, I would like to thank dr. Peter Schuur for being the first supervisor and his useful feedback and help during the research from the university. Furthermore, I also would like to thank ir. Wieteke de Kogel-Polak for being the second supervisor and useful input for this report.

I hope you enjoy reading this report!

Melle Edens

February 2019, Enschede

Glossary

Notion	Explanation	Introduced at page
X	Company X	p. 1
OEE	Overall Equipment Effectiveness. A measurement for the performance of the factory.	p. 3
Industry 4.0	Digitalization of all products and processes.	p. 3
KPI	Key Performance Indicator	p. 6
MACHINE X	Machine X.	p. 8
CycleTime(1)	This is the average cycle time to make 1 product over a period of time.	p. 15
CycleTime(2)	This is the cycle time of a machine or process at a certain point in time.	p. 15
HP	SubStation10.2	p. 23
PCP	SubStation5.1	p. 23
Crawl height (Dutch: kruiphoogte)	The distance between the mold and the plunger where the plunger is slowed down.	p. 33
Cavity (Dutch: mal) up/down	The movement of the mold going up or down.	p. 35
Plugs	Small pieces that can be placed under the mold such that the distance to the SubStation2.1 station can be reduced.	p. 39
Plunger (Dutch: stamper)	Part of the SubStation10.2 that stamps the materials together.	p. 11

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List of Figures and tables

1. Introduction

This report is written for completing the master of Industrial Engineering & Management at the University of Twente. This is reached by doing research at Company X (X) located in Place X with a duration of approximately six months. The research is executed within the Research and Development department of X.

In this first chapter, the company is introduced in section 1.1. In section 1.2, the overall production process of the Product A is described. After that, in section 1.3 the research is introduced by describing the motivation of the research, the problem description, the research objective and scope and finally the research questions. In the last section, section 1.4, the research framework is explained by connecting the research questions to the chapters and which data or literature is needed for solving each research question.

1.1. Company description

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1.2. Process description

The production plant in Place X produces approximately 80 different Product A. In Figure 1.2 and on the front page of this report, we can see several Product A Company X is producing varying in size.

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The production process starts with the raw materials coming in with a truck and stored in the warehouse. These raw materials are going to the SubStation2.1ing process when needed for an order. In this SubStation2.1ing process, grains, resins and fillers are combined and sieved. Next, the SubStation2.1 is checked on quality. When the quality of the SubStation2.1 is good enough, it has to rest for a couple of hours before it is ready for the next production step. In this next step, the pressing takes place. Before the pressing is done, several components, like the SubStation2.1, SubStation3.2, label and ring are processed all together into a wheel. During this process, each component is added step by step and eventually pressed to a so-called “Product A”. After stacking, the Product A are baked in the oven. Then the plates are cooled and unstacked to send them to the last quality control. When the quality is good enough again, they are packed at the packing line and sent to the warehouse where they are ready for distribution. The whole process in a flow chart depicted in Figure 1.3**.**

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Figure 1.3. Complete production process overview.

1.3. Research introduction

In this section, the motivation for the research is explained. Further, the main problem is described and the research scope and objective are elaborated. Finally, the main research question and the sub questions are formulated.

1.3.1. Motivation for research

An important worldwide project for Company X is the implementation of Industry 4.0 in all the production processes. Simply said, Industry 4.0 is the fourth phase of industrialization which comes down to the digitalization of all products and processes. During the implementation of Industry 4.0, the intelligent factory is originated and therefore intelligent manufacturing. The production plant located in Place X is chosen to be the pilot plant regarding the Industry 4.0 project.

At the start of 2018, the plant in Place X started with this project as pilot-plant for Company X. During the first half-year of 2018, the processes of raw materials, storage, SubStation2.1ing and platforms have been mapped. The objective of this was to improve the traceability within the production process and optimize the quality of the SubStation2.1. Also for Company X, the optimization of the end product and production process is of importance. So, the next step within the process is to improve and digitalize the pressing process. Currently, within this pressing process Company X experiences losses in terms of productivity. Company X uses the Overall Equipment Effectiveness (OEE) as measurement for their machine efficiency. The OEE concerns the availability, performance and quality rate of the machine. The losses regarding this OEE can be due to two causes, namely downtime and cycle time losses. Since January 2018, the losses on Machine X, the press that is investigated, are divided as follows:

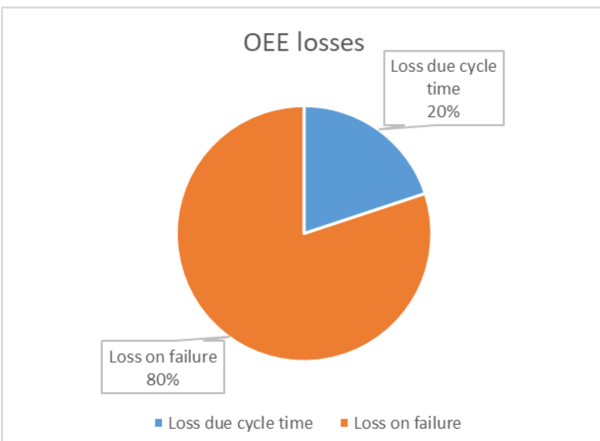

Figure 1.4. OEE losses on Machine X (Company X, 2018).

1.3.2. Problem description

As Company X wants to optimize their production process overall, we investigate every process on its own on optimization possibilities. Currently, the cycle times within the pressing process, especially Machine X for this research, are suboptimal. There are several factors that influence the cycle time during the pressing step. Nowadays, there is some information about the factors influencing the cycle time at the presses negatively. However, this information should be sharpened to take directed actions in order to come to an improved cycle time. So, with the project of Industry 4.0 in mind, the question comes up on how to get more insight in the factors that have a negative impact on the cycle time and what actions to take. For giving an idea about the cycle time, below an equation is given on how Company X determines the cycle time. On a later point in this research, cycle times within Company X are described more deeply. So, average cycle time, from now on this is stated as CycleTime(1), is computed as follows:

$$CycleTime(1) = \frac{Production\ hours\ realized * 3600}{Number\ of\ "good"\ products\ made} \qquad (e1.a)$$

The suboptimal cycle times are mainly caused by the machine settings. More specifically the combination of the machine settings. Currently, it is not clear which settings are leading to an improved cycle time of the pressing process. So, the bottleneck or bottlenecks of the process are not clear. Further, the short stops of the machine are of importance, because a lower cycle time with a same increase in short stops does not result in a better productivity overall. So, comparing it to Figure 1.4 the 20% of the losses due to cycle time have the main focus within this research. However, also a part of the 80% loss is investigated since that one cannot increase such that the productivity overall does not increase. Therefore, the main problem is formulated as follows:

> **"It is not clear which combination of machine settings, taking into account the quality requirements, lead to an improved cycle time with limited failures."**

The main problem consists of two aspects. The first aspect is more or less a technical issue where the best possible settings are investigated. The second aspect is to evaluate different combinations of settings to reduce the cycle time and improve the OEE overall.

1.3.3. Research objective and scope

Since the core problem is defined as above and the main goal from Company X itself is stated as follows: "The common goal for Company X is to optimize the cycle times of the SubStation5.1ing process", an overall research objective is formulated as follows:

> **"Get more insight in the factors that influence the cycle time negatively in order to take directed actions with respect to these factors such as to improve the cycle time and overall productivity of the SubStation5.1ing process."**

The so-called SubStation5.1ing process is explained in chapter 2 with a more detailed overview and description of this process. A sub objective of this research is also to investigate the consequences of this possible improved productivity. These consequences concern the inventory of help materials needed at both the baking and packing process.

Since this research is conducted within limited time, some restrictions are formulated. First, the pressing hall consist of a lot of different machines. For this research, only one press, from now on mentioned as Machine X, is investigated more deeply. However, when finding a good solution for this certain press, it is rolled out to the other presses as well. Further, the SubStation2.1 coming from the SubStation2.1ing department is assumed to be of good quality. Moreover, the OEE losses on cycle time as mentioned in the previous section are the main focus point and therefore the loss on downtime is of less importance of this research. For this loss on downtime, only the short stops are taken into account. Therefore, downtime like changeovers and set-up time are left out of the scope of this research. So, below in the same figure as seen in section 1.2 the main focus of this research is marked in green. Further, the sub objective to check the consequences of possible implementations is marked in blue.

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Figure 1.5. Research scope of production process, where green is the main focus and blue is a side scope.

1.3.4. Research questions

In this section, the research questions are formulated. First, a main research question is formulated to come to a well-founded conclusion when answering this main research question. In order to formulate such an answer, it is divided in several sub questions. The main research question is formulated as follows:

> **"To what extent can the productivity of the pressing process, specifically at Machine X, within Company X be improved?"**

As already mentioned, sub questions are also formulated to come to a structured answer. First, an analysis of the current situation is performed. The SubStation5.1ing process itself, the cycle time definition, current cycle times and insight in the factors that influence the cycle time are analyzed. Last, a small analysis on the current short stops is executed, because as mentioned these short stops cannot increase such that the productivity does not increase. Therefore, the following sub questions are formulated:

1. How is the current process of Machine X designed?
2. How is cycle time defined within Company X?
3. What are the cycle times of Machine X?
4. What other KPIs are important for Company X?
5. Which factors could influence the cycle time?
6. Which of these factors are the bottlenecks in the process?
7. How are the short stops distributed within the stations at the press?

Next, some literature research needs to be done. In order to find ways on how to reduce cycle times, several options are investigated. Since the cycle times are stochastically distributed and in consultation with Company X, a simulation model is used and we elaborate this decision in section 3.2. Before building this model, the best suitable type of simulation within the situation of Company X is defined. So, the following sub questions are formulated:

8. What is written in literature about reduction of cycle times?
9. What type of simulation models are known in the literature and which of these suits the situation within Company X the best?

Now that literature research is also done, alternative solutions can be proposed. Several options for improving the cycle time of the SubStation5.1 could be tested and analyzed by means of a simulation model. Further, these possible improvements have consequences for the materials needed at the baking and packing process. Therefore, the following sub questions are formulated:

10. What alternative solutions can be thought of in order to achieve an improved cycle time at the SubStation5.1?
11. Which of these alternatives has the best performance?
12. How does this best alternative influence the inventory levels of help materials at the next production process steps?

Further, the finally chosen improvements are implemented within a real-time order or period to test if the best solution according to the simulation model shows the same performance as on the real pressing process.

13. To what extent do the implemented settings meet the expectations as concluded from the simulation model?

1.4. Research outline

In this section, the research framework to answer the research questions is designed. Each chapter within this research is connected to some research questions and methods of data and information gathering. An overview of the framework and therefore the outline of the report is shown below.

1) The introduction of this research, where the company is introduced. Further, the production process and problem statement are described. For getting the problem clear, interviews are conducted in order to formulate a main research question.

2) In the second chapter the analysis of the current situation is done. First, the process is described more thoroughly. Further, data is collected and analyzed for getting a good overview of the current cycle times and the process bottlenecks. The first seven sub questions are answered in this section.

3) The third chapter consists of a literature review. Within the literature, possible solutions on how to solve the problem are investigated. Literature research is done by searching for papers and using libraries. The eighth and ninth sub question are answered within this chapter.

4) Next, possible solutions are designed by using both the literature and practical ideas. These solutions are evaluated by means of a simulation model such that the best solution can be identified. The tenth sub question is answered in this chapter.

5) Eventually, this best alternative is analyzed by looking at the performance and the inventory of the help materials needed at the baking and packing process. The eleventh and twelfth research questions are answered in this chapter.

6) Within this chapter, we discuss the limitations of this research. Besides, options for further research are formulated.

7) In this chapter, we discuss the results after implementing the best experiment. The results are discussed and compared to the results obtained from the simulation model. So, the thirteenth question is answered in this chapter.

8) Finally, the conclusions of this research are drawn. This is done by answering the main research question. Also an implementation plan is proposed for implementing the found solution. Further, some general recommendations about the research are given.

2. Context analysis

In this chapter, the context analysis is described. First, in section 2.1 the overall process of creating the Product A at the SubStation5.1 (MACHINE X) is explained. In section 2.2 the cycle time definition is explained, the current cycle times at Machine X are analyzed and other important Key Performance Indicators are explained. Next, a factor analysis is executed in order to find the bottlenecks within the process that influence the cycle time negatively. Lastly, a short analysis on the short stops of each station is executed.

Recap

Before analyzing the current situation, we give a small recap of what can be concluded from the first chapter. We observed a serious loss on the Overall Equipment Effectiveness for X partly caused by a cycle time of the pressing process that is too high. We want to know which factors influence this cycle time and therefore we perform this context analysis.

2.1. SubStation5.1 process

In this section, we describe the process of producing the Product A in order to answer the first sub research question:

- How is the current process Machine X designed?

We describe this process stepwise by first giving an overview of the whole process and the product. Next, each department is explained separately. This separate explanation is done by using two point of views, namely the mold and the product point of view and comparing a schematic overview with a real-time picture to give a better imagination of the process. We also show a picture of the whole process and compare it to the complete schematic overview.

We can see an overview of the whole process in Figure 2.1 and Figure 2.2 from two different points of view**,** where the Machine X.1 circled red, the Machine X.2 green and the conveyor belt blue**.** So, the process consists of three parts. In Figure 2.3 from left to right, we see the Machine X.1, Machine X.2 and a conveyor belt. In sections 2.1.1, 2.1.2 and 2.1.3, we explain each department step by step. Finally, we come back to the whole process to explain the complete route that a product goes on.

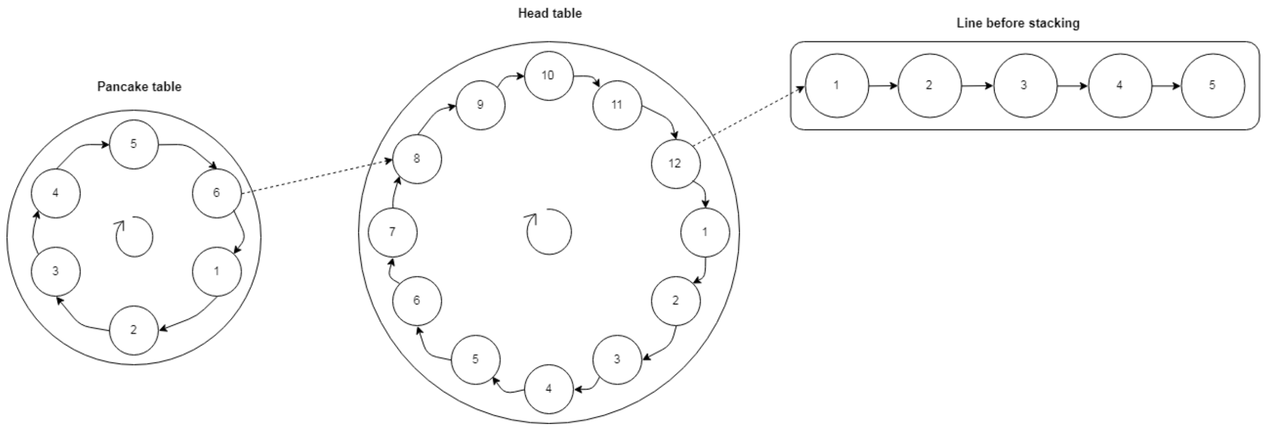

Figure 2.3. Schematic overview of the whole pressing process.

We can see the composition of the product in Figure 2.4. The upper two parts, the SubStation4.1 as number 1 and the SubStation2.1 as number 2, correspond to the Machine X.1 and therefore are the elements of the “pancake”. The other three parts, the SubStation3.2 as number 3, the label as number 4 and the ring as number 5, are corresponding to the process on the Machine X.2. All these five components together create the final wheel. We will refer to this figure in the sections when needed.

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2.1.1. Machine X.1

This table consists of six stations and thus six molds which we can see in Figure 2.5 and Figure 2.6 both in real time and schematically. When all six jobs are finished, the table rotates such that the next job can take place. We first explain this by using the point of view of the mold starting at station 1. The numbers in the figure of the real press correspond with the numbers in the schematic overview. The Machine X.1 consists of six molds which are moving to the next station when all six jobs on each station are finished.

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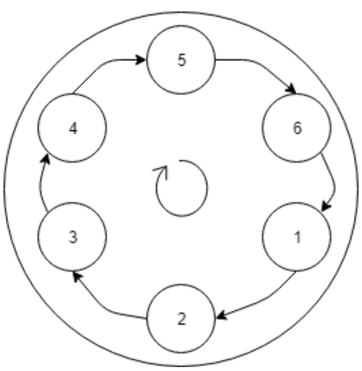

Figure 2.6. Schematic overview of the Machine X.1, where the number corresponds with Figure 2.5.

Mold point of view

1. At the first station, the mold is SubStation1.1ed if necessary. After a period of time the mold could become slippery and therefore needs to be SubStation1.1ed with magnesium.
2. At this station, the mold receives the SubStation2.1 equally divided on itself. This SubStation2.1 correspond to element 2 in Figure 2.4.
3. At this station, remainders of the SubStation2.1 accidentally ended up at the edge or middle of the mold are removed.
4. At this station, the mold receives a SubStation4.1 on top of the SubStation2.1. The SubStation4.1 corresponds to element 1 in Figure 2.4**.**

5. At this station, the press plunger is pressing the label and SubStation2.1 on the mold to create the "pancake" built up of element 1 and 2 in Figure 2.4.
6. At this station, the pancake is taken out of the mold and the empty mold moves to the first station.

Product point of view

1. In terms of product, at this station nothing happens.
2. At this station, the SubStation2.1, element 2 in Figure 2.4, needed for creating the pancake is inserted.
3. At this station, nothing happens in terms of the product.
4. At this station, the SubStation2.1 receives a SubStation4.1, element 1 in Figure 2.4**,** on top.
5. At this station, the pancake is created by pressing the SubStation2.1 and SubStation4.1 together.
6. At this station, the mold becomes empty by means of a robot arm that picks the pancake. Next, the mold moves to station 1.

2.1.2. Machine X.2

This table consists of twelve stations and thus twelve molds, and is depicted both in real pictures and a schematic overview in Figure 2.7, Figure 2.8 and Figure 2.9. This table also rotates with the same logic as at the Machine X.1. Again, we describe both point of views. The mold "starts" at station 1. The waiting stations at this table are present due to space restrictions. When the machine has a breakdown, an operator or engineer needs enough space to inspect the machine. For this table, we also attached a video of the process to give an extra visual imagination of the process.

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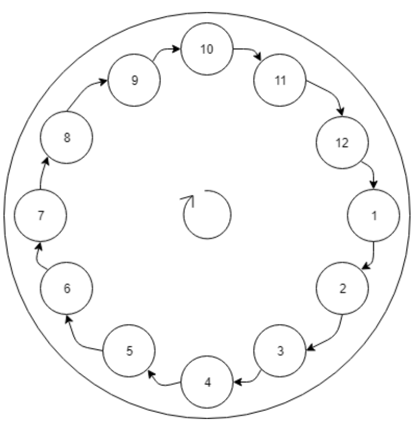

Figure 2.9. Schematic overview of the Machine X.2 with the number corresponding to the number in Figure 2.7 and 2.8.

Mold point of view

1. At this station, the mold is waiting.
2. At this station, the mold receives the ring that can be seen in Figure 2.4 as element 5.
3. At this station, the mold receives a label which is element 4 in Figure 2.4.
4. At this station, the mold receives a glass cloth, element 3 in Figure 2.4, on top of the label.
5. At this station, the mold is waiting.
6. At this station, the mold is waiting.
7. At this station, the mold is waiting.

8. At this station, the mold receives the pancake from the other table on top of the already placed ring, label and SubStation3.2.
9. At this station, the mold is waiting.
10. At this station, the SubStation10.2 plunger presses all components that can be seen in Figure 2.4 on the mold together such that the wheel is created.
11. At this station, the mold is waiting.
12. At this station, the mold becomes empty by means of a robot that picks the “wheel” out of the mold. Next, the mold moves to station 1.

Product point of view

1. In terms of product, nothing happens at this station.
2. Here the ring of the final product is inserted.
3. At this station, the ring receives the label on top.
4. At this station, the SubStation3.2 is inserted on top of the label.
5. Nothing happens.
6. Nothing happens.
7. Nothing happens.
8. At this station, the pancake from the other table is inserted on the components, the ring, label and SubStation3.2, inserted at station 2, 3 and 4.
9. Nothing happens.
10. At this station, the green “wheel” is created by pressing all components together.
11. Nothing happens.
12. At this station, for the product itself nothing happens. It is only moved to the next department.

2.1.3. Conveyor belt

We can see the conveyor belt in Figure 2.10 in real and a schematic overview in Figure 2.11. It consists of five places which are explained below. The number in both figures correspond with each other. For this line, only the product point of view is described.

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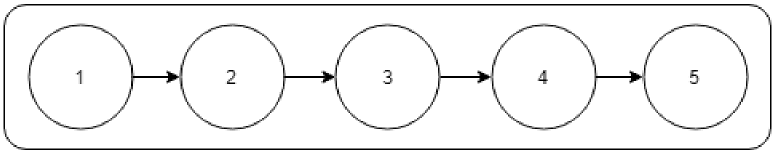

Figure 2.11. Schematic overview of the conveyor belt with the number corresponding to Figure 2.10.

1. The wheel coming from the Machine X.2 is placed on place 1, where it is waiting till station 2 is free.
2. At this station, the wheel is weighed. The weight of the wheel should be between the lower and upper limit.
3. At this station, the wheel is measured on thickness. The thickness of the wheel should be between the lower and upper limit.
4. At this station, the wheel is waiting until station 5 becomes free.
5. At this station, the wheel is picked up by a robot and placed on a plate, which we can see in Figure 2.10 on the right side. These plates are stacked before going into the baking process. Apart from that, when a wheel does not meet one of the requirements it is thrown away by the same robot arm.

2.1.4. Route of a product

We describe the route a product goes on. At some points in time (T), at both tables two jobs are executed regarding the specific product.

T=1: The empty mold waits at station 1 on the Machine X.2.
T=2: The ring is inserted in the empty mold at station 2 on the Machine X.2.
T=3: The label is inserted on the ring at station 3 on the Machine X.2 and the empty mold arrives or is SubStation1.1ed at station 1 on the Machine X.1.
T=4: The SubStation3.2 is inserted on the label at station 4 on the Machine X.2 and the SubStation2.1 is divided on the mold at station 2 on the Machine X.1.
T=5: At station 5 on the Machine X.2, the components are waiting and at station 3 on the Machine X.1 the mold is cleaned if necessary.
T=6: At station 6 on the Machine X.2, the components are waiting and at station 4 on the Machine X.1 the SubStation4.1 is inserted on the SubStation2.1.
T=7: At station 7 on the Machine X.2, the components are waiting and at station 5 on the Machine X.1 the SubStation2.1 and SubStation4.1 are pressed together into a pancake.
T=8: At station 6 on the Machine X.1, the pancake is picked up and placed on the mold with the other components at station 8 on the Machine X.2.
T=9: At station 9 on the Machine X.2, the pancake and components are waiting.
T=10: At station 10 on the Machine X.2, all components are pressed into one wheel.
T=11: At station 11 on the Machine X.2, the wheel is waiting.
T=12: At station 12 on the Machine X.2, the wheel is picked up and placed on station 1 at the conveyor belt.
T=13: At station 1 on the belt, the wheel is waiting.
T=14: At station 2 on the belt, the wheel is measured on weight.
T=15: At station 3 on the belt, the wheel is measured on thickness.
T=16: At station 4 on the belt, the wheel is waiting.

T=17: At station 5 on the belt, the wheel is picked up and placed on a plate before going to the baking process.

So, a final wheel is produced within 17 steps. From t=3 until t=8, certain steps are processed parallel to each other which fastens the whole time from start until end. The route of a product is depicted in Figure 2.12.

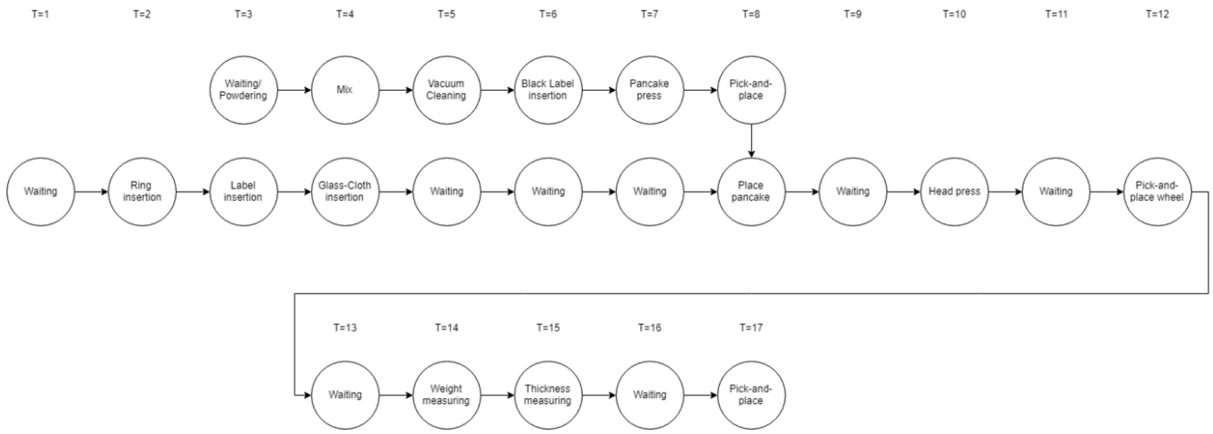

Figure 2.12. Route of a product.

2.2. Cycle times at the pancake process

In this section, the cycle time definition within Company X is explained. Next, the current cycle times are shown and analyzed. Furthermore, some other KPIs are discussed and analyzed. So, the second, third and fourth sub question are treated in this section.

2.2.1. Cycle time definition

Now that the process has been described, a definition of the cycle times within Company X can be given. Therefore, the following sub question is answered in this section:

- How is cycle time defined within Company X?

First of all, within Company X there are two different types of cycle time. The first one is the average product cycle time, also known as CycleTime(1), which is computed after a certain period of time. The second type is the machine or station cycle time, from now on stated as CycleTime(2). Obviously, the average machine cycle time over the same period of time is equal to the average product cycle time. Below, we discuss both types.

Average product cycle time – CycleTime(1)

As mentioned, the average product cycle time is computed over a certain period of time. It gives us the average time of producing unit from start until end. Simply said, this can be calculated with the equation that was stated in 1.3 (equation 1.a):

$$Cycle\ time\ (1) = \frac{\text{Poduction hours realized} * 3600}{\text{Number of good products made}} \qquad (e2.a)$$

Where

$$Production\ hours\ realized = Production\ hours\ planned - Total\ downtime(hours) \quad (e2.b)$$

Machine cycle time – CycleTime(2)

As we can see in Section 2.1. the total number of stations at the pressing process is 23. We have six stations at the Machine X.1, twelve station at the Machine X.2 and five at the conveyor belt. For this situation, we assume that a station is equal to a mold at the tables and the five spots on the conveyor belt are equal to five stations. This implies a utilization of 100% for all stations with the exception of the start and end of the process when not all stations are utilized. Since every job at each station is processed parallel to each other job, we can assume that there is one machine with 23 stations processing simultaneously. Therefore, we could say that the machine cycle time is the same as the longest station cycle time. Further, it means that after each point in time where all 23 jobs are executed, one product is created. Since the times of the conveyor belt are negligible, we only look at cycle times of the two tables. This implies that we only have 18 stations to look at. So, the product cycle time is assumed to be the same as the longest station cycle time.

According to Hopp & Spearman (2008), the definition of station cycle time is: *"The average cycle time at a station is made up of the following components:*

1. *Move time*
2. *Queue time*
3. *Setup time*
4. *Process time*
5. *Wait-to-batch time*
6. *Wait-in-batch time*
7. *Wait-to-match time*

In our case, we do not have any setup times at the stations. Moreover, batching times are not applicable since we only have single products. This means that only three components define the station cycle time. Move time is simply defined as the time a job spent being moved from the previous workstation. In our case, the move times for the six stations at the Machine X.1 are the same. The same counts for the move times of the Machine X.2. Queue time is defined as: "the time jobs spend waiting for processing at the station or to be moved to the next station. In our case, this means the second part of the definition. Lastly, the process time is simply the time a job is actually being worked on at the station. So, the machine cycle time, CycleTime(2), and thus product cycle time within our situation can be defined as:

"The maximum of the processing time at a station plus the corresponding move time of that station."

In others words, the machine cycle time is defined by the station that is the bottleneck in the process. For all other stations, the queue time is the difference between the machine cycle time and their own processing time.

Conclusion

So, if we assume no variation in the machine cycle time, it will eventually end up in the same average product cycle time as described earlier. However, there is always variation within the processing times of each station. Therefore, the first type of cycle time gives us only an average over a certain period of time. On the other hand, the second type of cycle time gives us a more detailed specification at a certain point in time. So, when we want to reduce this cycle time, we have to look at the machine cycle time. In our case, the cycle time is only built up by the process, move and queue time. Since, queue time is only the difference between the maximal process time and the process time of that station we do not investigate this part. Further in this research, we focus on the bottleneck stations that define the machine cycle time. Next, these bottleneck stations are investigated more deeply on how to reduce this machine cycle time.

2.2.2. Cycle times of type 1

In this section, the average cycle time of Machine X overall, CycleTime(1), is determined and analyzed. Therefore, the third sub question is answered:

- What are the cycle times of Machine X?

For analyzing the average cycle time, an analysis is executed on the cycle times in the period of slightly more than one year (September-2017 till October-2018) obtained by using a database within Company X. In Figure 2.13, the cycle times are shown in a graph over this period and in Table 2-1, the average, standard deviation, minimum and maximum is shown. The first thing to notice from the graph is that is fluctuating a lot over the period of time. For example, when comparing the minimal and maximal cycle time in terms of products, it equals a difference of approximately 620,000 Product A a year. Moreover, the cycle time has never reached the target time of 4.00 seconds. When comparing this target to the average cycle time again in terms of products, this equals approximately 452,000 pieces a year. Besides the fluctuating behavior of the cycle time, indicating a trend of the cycle time is rather difficult. However, when looking from week 12 till 36, which is also the most recent period, a clear upwards trend can be identified which underlines the importance of reducing the cycle times even more. This upwards trend is probably caused by the low attention paid to cycle times of the operator. So, the total number of Product A produced per year using the total production time realized in the same period is almost 4.9 million.

Table 2-1. Statistics of cycle time Machine X (Company X, 2018).

Description	Value (sec)
Average	4.244
Max	4.413
Min	4.060
Target	4.000

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2.2.3. Other KPIs

Besides the cycle times of the pressing process, some other aspects are important for Company X. In this section, these Key Performance Indicators are explained and analyzed. The fourth sub research question is answered:

- What other KPIs are important for Company X?

The most important KPI for Company X regarding the production process is the Overall Equipment Effectiveness (OEE). The OEE is a quantitative metric which is derived from the Total Productive Maintenance concept (Muchiri & Pintelon, 2008). It identifies and measures losses of important aspects of manufacturing regarding to availability, performance and quality rate (Muchiri & Pintelon, 2008).

Regarding the theory, the OEE is computed as:

$$OEE = Availability * Performance * Quality \qquad (e2.c)$$

Where Availability is the production time realized divided by the planned production time. Performance is the cycle time target multiplied by the number of products made which is divided by the realized production time. Last, Quality is simply the number of ‘good' products divided by the number of products in total. When substituting this into the formula above, you get the following formula:

$$OEE(1) = \frac{\#GoodProductsMade * CycleTimeTarget}{ProductionTimePlanned} \qquad (e2.d)$$

Within Company X, the OEE is measured differently, since most of the time the quality of the Product A is checked a few days later at the packing line. So, the computation for the OEE over a certain period of time is done as follows:

$$OEE(2) = \frac{\#ProductsMade * CycleTimeTarget}{ProductionTimePlanned} \qquad e2.e)$$

Where the difference with the "right" OEE calculation is that the products made in the case of Company X also includes bad quality Product A, whereas in the theoretical case only the products made that meet the quality requirements are taken into account. The OEE over the same period as the cycle time is shown in Figure 2.14. According to the target of 70% set by X, the OEE scores quite well over last year. On average it is about 78% with only one negative outlier.

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Obviously, an OEE of 100% or even more is desired, but in practice not realistic. As can be seen in Figure 2.14, the OEE does not reach the 100% or even 90%. So, there are losses on OEE that can be identified. These losses are divided in two categories within Company X. The first category is OEE loss due to downtime, where downtime means all short stops, changeovers and breakdowns or simply said when the machine is not in use. This OEE loss due to downtime is based on the number of products that Company X could have made in the production time planned if the cycle time is equal to the target cycle time minus the number of products that you could have made in the realized production time with again the cycle time target. When putting this in a formula, it is as follows:

$$OEE(2) loss\ due\ to\ downtime = \frac{PlannedProduction\ (seconds)}{CycleTimeTarget} - \frac{RealizedProduction\ (seconds)}{CycleTimeTarget} \quad (e2.f)$$

The OEE losses due to downtime are graphically displayed in Figure 2.15. A correlation between the OEE overall and the losses due to downtime is clear, since the negative peak in week 49 from Figure 2.14 corresponds with the negative upwards peak in week 49 in Figure 2.15**.**

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The second category of OEE losses are the losses due to cycle time. These cycle time losses are expressed in terms of products that you lost due to cycle times that are too high. It is based on the products that you could have made within the hours that the machine is in production if the cycle time is equal to the target and the products that really are produced. So, it is also dependent on the target cycle time and calculated as follows:

$$OEE(2)\ loss\ due\ to\ cycle\ time = \frac{RealizedProductionHours * 3600}{CycleTimeTarget} - \#ProductsMade \quad (e2.g)$$

In Figure 2.16, the OEE losses due to cycle time are graphically shown. Obviously, there is a clear correlation between loss due cycle time and increase in cycle time. The week numbers of the peaks both up and downwards of Figure 2.16 correspond with the cycle time progress in Figure 2.13.

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2.3. Factor analysis of CycleTime(2)

In this section, the factors that have impact on the cycle times of the pressing process are investigated. Further, the factors that have the largest negative influence are identified to be defined as bottlenecks within the process. Also, a short stop analysis is executed since these short stops are not allowed to increase with the same degree as the cycle time decreases. The fifth, sixth and seventh research question are discussed within this section:

- Which factors could influence the cycle time, CycleTime(2), at Machine X?
- Which of these factors are the bottlenecks within this process?
- How are the short stops distributed within the stations at the press?

The cycle times can be influenced by a lot of factors. Each station at the pressing process can influence this cycle time. First, the components that construct the station cycle times are identified. Next an analysis on these station cycle times is performed. With these data the bottlenecks within the total CycleTime(2) can be identified. Lastly, we execute a small analysis on the short stops which have an influence on the final OEE.

2.3.1. Stations

As mentioned in section 2.2.1, CycleTime(2) is the “slowest” station cycle time of one of the tables and the rotation time of the corresponding table. So, all machine settings that can be adjusted in order to change the cycle time are factors that could influence this cycle time. Further, the rotation speed of both tables could be adjusted. Each station has their own settings and therefore their own changes. Below, per station an explanation is given plus the settings that can be adjusted. First, the stations at the Machine X.1s are described.

1. **SubStation1.1ing station.** As mentioned, at this station the mold is SubStation1.1ed for making the mold rougher. However, this action, which is also the only one at this station, is not done at every mold but only when needed. So, this station can be considered as fixed.
2. **SubStation2.1 station.** At this station, several steps are performed before the SubStation2.1 is divided amongst the mold. First, the SubStation2.1 is divided on the station. Then the reservoir is moved to the mold where the SubStation2.1 is divided equally on the mold by going downwards after the reservoir moves back for getting new SubStation2.1 by going upwards. So, both the up- and downwards and for- and backwards movements are adaptable.
3. **SubStation3.1 station.** At this station, the SubStation3.1 option is only used when necessary and therefore not a constant process. So, this station is also to be considered as fixed.
4. **SubStation4.1 station.** At this station, the labels are picked up from a pile and put on the conveyor belt where the labels are transferred to the end of the belt where a robot arm places them on the mold. Since it is done sequentially, only the slowest step has an impact on the eventual final cycle time.
5. **Press station.** At this station, the pancake wheel is created by pressing the SubStation2.1 and label together. The pressing process consists of 5 parts. First, the plunger goes downwards after the pressure is built up before the real pressing takes place. Then decompressing step takes place and finally the plunger goes upwards. All these steps have processing time and also all these steps are adjustable.

6. **Pick-and-place station.** This station consists of two parts. The first process is to push the mold upwards to be ready for the second process which is the transfer from the pancake to the Machine X.2. Both processes have a certain processing time which are adjustable.

Secondly, the stations at the Machine X.2 are explained. Also, the settings corresponding to this Machine X.2 are described. Since the waiting stations do not have any processing time, they are left out of the analysis at all.

1. **SubStation1.2.** At this station, the ring is inserted in the middle of the mold. For this station, the same holds as for the SubStation4.1 station. The rings are on a conveyor belt in sequential line. So, it is only delayed when a ring is not placed or place wrong on the belt.
2. **SubStation2.2.** At this station, again the same procedure as for the SubStation4.1 station holds.
3. **SubStation3.2 station.** Also, at this station the same procedure as for the SubStation4.1 station holds.
4. **Press station.** At this station, the same steps as mentioned for the pancake plunger are executed. So, also five parts that determine the station cycle time.
5. **Pick-and-place station.** At this station, the final "green" wheel is picked up and placed on the measuring line. The same steps as for the pick-and-place station are executed. So, also the same adaptable settings.

2.3.2. Station cycle times and bottlenecks

In this section, the cycle times per station are given. Later on in chapter 4, we discuss this more thoroughly. Furthermore, the rotation time of both tables is mentioned in the tables of the total time. The data is based on a period of one week. Since the data is constantly kept updated, we can assume that gives us enough significant data. The fixed stations as the SubStation1.1 station, SubStation3.1 station and waiting stations are left out of this analysis, because they assumed to be of no influence on the cycle time. The cycle times per station are given in Table 2-2 and Table 2-3.

Table 2-2. Machine X.2 station cycle times (Company X, 2018).

Station	Average (sec)	Standard Deviation (sec)
SubStation1.2	2.7071	0.0207
SubStation2.2	2.0461	0.0244
SubStation3.2 station	2.2126	0.0187
Press station	3.3042	0.0148
Pick-and-place station	2.4265	0.0207
Rotation time	1.0135	0.0071

Table 2-3. Machine X.1 station cycle times (Company X, 2018).

Station	Average (sec)	Standard deviation (sec)
SubStation2.1 station	2.9655	0.0340
SubStation4.1 station	2.5705	0.0249
Press station	2.1193	0.0260
Pick-and-place station	2.0892	0.0229
Rotation time	1.0666	0.0065

Above, the cycle times per adjustable station of both tables are given. The slowest station of the Machine X.2 is obviously the press station and at the Machine X.1 it turns out to be the SubStation2.1 station. These values are based on historical data. Now that all stations are analyzed, the bottleneck or bottlenecks of the process regarding the cycle times are identified. From the previous section, the press station of the Machine X.2 turns out to be the station with the highest cycle time when adding up the rotation time. Therefore, the press station of the Machine X.2 is defined to be the main bottleneck of the SubStation5.1ing process. However, the other stations that are adjustable are also defined as sub bottlenecks. The most important sub bottlenecks are the pick-and-place stations of both tables, the press station of the Machine X.1 and the SubStation2.1 station.

2.3.3. Short stop analysis

Since the Overall Equipment Effectiveness is also an important KPI, the short stops regarding the station of the pressing process cannot increase such that the OEE stays on the same level or even drops below the current level. Therefore, a short analysis is done on the current short stops of the stations where it is investigated on how often they occur and what the average stop time is. With this information, the availability per station is determined.

The analysis is based on data of the same period of time as for the cycle times, so from September 2017 till August 2018. First, the total stop time and total frequency is listed in order to compute the average stop time based on this period. In Table 2-4 these data is given per station that experienced a failure during this period.

Table 2-4. Short stop analysis total (Company X, 2018).

Factor	Total stop time	Frequency	Average stop time
Table PCP	11:00:01	705	0:00:56
Table HP	41:24:44	2640	0:00:56
SubStation1.2	56:31:36	4087	0:00:50
SubStation2.2	10:57:54	807	0:00:49
Glass cloth	72:26:02	5650	0:00:46
Black paper	61:52:36	4587	0:00:49
Plunger PCP	3:53:16	245	0:00:57
Plunger HP	16:07:40	1225	0:00:47
SubStation2.1 material	93:03:14	5675	0:00:59
SubStation2.1 station	2:39:20	129	0:01:14
Pick and place PCP-HP	36:31:11	2861	0:00:46
Pick and place HP-Line	3:14:09	4087	0:00:03

With the average stop time per station and the average frequency per hour per station, the final average stop time per hour can be determined in order to compute the total stop time in one hour on Machine X. When adding up the last column in Table 2-5**,** the total average stop time per hour equal 4 minutes and 41 seconds. When translating this to the availability, this means that the availability of Machine X per hour is equal to approximately 92% on average. Further, when translating this to loss due to downtime it comes down to about 70 Product A per hour and 1686 Product A per day.

Table 2-5. Short stop analysis average (Company X, 2018).

Factor	Average stop time	Number of stops/hour	Average stop time/hour
Table PCP	0:00:56	0.134	0:00:08
Table HP	0:00:56	0.510	0:00:29
SubStation1.2	0:00:50	0.793	0:00:39
SubStation2.2	0:00:49	0.155	0:00:08
Glass cloth	0:00:46	1.069	0:00:49
Black paper	0:00:49	0.902	0:00:44
Plunger PCP	0:00:57	0.045	0:00:03
Plunger HP	0:00:47	0.236	0:00:11
SubStation2.1 material	0:00:59	1.067	0:01:03
SubStation2.1 station	0:01:14	0.024	0:00:02
Pick and place PCP-HP	0:00:46	0.546	0:00:25
Pick and place HP-Line	0:00:03	0.240	0:00:01

2.4. Conclusion

In order to conclude this chapter, the first seven sub questions are answered in this section. First, the design of the SubStation5.1ing process is described. The SubStation5.1 process can be described as two sequential processes, the pancake and Machine X.2 that are processing parallel to each other. At the last step of the Machine X.1, the pancake is transferred to the Machine X.2 where it moves further till the last station where it is transferred to the measuring line where the wheel is tested on weight and thickness before it is packed between plates. For an extra visualization, we refer to the attached video.

Secondly, the cycle time definition within Company X is slightly different compared to the theory. The theory states that cycle time is the time between the beginning and the end of a process, where within Company X the cycle time, as we know as CycleTime(2), is defined as follows:

"The maximum of the processing time at a station plus the corresponding move time of that station."

Further, the computation of the average cycle time, known as CycleTime(1), is commonly done after a certain period of time and therefore done as follows:

$$Cycle\ time(1)(seconds) = \frac{\text{Production hours realized} * 3600}{\text{Number of products made}} \qquad (e2.h)$$

Thus, the difference between the definition and the computation is that the definition gives the cycle time at a certain point in time and the computation an average over a period of time. The cycle times within Company X are quite fluctuating over the last year. On average it is 4.26 seconds which means almost 4.9 million Product A a year. Moreover, over the last half year a clear upwards trend in the cycle times is observed due to the low attention of operators to these cycle times. Other important key performance indicators for Company X are the Overall Equipment Effectiveness, loss due to cycle time and loss due to short stops.

The factors that can influence CycleTime(2) are listed below in Table 2-6.

Table 2-6. Stations that could influence the machine cycle time.

Machine X.1	Machine X.2
SubStation2.1 station	SubStation1.2
SubStation4.1 station	SubStation2.2
Press station	SubStation3.2 station
Pick-and-place station	Press station
Rotation time	Pick-and-place station
	Rotation time

After performing an analysis about the cycle times of each station, the bottlenecks of the process are identified. For the Machine X.1, the clear bottleneck is the SubStation2.1 station which has a duration of 2.97 seconds with the SubStation4.1 station on the second place with 2.57 seconds. For the Machine X.2, the bottleneck is even more clear with the press station having a duration of 3.30 seconds with the SubStation1.2 coming second with 2.71 seconds. All to all, the SubStation10.2 is the number one bottleneck. However, the other stations are also indicated as improvable. Further the availability of the stations all together is loosely 92 percent with the SubStation2.1 station as most critical station regarding the number and time of short stops.

All in all, we encountered different bottlenecks which result in a serious loss of products. In the worst case of the past it costs Company X 82 Product A per hour. At first sight, this number seems not that urgent, but when translating it to five different presses per week it costs X 68,727 Product A per week. Considering that one press produces about 17,000 Product A a day, this is equal to approximately a loss of 4 presses a day. In chapter 3, we discuss some literature in order to improve this situation. Next, in the fourth chapter we investigate several improvements possibilities in order to solve these bottleneck problems and therefore increase the productivity. Below in Figure 2.17, we can see this schematically.

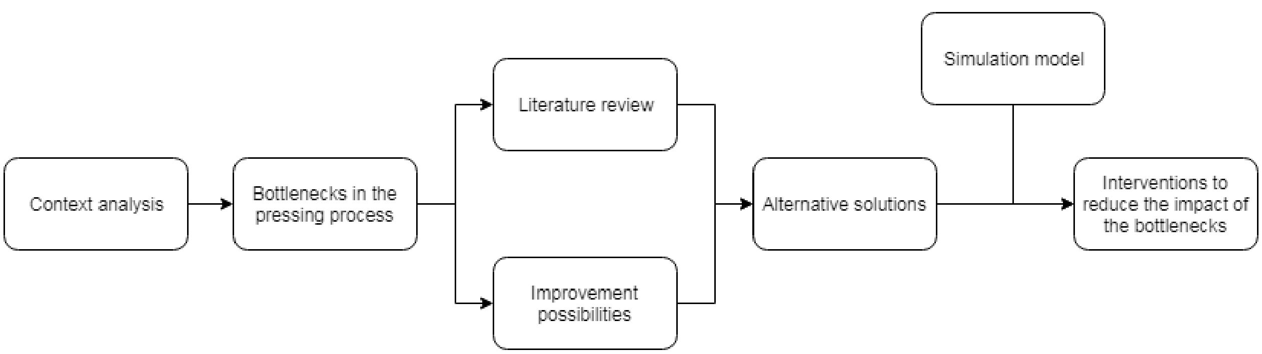

Figure 2.17. Design of solving the problem from context analysis till solutions for the existing problem.

3. Literature review

In this chapter the literature review is executed. In section 3.1, literature is reviewed about the reduction of cycle time and especially on methods how to reduce these cycle times. Further, in section 3.2 the simulation part is discussed. First, the definition of simulation is investigated. After that, several types of simulation models are discussed in order to find the best suitable model in the situation of Company X. Thirdly, a similar research is discussed to show that simulation can be useful within bottleneck problems and we shortly discuss the Design of Experiments as another useful tool.

3.1. Cycle time reduction strategies

In this section, we will discuss three strategies for reducing cycle times, Lean Manufacturing, Six Sigma and Theory of Constraints.

3.1.1. Lean Manufacturing

The term lean manufacturing was first introduced in 1990 in the book, *The machine that changed the world* (Womack, Jones, Roos 1990). This was followed by a second book in 1996, Lean Thinking (Womack and Jones 1996) that outlined the lean "philosophy". The focus of lean was on flow, the value stream and eliminating *muda*, which is Japanese for waste. According to Theisens (2016), Lean Manufacturing can be defined as:

"Lean manufacturing aims to eliminate waste in every area of production including customer relations, product design, supplier networks and factory management. Products with excellent quality must be developed and delivered when the customer wants ("Just in Time"). Lean manufacturing aims to eliminate waste in every area of production including customer relations, product design, supplier networks and factory management. Products with excellent quality must be developed and delivered when the customer wants ("Just in Time"). (Theisens, 2016)*"*

Further, Nave (2002) states that there are five essential steps in lean:

1. Identify which features create value.
2. Identify the sequence of activities called the value stream.
3. Make the activities flow.
4. Let the customer pull product or service through the process.
5. Perfect the process.

3.1.2. Six Sigma

The development of Six Sigma arose during the years 1985 till 1987 at Motorola. Six Sigma was conceived as a method for creating radically better products and processes that would enable Motorola to compete more effectively with the Japanese. In fact, the goal of Six Sigma was to reduce defects into the part per million range. According to the Theisens (2016), Six Sigma can be defined as:

"Six Sigma is a rigorous and systematic methodology that utilizes information (management by facts) and statistical analysis to measure and improve a company's operational performance by preventing 'defects' i.e. meet and exceed stakeholders expectations. (Theisens, 2016)*"*

Six Sigma, which started as a means for identifying and reducing variability in processes, now offers its own systems analysis approach (Hopp & Spearman, 2008). This method is called DMAIC which stands for:

- **Define** the problem.

- **Measure** performance and quantify the problem.
- **Analyze** using mostly statistical techniques.
- **Improve** the situation.
- **Control**, as in "keep the process in control".

The DMAIC approach is extremely useful in addressing problems that Six Sigma was originally designed to handle (Hopp & Spearman, 2008). It shows its quality control roots in the analyze and control steps (Hopp & Spearman, 2008).

3.1.3. Theory Of Constraints

The third strategy we explain, is the Theory Of Constraints (TOC). The following is cited from Nave (2002):

"TOC focuses on system improvement. A system is defined as a series of interdependent processes. An analogy for a system is the chain: a group of interdependent links working together toward the overall goal. The constraint is a weak link. The performance of the entire chain is limited by the strength of the weakest link. In manufacturing processes, TOC concentrates on the process that slows the speed of product through the system. It consists of five steps:

1. *Identify the constraint.*
2. *Exploit the constraint.*
3. *Subordinate other processes to the constraint.*
4. *Elevate the constraint.*
5. *Repeat the cycle.*

By focusing on constraints, this methodology produces positive effects on the flow time of the product or service through the system. Reduction of waste in the constraint increases throughput and improves throughput time."

3.2. Simulation models

As already mentioned in section 1.3.4. a simulation model is used for improving the cycle time. A simulation model is chosen because of three reasons which are listed below:

- **Company.** In consultation with the company it is decided to use simulation as a tool for solving the problem and improving the process. By means of a simulation model, we can provide the company a clear overview of the parts of the process.
- **Stochastic times.** The processing times of the stations have a stochastic character. A simulation model can take into account this uncertainty. Simulation can use statistical distributions or discrete historical data as input for the processing times to deal with this uncertainty.
- **Scenario testing.** Finally, we want to test several scenarios which are afterwards validated in a real time experiment. A simulation model is suitable for testing different input settings and perform a sensitivity analysis.

So, first a definition and applications of simulation are formulated. Also, the benefits and drawbacks of a simulation study are discussed. Thirdly, we investigate several types of simulation models in order to find the best suitable model for this research. Finally, optimization within simulation is described since we want to achieve the best possible settings such as the cycle time can be improved.

3.2.1. Definition and applications of simulation

Within the theory, several definitions of simulation are described. We have listed two definitions below:

"In a simulation we use a computer to evaluate a model numerically, and data are gathered in order to estimate the desired true characteristics of the model. (Law, 2015)*"*

"Experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better understanding and/or improving that system. (Robinson, 2001)*"*

Furthermore, simulation has a lot of different possibilities in terms of application. Below we can find a list of several examples as given in Law (2015):

- Designing and analyzing manufacturing systems.
- Evaluating military weapons systems or their logistics requirements.
- Determining hardware requirements or protocols for communications networks.
- Determining hardware and software requirements for a computer system.
- Designing and operating transportation systems such as airports, freeways, ports and subways.
- Evaluating designs for service organizations such as call centers, fast-food restaurants, hospitals and post offices.
- Reengineering of business processes.
- Analyzing supply chains.
- Determining order policies for an inventory system.
- Analyzing mining operations.

3.2.2. Benefits and drawbacks of simulation

Law (2015) describes five benefits regarding simulation in comparison to other models as solving approach.

- Most complex, real-world systems with stochastic elements cannot be accurately described by a mathematical model that can be evaluated analytically. Thus, a simulation is often the only type of investigation possible.
- Simulation allows one to estimate the performance of an existing system under some projected set of operating conditions.
- Alternative proposed system designs (or alternative operating policies for a single system) can be compared via simulation to see which best meets a specified requirement.
- In a simulation we can maintain much better control over experimental conditions than would generally be possible when experimenting with the system itself.
- Simulation allows us to study a system with a long time frame—e.g., an economic system—in compressed time, or alternatively to study the detailed workings of a system in expanded time.

Further, several drawbacks of simulation are described in Law (2015).

- Each run of a stochastic simulation model produces only estimates of a model's true characteristics for a particular set of input parameters. Thus, several independent runs of the model will probably be required for each set of input parameters to be studied. For this reason, simulation models are generally not as good at optimization as they are at comparing a fixed number of specified alternative system designs. On the other hand, an analytic model, if appropriate, can often easily produce the exact true characteristics of that model for a variety of sets of input parameters. Thus, if a “valid” analytic model is available or can easily be developed, it will generally be preferable to a simulation model.

- Simulation models are often expensive and time-consuming to develop.
- The large volume of numbers produced by a simulation study or the persuasive impact of a realistic animation often creates a tendency to place greater confidence in a study’s results than is justified. If a model is not a “valid” representation of a system under study, the simulation results, no matter how impressive they appear, will provide little useful information about the actual system.

3.2.3. Types of simulation models

Law (2015) describes five main types of simulation. In this section we describe each type of simulation.

Monte Carlo simulation

Monte Carlo simulation is widely used to solve certain problems in statistics that are not analytically tractable. Law (2015 states: “We define Monte Carlo simulation as a scheme employing random numbers, that is, U(0,1) random variates, which is used for solving certain stochastics or deterministic problems. Thus, a stochastic discrete event simulation is included in this definition.”

Discrete-event simulation (DES)

Discrete-event simulation concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time. (In more mathematical terms, we might say that the system can change at only a countable number of points in time.) These points in time are the ones at which an event occurs, where an event is defined as an instantaneous occurrence that may change the state of the system. Although discrete-event simulation could conceptually be done by hand calculations, the amount of data that must be stored and manipulated for most real-world systems dictates that discrete-event simulations be done on a digital computer.

Continuous simulation

Continuous simulation concerns the modeling over time of a system by representation in which the state variables change continuously with respect to time. Typically, continuous simulation models involve differential equations that give relationships for the rates of change of the state variables with time. A type of continuous is simulation is System Dynamics. This is a top-down approach that is used for designing and improving policies or strategies in business, government and the military.

Agent-based simulation

Agent-based simulation is a modeling and computational framework for simulating dynamic processes that involve autonomous agents. An autonomous agent acts on its own without external direction in response to situations the agent encounters during the simulation. A typical agent-based simulation has three elements:

1. Agents, their attributes and behaviors.
2. Agent relationships and methods of interaction. An underlying topology of connectedness defines how and with whom agents interact.
3. Agents’ environment. Agents interact with their environment in addition to other agents.

Spreadsheet simulation

Spreadsheet simulations are widely used for performing risk analyses in application areas such as finance, manufacturing, project management, and oil and gas discovery. DES and Monte-Carlo simulation can sometimes be done in spreadsheets such as Microsoft Excel if the problem is not that complex. This is only applicable if:

- Only simple data structures are available
- Complex algorithms are difficult to implement.
- Spreadsheet simulations may have longer execution times than simulations built in a discrete-event simulation package.
- Data storage is limited.

3.2.4. Optimization within simulation

According to Law (2015), the ultimate is to find a combination of the input factors that optimizes a key output performance measure. Well, in our case this complies with this statement. In general, the input factors of interest could include discrete quantitative variables, continuous quantitative variables or qualitative variables. Normally, we assume that an alternative solution is given and that the number of alternatives is relatively small. However, we eventually want to look at all possible combinations of input factors. Law (2015) states that is helpful to thinks of this problem in terms of classical mathematical optimization.

Further, Olafsson & Kim (2002) states the following:

"Simulation optimization is the process of finding the best values of some decision variables for a system where the performance is evaluated based on the output of a simulation model of this system."

Also, they say when the optimization involves selecting the best of a few alternatives, which consists of the following set of alternatives: $\Theta = \{\theta_1, \theta_2, \ldots, \theta_m,\}$, with m relatively small, it may be possible to evaluate every solution and compare the performance. However, this only counts when having a deterministic context. Since the output has a stochastically character, we need further analysis. Several approaches have been developed to address this problem, like subset selection, indifference-zone ranking and selection and multiple comparisons procedures. However, subset selection does not seek for an optimal solution, but only reduces the region to a subset of solutions.

The most common approach is to define an indifference zone δ for the performance and develop a procedure that selects a solution with performance that is within delta units of the optimal performance with a given probability, that is, if θ^* is the optimal solution and θ is the selection solution then

$$Prob[|f(\theta) - f(\theta^*) < \delta|] \geq 1 - \alpha$$

where $1 - \alpha$ is the desired probability (Ólafsson & Kim, 2002).

Another approach to selecting the best solution are Multiple Comparisons Procedures. They compute simultaneous confidence intervals for $f(\theta_i) - f(\theta^*), i = 1, \ldots, m$, where θ is as before the optimal solution (Ólafsson & Kim, 2002).

When it is not possible to evaluate every solution using a statistical selection procedure, one could consider a random search approach. This is typically an iterative process like this:

0. Select and initial solution θ(0) and simulate its performance X θ(0) . Set k = 0.
1. Select a candidate solution θ c from the neighborhood N (θ(k)) of the current solution and simulate its performance X (θ c).

2. If the candidate θ c satisfies the acceptance criterion based on the simulated performance, then let θ(k+1) = θ(k); otherwise let θ(k+1) = θ(k).
3. If stopping criterion is satisfied terminate the search; otherwise let k = k + 1 and go back to Step 1.

3.3. Similar research and Design of Experiments (DOE)

In this section we discuss a research performed about discrete event simulation and a bottleneck analysis to show that simulation can be useful for solving the problem and give the definition of Design of Experiments.

The title of the paper, written by Faget, Eriksson & Herrmann (2005) is as follows:

"Applying discrete event simulation and an automated bottleneck analysis as an aid to detect running production constraints."

They describe that discrete event simulation is an important decision support tool to evaluate changes in manufacturing, distribution or process facilities. Further, the objective of this research was to automate the bottleneck analysis facilitating the understanding and adoption of simulation by decision makers without knowledge of simulation. However, this is different from our objective, it shows how simulation can help when one wants to analyze bottlenecks. As a methodology for the simulation project, they used the following steps:

- System definition where they describe the scope and objective of the research
- Conceptual model to validate with the system definition
- Simulation model to verify with the conceptual model and validate with the system definition
- Finally, the application phase.

For the application phase, they used a Plan-Do-Check-Act cycle. In the Plan phase they identify the bottlenecks and make a rough problem analysis. In the Do phase, they execute an in-depth analysis and propose improvements. These are tested with the simulation model. In our case, we identified the bottlenecks in chapter 2 already. In chapter 4, we will perform an in-depth analysis on these bottlenecks and propose improvements. These proposed improvements will be tested by means of our simulation model. In their conclusion, Faget, Eriksson & Herrmann (2005) state the following:

"*As a result discrete event simulation can be successfully applied to support running production systems in their improvements efforts for lean manufacturing*. (Faget, Eriksson, & Herrmann, 2005)"

For discussing the principle of Design of Experiments (DOE), we first give two definitions, after we describe why we chose to not use Design of Experiments within this research. Theisens (2016) says the following about DOE:

"A systematic and highly efficient way to carry out experiments. Relationships between factors and responses are investigated. Interactions are also mapped. (Theisens, 2016)*"*

Furthermore, in an article about the necessity of DOE in manufacturing industries Tanco, Viles, Ilzarbe & Álvarez (2007) say the following about DOE:

"We understand the Design of Experiments as a methodology for systematically applying statistics to experimentation. It consists of a series of tests in which purposeful changes are made to the input variables (factors) of a product or process so that one may observe and identify the reasons for these changes in the

output response. DoE provides a quick and cost-effective method to understand and optimize products and processes. Although these techniques are commonly found in statistics and quality literature, they are hardly used in industry. (Tanco, Viles, Ilzarbe, & Álvarez, 2007)*"*

3.4. Conclusion

In this section, we give an answer to the eighth and ninth sub question. We will combine several parts of methods to create a framework for improving the cycle time. We will use the first step of Theory Of Constrains, identifying the bottlenecks. This is already performed in chapter 2. In that chapter, we concluded that the SubStation2.1 station and the SubStation10.2 station are the bottlenecks. Next, we want to analyze these two bottlenecks more deeply and thus we use the measure and analyze step of DMAIC. We will investigate how these bottlenecks are built up. In other words, which split times define the eventual process time and thus the machine cycle time. Next, we use the improve step of DMAIC to investigate which improvement options are available and implement them to improve the cycle time and the core principle of Lean Manufacturing, eliminating waste. During the rest of the report we do not explicitly mention these steps, but in chapter 8, the conclusion, we answer the main research question using the steps mentioned above.

These improvements are tested by means of a simulation model. Therefore, we need to define which type of simulation model suits this situation. The pressing process can be seen as a sequence of events that evolves over time by a representation in which the state variables change instantaneously at separate points in time. Further, the article of Faget, Eriksson & Herrmann (2005) also shows us that discrete event simulation can be very useful to accomplish improvements in production systems. So, we chose to use a discrete-event simulation for creating a simulation model. Furthermore, using DOE seems useful to apply even in our case. However, we chose to use simulation over DOE, because of the earlier mentioned stochastic character of the machine cycle times and due the fact that simulation provides us output information over a longer period of time in quite a short time. That does not mean that we say to completely neglect Design of Experiments, since for some parts of the industry it could be more useful than simulation, but we come back to this in our recommendations in chapter 8.

4. Alternative solutions and model

In this chapter, alternative solutions are proposed and tested. First, in section 4.1 the improvement possibilities are suggested. Next, these improvement suggestions are tested by the simulation model with the use of experiments. The software package that is used for the discrete event simulation is Siemens Plant Simulation version 13.0.

First, we give a small recap of the situation as described in section 2.4. The urgent bottlenecks that cause a serious loss in number of products are identified as the SubStation10.2 station and the SubStation2.1 station. In section 4.1. we come up with some ideas to reduce these bottlenecks in order in increase the productivity. Also as mentioned, the other stations still need to be taken into account. So, also improvement options for these stations are investigated.

4.1. Cycle time improvements

In this section, we discuss the improvement options regarding the machine cycle time, CycleTime(2). First, we describe qualitatively the bottleneck stations in detail. In a summary of that, we explain the improvement options per station. Next, we describe the process of the data preparation and which data to use as input for the simulation model which is discussed in the next section. Before we start with this section, a short recall is described in order to make the options proposed better understandable.

SubStation10.2 crawl height and plunger & SubStation2.1 station cavity up and down

In Figure 4.1 on the left side, we can see a schematic overview of the plunger of the SubStation10.2 moving down to press the components together at the mold. As indicated, unscaled, with the crawl height (Dutch: kruiphoogte) varying from 0 till 3 millimeters. At the right side of Figure 4.1, we can see a schematic overview of the SubStation2.1 station. In this we can see the mold which is going up, this equals the cavity going up, and the station with the SubStation2.1 on it which is spread when the station is going down. Later on in this section, also pictures of the real stations are shown in order to explain the improvement options.

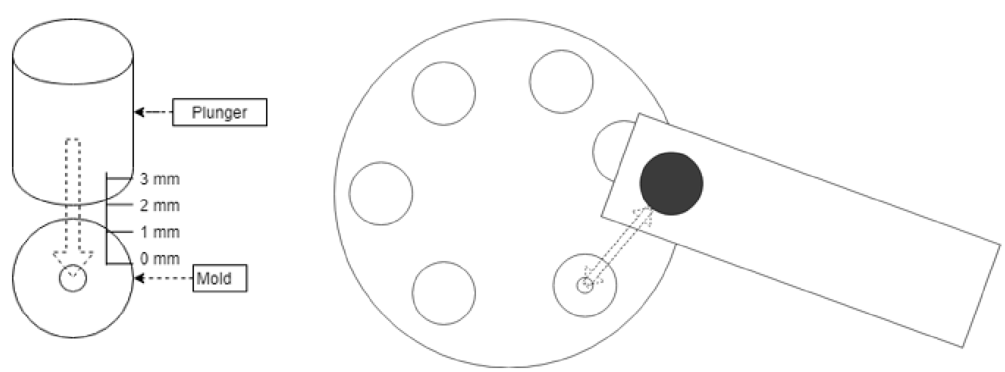

Figure 4.1. Schematic overview of principle of crawl height (left) and cavity going up and down (right).

4.1.1. Improvement options

In this section, we discuss the options for improving CycleTime(2). Per bottleneck station, we investigate and describe the options. The improvement options are obtained by means of interviews with several engineers and previous projects performed within Company X. Further, we describe some general improvements and limitations. Finally, we decide which improvement options we take into account for the model input and experimental design. Within this decision, it is also mentioned on how to reduce it.

SubStation10.2

The SubStation10.2 consists of several parts which determine the final cycle time of the SubStation10.2. So, we can put the calculation of the SubStation10.2 cycle time into the following formula:

$$CycleTime(HP) = MovetimeDown + PressBuiltUpTime + PressingTime + DecompressTime + MovetimeUp$$

Where:

- The time that the press plunger is moving down is determined by the crawl height which can vary between zero and three millimeters. Where a crawl height of 3 millimeter means that the plunger is slowed down at 3 millimeters before pressing the component at the mold. We can see this principle in Figure 4.2 in reality and in the earlier mentioned Figure 4.1 schematically**.** Secondly, the time that the plunger is moving down can be set. Currently, it is set on 80% of its power.
- The time to build up the pressure is determined by the pressure needed for the next step. This is a simple setting that cannot be adjusted.
- The pressing time is determined by the pressure. So, this time depends only on the pressure that is used. The tolerances of this pressure are between 110 and 130 bar. Currently, they set the pressure on 120 as average of both tolerances.
- The decompressing time is set as fixed and can therefore be seen as non-adjustable factor.
- The time that press plunger is moving up is also fixed and can therefore not be adjusted.

Confdential

SubStation2.1 station

The SubStation2.1 station consists of several parts which determine the cycle time of this station. In a formula it can be stated as follows:

$$\begin{aligned} CycleTime(Mix) &= \max(MoveTimeDown, TimeCavityUp) \\ &+ \max(TimeMixReservoirForward, TimeMixReservoirBackward) \\ &+ \max(MoveTimeUp, TimeCavityDown) \end{aligned}$$

Where:

- The first maximization is determined by the time the platform for the SubStation2.1 has to go down onto the mold and time the cavity (Dutch: mal) has to go up. In Figure 4.3, we indicate in red the cavity up movement which is the mold being pressed upwards and in green the SubStation2.1 station down movement which is done to place the SubStation2.1 onto the mold. Again, in the earlier mentioned Figure 4.1 we can see this schematically. This time is mostly dependent on the distance between the platform and the mold.
- The second one is determined by the time the station with the SubStation2.1 on it moves forward to the mold and the time the station without the SubStation2.1 is going back. These two times are compared and the longest time determines this part of the formula for computing the cycle time of the SubStation2.1 station. In Figure 4.4, we can see in red the movement of the SubStation2.1 station moving forward and in green the backward movement.
- The third one is determined by the same as the first, with the only difference that it now concerns the station going up and the cavity down. This time is also dependent on the distance and can therefore be considered to be reducible.

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General

Furthermore, there are some general adjustments possible besides the two bottlenecks stations. These adjustments also could influence CycleTime(2) positively. The first thing to mention is that if all the stations are perfectly linked together, CycleTime(2) will decrease. Therefore, it could be useful to improve all stations, also if it does not influence the final CycleTime(2). Below we list the possible general improvements:

- **Synchronization of the press.** As already mentioned above, when all stations are perfectly synchronized to each other, it results in a lower CycleTime(2). Therefore, we consider this as improvement possibility and input for the simulation model.
- **Height of Machine X.1.** Currently, the height of both tables is not equal. This has a consequence that the pick-and-place robot between both tables needs to go up when leaving the Machine X.2. When both tables are at the same height, this movement step does not longer to be taken and result in a lower cycle time for the pick-and-place robot and a better synchronization.
- **Height of inlay stations.** Further, the height of inserting the components like the ring, label, SubStation3.2 and SubStation4.1 can be closer to the mold. This reduction in distance results in a lower station cycle time and also a better synchronization of the press.

Limitations

The most important limitation of the improvement possibilities is the rotation time of both tables. Since both tables are driven by a hydraulic system and show quite a constant rotation speed, it is difficult to adjust the rotation speed. Another reason for not increasing the rotation speed is that the SubStation2.1 in the mold at the Machine X.1 can be dislocated when the table rotates faster and have to stop at the next station. A second limitation is that the speed and thus time of distributing the SubStation2.1 over the station depends on the recipe of that specific wheel. Therefore, we do not take into account improvement options on the distribution speed.

Summary

All in all, we have several options for improving CycleTime(2). Below, we list those that we investigate by using the simulation model. In section 4.3, we determine the experimental factors resulting from these improvement options and select the ranges corresponding to these factors.

- **SubStation2.1 station distances.** The SubStation2.1 station time is dependent on the time moving up and down. From that, we can say that is dependent on the distance that the station has to move up or down. We zoomed in on the SubStation2.1 station in Figure 4.5 below indicated with number 1. By reducing this distance, we could achieve a shorter cycle time for the SubStation2.1 station. For achieving this reduced distance, we use so-called "plugs" which are placed under the mold, indicated with a green arrow in figure number 2 in Figure 4.5, such that it gets higher. We can see these "plugs" in Figure 4.5 indicated with number 3 schematically. By placing such plugs, we can reduce the distance the mold should go up in order to reduce the total machine cycle time. In picture number 4 in Figure 4.5 we can see the plugs and the SubStation2.1 station combined. For the mold, three plugs are needed to create enough stability. More plugs are not possible due

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- **SubStation10.2 crawl height.** The time that the SubStation10.2 plunger is moving up and down is dependent on the so-called crawl height of the plunger. Also for this option, it holds that reducing this height could result in a lower cycle time for the SubStation10.2.
- **SubStation10.2 time.** Further, the time of pressing could be reduced. However, this should be tested in reality before considering this option due to quality issues. With a shorter pressing time, the wheel could decrease such in quality that is not accepted.
- **Moving time down SubStation10.2.** The time that the press plunger is moving down can be reduced by changing the setting of the time. Currently, it is on 80%, but 90% could be an option taking into account the quality of the wheel.
- **Synchronization machine.** As mentioned, improving the synchronization can result in a reduced CycleTime(2). In order to achieve this, we have decided to focus on the following three options:
    - **Synchronization tables.** When both tables have the same height, the time for the pick-and-place robot can be reduced since the robot does not have to go up or down when moving between the tables. This also results in a better synchronization overall.
    - **Height other inlay stations.** Also for the other stations where parts are laid in, the height can be reduced in order to reduce time and improve synchronization. This can be obtained by using the same "plugs".
    - **Waiting time stations.** Currently, stations are waiting for other stations before start processing. In order to reduce these waiting times, unexpected delay can be prevented.

4.1.2. Data

The data obtained regarding the station cycle times and thus of influence on CycleTime(2) have to be prepared before using it. In this section, we describe the steps that we have taken in order to get a clear overview of all the data that is needed as input for the simulation model. Secondly, we discuss all the data that is left out of the model and what is used as input.

Data preparation

Since the dataset obtained over a period of a week in the period of 19 till 26 November 2018 is quite unorganized and large, we have to filter it before we can use it. Only data for this week is chosen, since it just was available since 18 November. The reason for picking only one week is because of the time constraint of this research. For preparing the data before analyzing it for using it as input data for the simulation model, we go on several steps. Each step is briefly discussed below.

1. **Replace names.** First, we have to replace all codenames by the real station names or part names of a station. In this way, it becomes easier to distinguish between stations.
2. **Remove failures.** Secondly, we decide to remove the moments that the machine was subject to failure, because we are only interested in the cycle time when the machine is running normally.
3. **Remove blanks and zeroes.** Next, we remove the blank cells or the cells with a value of zero, because these values do not have a significant contribution to the eventual analysis.
4. **Remove obscure data.** As fourth, we remove the data that show obscure characteristics. This is mostly data that is inexplicable or data that can be defined as outlier.
5. **Remove irrelevant data.** Next, we remove the remaining irrelevant columns of data that are of no use regarding the station cycle times.
6. **Remove fixed data.** The last removal step is to delete the data that can be considered as fixed. This is the data that is not subject to improvement as stated in the previous section.
7. **Store data.** Finally, we store the data separated per station such that the analysis can be done in an uncluttered way.

Data usage

Now that we have prepared the data for analyzing it, we can discuss which data we have left out of the final dataset and which data we are going to analyze as input data for the simulation model. The specified left-out and input data can be found in Table 4-1. Since, we leave out split times for station that are classified as fixed or non-investigatable, we use them as fixed input times.

Table 4-1. Input data that is used in the simulation model and data that is left out.

Input data	Left out data
Rotation time Machine X.2	Split times SubStation1.2
Rotation time Machine X.1	Split times SubStation2.2
SubStation2.1 station – Cavity up	Split times SubStation3.2 station
SubStation2.1 station – Cavity down	Split times SubStation4.1 station
SubStation2.1 station – Station up	Split times SubStation5.1 station
SubStation2.1 station – Station down	

SubStation2.1 station – Station forward	
SubStation2.1 station – Station backward	
SubStation10.2 – Downward	
SubStation10.2 – Pressure built up	
SubStation10.2 – Pressing	
SubStation10.2 – Decompressing	
SubStation10.2 – Upwards	
Pick-And-Place PCP-HP	

Besides the processing times of the stations or even parts of the stations, we also need some distances as input data, because as mentioned before there are some serious possibilities to obtain a profit in CycleTime(2). In Table 4-1, we can see the distances we use as input data.

Table 4-1. Distances per station that is used as input data.

Station	Distances used
SubStation2.1 station	Distance between inserting the SubStation2.1 and the mold
SubStation4.1 station	Height of inlay (distance between inlayer and mold)
SubStation3.2 station	Height of inlay (distance between inlayer and mold)
SubStation1.2	Height of inlay (distance between inlayer and mold)
SubStation2.2	Height of inlay (distance between inlayer and mold)
Pancake and Machine X.2	Height of Machine X.1 (distance between Machine X.1 and Machine X.2)

4.2. Simulation model

In this section, the simulation model is explained. First, we give a general description of the model and its parts. Moreover, we list the assumptions and explain the logic behind the model. Further, we discuss the input data and show the validation step. Secondly, we describe the experimental design of the model. We determine the warm-up period if necessary, the run length and the number of replications. Furthermore, the experimental factors and corresponding ranges are described. Next, we determine the output values of the experiments.

4.2.1. System description

General description

The simulation model built for analyzing the improvement possibilities is created by using the software package of Tecnomatrix Plant Simulation v13 developed by Siemens. Within this software, we have created a control panel to keep track of the simulation. It is shown in Figure 4.6. The figure under "Pressing Process (MACHINE X), in the left upper corner shows us the created model where the tables plus conveyor belt are modeled. Also from this control panel, we can adjust the settings of the simulation model for experimenting. It gives us an overview of the performance of the model by looking at the KPIs or periodic data. Next to these functionalities, it shows us some controlling parts to make sure that the model correctly simulates the real process. Some more important logic of the simulation model is elaborated later on in this section.

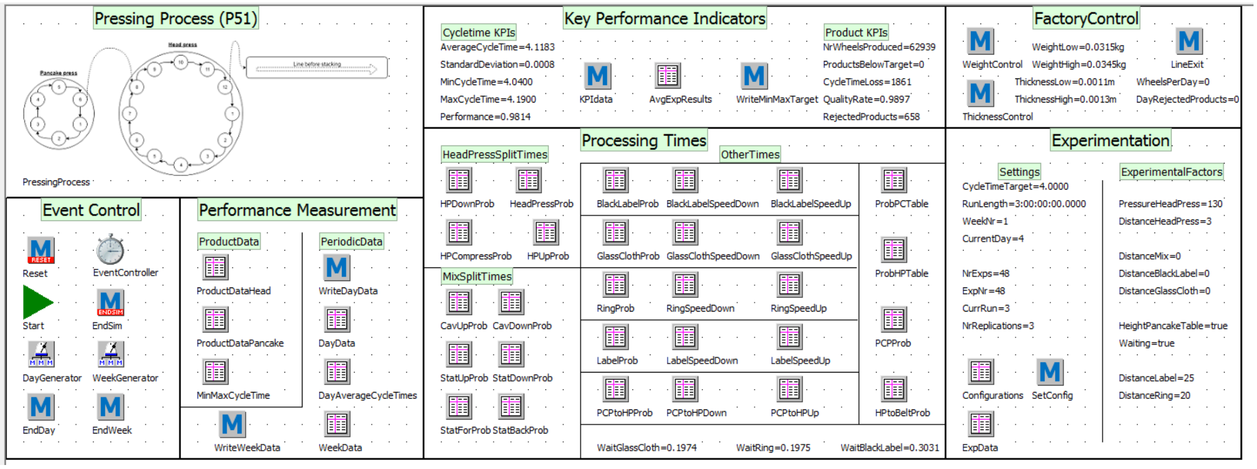

Figure 4.6. Overview Simulation Control Panel.

Assumptions

Since a simulation model cannot exactly represent the real-life situation, we have to make several assumptions. Below, these assumptions are listed with a short explanation.

- **Maintenance/short stops.** Since the focus of the simulation model is mainly on improving the cycle time and it is quite hard to implement all the machine stops such that we can approach the correct OEE, we decide to take the failures of the machines out of the simulation model. In chapter 6 where we planning to implement the improvement suggestions, we can make a comparison for the OEE.
- **No set-up times**. Since the main focus of this research is on the cycle time and therefore the realized production hours, set-up times are left out of the model.
- **No changeover times.** Since the main focus of this research is on the cycle time and therefore the realized production hours, changeover times are left out of the model.
- **Constant production.** We assume that the production plant is constantly running.
- **No shifts.** Within Company X there are 3 different shifts, but the conditions are exactly the same for all shifts. So, we can assume that there are no shifts.
- **One product type.** Since the product types only differ slightly and are of no influence on the cycle times, we assume that there is only one product type. This means that the SubStation2.1 station is assumed to be on its maximum power ability as described by Company X.
- **SubStation2.1 supply.** We assume that there is a constant supply of SubStation2.1.
- **Components supply.** We assume that there are always components like rings, SubStation3.2s, labels and SubStation4.1s present.
- **No SubStation1.1ing.** We assume that the SubStation1.1 station has no processing time, because it does not take place continuously.
- **No SubStation3.1.** For the SubStation3.1 station, the same holds as for the SubStation1.1 station.
- **Start of simulation.** We assume no specific starting day of the week since we assumed constant production. So, the model simply starts at time = 0.000.

- **Speed inlay stations.** The speed for all stations where something is laid in, thus: ring, label, SubStation3.2, SubStation2.1 and SubStation4.1 station is assumed to stay on the same level when implementing other settings. So, the time is linear dependent on the distance.

Logic of the model

In our simulation model, we have three important method or methods containing some logic. We discuss them subsequently in this part.

- **Arrive.** Within this method, each pancake and wheel gets their processing times per station based on historical data over the month November 2019. This input data per station is discussed later on in section 4.2.2. Further, each product gets its own product ID such that the data per wheel is available. This method is chosen instead of simply give the machines a certain distribution due to the fact that empirical data can be used more efficiently. Now, we can store data per product and machine.
- **ExitStation.** Within this method, we make sure that a product can only leave the station if:
    - This next station is empty such that the product can enter it.
    - The job on the previous station is finished such that a new product can enter the current station.

  This method is used for each station such that the system can only move if all jobs are done on each station. It is called if a job is finished. In Figure 4.7, we can see a flow chart of this process.

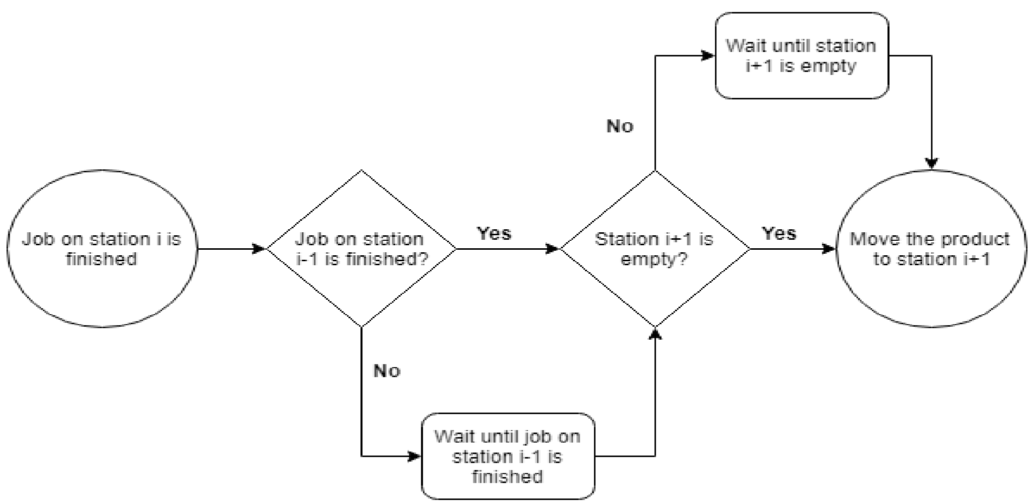

Figure 4.7. Flow chart of the ExitStation method used in the simulation model.

- **LineExit.** This method makes sure that the completed product can only be placed between plates if:
    - The weight of the wheel is within the tolerances allowed.
    - The thickness of the wheel is within the tolerances allowed.

  Otherwise, the wheel is thrown away. This method is called at the end of the conveyor belt. A flow chart of this process is given in Figure 4.8.

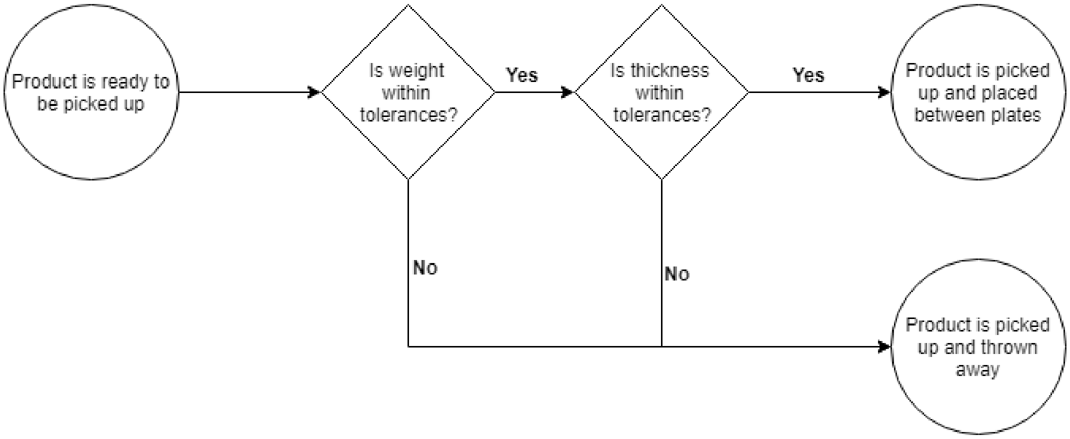

Figure 4.8. Flow chart of the LineExit method used in the simulation model.

4.2.2. Input data

Within this section, the input data of the processing times are discussed. We use the dataset as described in section 4.1.2. Per station, we give the probabilities of a certain split cycle time or station cycle time. We cannot fit a statistical distribution because the number of unique outcomes is too low. Therefore, we use historical data, again based over the period of November 2019, with computing the probabilities by simply divide the frequency of a certain time by the total number of observations. In Appendix A, the probabilities per station or split station can be found for more information. In Table 4-2, we give an example of these probabilities, in this case for the rotation time of the Machine X.2.

Table 4-2. Example of input data used with corresponding probabilities.

Time (sec)	Probability
1.00	0.0993
1.01	0.4914
1.02	0.3694
1.03	0.0400
Total	1.0000

Secondly, we need the distances of certain stations as input to determine the speed of some split times. This is needed because we want to reduce these distances in order to improve CycleTime(2). We can find the distances of the stations where we these in Table 4-3.

Table 4-3. Distances used per station as input data for the simulation model.

Station	Distance
SubStation2.1	25 mm
Ring	20 mm
Label	25 mm
Glass cloth	27 mm
SubStation4.1	29 mm
Pancake to Machine X.2	12 mm

4.2.3. Validation

In this section, we validate the model in order to check if it shows us results which are significant enough to accept them. We use a different order, thus dataset, as used to construct the input data distributions to prevent that the model remembers the dataset used as input. Further, we assume that the machine is constantly running. This means that we only look at the realized production time of one order and look at the number of Product A produced. After that, we compare the real output with the simulation output to check if the model gives us results that are significant. This comparison is executed by performing a paired t-test. For the input of this test, we use a run length of 1 day. Per hour we take the average cycle time based on the average cycle time of the products made in that specific hour.

Before we can perform the paired t-test, we need to check if the data is normally distributed. In order to this, we performed a goodness-of-fit test on the differences of the paired data. A common known test to do this is the chi-square test. Within this test, we want to find the chi-square statistic, χ^2. This can be achieved by adding up the sum of the squares of the deviations between the observed and expected counts divided by the expected counts. In a formula this looks as follows:

$$\chi^2 = \sum_{all\ values} \frac{(Obs - Exp)^2}{Exp}$$

Next, we need to define the degree of freedoms such that we can look up the critical value which should be larger than the found χ^2 in order to conclude that a normal distribution can be assumed. In our case, we have 24 data points and we used 4 intervals since there was data on the right hand side of the graph that could be merged. After performing several calculations, we found $\chi^2 = 8.333$ which is smaller than 11.345 that follows from using 4-1=3 degrees of freedom and a significance level of 0.01. Therefore, we assume a normal distribution for the paired t-test.

Within this paired t-test, we chose to use the paired t-interval in order to determine there is a significant difference or not. This paired t-interval can be described as follows:

1) First, we compute the mean of the differences.
2) Next, we compute the standard deviation of the differences.
3) Thirdly, we determine the t-value for this case with n-1=3 degrees of freedom and a significance level of 0.01.
4) Now we can determine the confidence interval in order to look if the difference between the data sets is significant or not.

After performing these steps, we obtain the following results:

Table 4-4. Statistics of the validation of the simulation model.

Description	Value(s)
Mean	-0.00654
Standard deviation	0.01166
T-value	2.80734
Confidence interval	[-0.013224; 0.0001378]

From this table we can conclude that there is no significant difference between the output of the simulation and the output from the real press, because we see that zero is between the lower and upper bound of the confidence interval.

4.3. Experimental design

In this section, we discuss the experimental design that is used to obtain the results. First, we investigate the warm-up period if necessary. Next, the run length plus the number of replication is determined. After that, the input factors which are adjusted during the experiments are described including their ranges. Finally, we describe the output of the model in terms of the KPIs.

4.3.1. Warm-up, run length and number of replications

Before starting the experimental phase of the simulation, we need to investigate if a warm-up period is necessary and if so, how long this period should be. Further, the run length of the simulation needs to be determined. Lastly, the number of replications needs to be defined in order to know how much replications we need per experiment.

First, the necessity of a warm-up period is investigated. When the system is running with all stations occupied, the character of the system is really steady state. So, only for the first 12 Product A there is a difference in cycle time. Since this number is very marginal in comparison with the total number of Product A that can be produced in one day, we can conclude that there is no warm-up period is necessary.

Next, we have to determine the run length to obtain results that give a good representation of reality. Since a relative long run length results in a time consuming experimentation, we decided to use a run length of 7 days which gives us a good indication regarding the results per day and thus week, month and year if needed.

Furthermore, we need to determine the number of replications. Performing more replications per experiment reduces the variability of the outcomes. However, it turns out that the differences are not significant when using one or more replications. Since we want to prevent that unexpected outliers occur, we chose to use 3 replications per experiment.

4.3.2. Experimental factors

Next, we need to define the experimental factors which we are planning to vary. These factors can be linked to the improvement options as mentioned in section 4.1. However, we do not take into account all improvement options within the simulation model. The height of inlay at the ring, SubStation3.2 and SubStation2.2 are left out of the experiments. This also holds for the height of the Machine X.1. With a simple calculation we observed that an improvement does not result in a better cycle time even after improving all other stations and leaving out these factors result in a much shorter simulation time. However, we advise to take the improvement possibilities of these stations into account in order to prevent a possible unexpected bottleneck in the production process. We categorize them into three groups: input factors, experimental factors and other factors.

Input factors:

Pressing time of the SubStation10.2. We have decided to experiment with the pressing time and how that is affecting the quality of products. However, this is just an adjustment that has to be tested in a real experiment, we decided to use the relevant outcomes of these experiments as extra input for the model and thus not an experimental factor.

Moving time down of the SubStation10.2. We also use this improvement option as input for the model instead of an experimental factor, since it is only a change in settings.

Experimental factors:

- **Distance of SubStation2.1 station to mold.** This concerns the distance that station and/or cavity has to go up and/or down when inserting the SubStation2.1 into the mold. We will investigate several lengths of the previous called "plugs" in order to reduce the distance. Due to these "plugs", the stability of the mold also reduces and therefore the probability of reduction due to quality could increase. We have to say that this quality affection is just an assumption and has to be checked in reality on what scale it will affect the quality of the final Product A. Further, we are not sure what distance reduction the plugs accomplish. Therefore, we also estimate this reduction instead of an exact distance reduction.
- **SubStation10.2 crawl height.** This is just a setting on the SubStation10.2 which should always be on zero. So, we can say on forehand that this will results in a better CycleTime(2). However, we take it into account, because we are going to test several scenarios.
- **Distance inlay SubStation4.1 station.** For this station, the same procedure holds as for the SubStation2.1 station with the only difference that this does not concerns cavity or stations going up or down but simply the distance of the inlayer to the mold. We have to take into account that the SubStation4.1 is still inserted correctly, so we have to keep a small margin of space between the inlayer and the mold.
- **Waiting times.** For this factor, we also have two options. Either there is waiting time or not. When there is waiting time, this will cause a delay in CycleTime(2).

Other factors:

- **Distance inlay SubStation1.2.** For this station, the same holds as for the SubStation2.1 station with the only difference that this does not concerns cavity or stations going up or down but simply the distance of the inlayer to the mold. We have to take into account that the ring is still inserted correctly, so we have to keep a small margin of space between the inlayer and the mold.
- **Distance inlay SubStation2.2.** For this station, the same procedure holds as for the SubStation1.2.
- **Distance inlay SubStation3.2 station.** For this station, the same procedure holds as for the ring and SubStation2.2.
- **Height of Machine X.1.** Within this factor, we can choose to make the height of the table equal to the other table or stay at the same level. With the same level, the pick-and-place robot does not have to go up and down anymore.

4.3.3. Experimental ranges

Now that the experimental factors are defined, we can set various ranges per factor. The factors, minimum value, maximum value and increment level are shown in Table 4-5.

Table 4-5. Experimental ranges used as input for the experiments executed with the simulation model.

Experimental/input factor	Minimum	Maximum	Increment
Pressing time (seconds)	1.1	1.3	0.1
Moving time	80%	90%	10%
Distance SubStation2.1	0	1	1

Crawl height (mm)	0	3	1
Distance SubStation4.1 (mm)	25	29	4
Waiting time	0	1	1

We have to notify that the binary values for the distances between the tables and waiting times, mean that there is no distance or it stays the same. Moreover, for the SubStation2.1 station it is also chosen to take a binary range, because inserting the plugs does not simply mean that the time is linearly reduced. This is caused by the fact that when inserting the plugs, the system reacts to that which could result in a delay. Therefore, we make an assumption for this experimental factor that the effect is estimated on a certain decrease in cycle time. Since we want to use a full-factorial experimental design, all possible combinations of experiments are conducted. Since some factors are considered as input, they are left out of the experimental design. This results in, (2^3)*(4^1) = 32 experiments in total.

4.3.4. Output values

Now that we have determined the run length, number of replications and the experimental factors and ranges, we can decide which output values we want to see in order to judge the experiments. These output values are linked to the KPIs as defined earlier. We list the output values selected below with a short explanation. Later on in chapter 5, we discuss the results and thus these output values.

- **Average CycleTime**. This is the average cycle time obtained in an experiment. This is computed by the formula as mentioned in section 1.3.2. and based on the "good" products only.
- **Standard deviation**. This is the standard deviation of the cycle time. This is calculated by looking at the cycle time of each week and compare it with the average cycle time as computed above. This gives us an indication if the system is whether stable or not.
- **QualityRate.** Since we are interested in how much Product A are defined as "good enough" to go the next step in the production phase, we want to know what the quality rate is. This is simply computed by dividing the number of good products by the total number of products. Again, we have to say that the quality rate is just an assumption based on some interviews and should be investigated after implementing the plugs onto the molds of the Machine X.1.
- **Products below target.** Since we opt to improve the cycle time, it could occur that the CycleTime(2) reach below the cycle time target of 4 seconds. This output value shows us the number of products that reach this output value.
- **MinCycleTime.** This concerns the lowest cycle time for a product observed. In other words, this means the lowest CycleTime(2).
- **MaxCycleTime.** This concerns the highest cycle time for a product observed. In other words, this means the highest CycleTime(2).
- **Bottleneck Analyzer.** We also use the bottleneck analyzer function of PlantSimulation. This gives us an insight in which stations were the bottleneck during each run. We express this in percentage per station.

4.4. Conclusion

In this chapter we answer the tenth sub question which is formulated as follows:

- *"What alternative solutions can be thought of in order to achieve an improved cycle time at the SubStation5.1?"*

We found several options in order to improve the cycle time, in this case CycleTime(2). From these improvement options we get several interventions that we test using a simulation model. We list these interventions below in Table 4-6 with the corresponding values that we analyze in the next chapter.

Table 4-6. Overview of the interventions proposed in this chapter in order to reduce the cycle time.

Intervention	Experimental range	Input or experimental factor
Pressing time reduction	[1.1; 1.3]	Input
Moving time down of the SubStation10.2	[80%; 90%]	Input
Crawl height of the SubStation10.2	[0;3]	Experimental
Distance SubStation2.1 station	[0;1]	Experimental
Waiting time	[0;1]	Experimental
Distance SubStation4.1	[25;29]	Experimental

As mentioned, these interventions are tested by using a simulation model. This model is validated by comparing it to a real-time order. With the use of a paired t-test we concluded that the model is not significant different from reality. Further, we use a full-factorial experimental design in order to find the best solution. We analyze the experiments based on the following output values:

- Average cycle time.
- Standard deviation of the cycle time.
- Percentage of “good” Product A.
- Number of Product A below the cycle time target.
- Minimal cycle time.
- Maximal cycle time.
- Bottleneck contribution.

In chapter 5, we discuss the results from the conducted experiments. Further, we perform a sensitivity analysis by changing some fixed input settings. Thirdly, the best experiments are also analyzed by looking at the consequences for the next steps in the production process.

5. Results

In this chapter we discuss the results that follow from the conducted experiments. First, we look at the best experiments regarding the selected output values. Further, we perform a sensitivity analysis regarding the target of the cycle time in order to check how a certain configuration performs concerning the number of products below that target. Finally, we look at the global impact at the next steps in the supply chain and the savings of this project.

Recap

Before analyzing the results from the simulation model, we give a small recap on what is investigated in chapter 4. We observed three main bottlenecks that could seriously affect the machine cycle time positively, namely:

- SubStation10.2 station on the Machine X.2
- SubStation2.1 station on the Machine X.1
- Waiting time of the inlay station

Now we want to know which combination of adjustments at these stations result is expected to be the best option for X. Therefore, we simulated all possible combinations of settings in order to find this best solution. In this chapter, we discuss the results of these simulation and their impact.

5.1. KPIs

In this section, we discuss the experiments performed by looking at the output values as mentioned in section 4.3.4. We divide it in two parts, the first part contains the six KPIs and the second part contains the bottleneck analysis.

5.1.1. Experiments

After performing the 32 experiments, we obtain the results for each experiments regarding the output values. First, we show the results per output value per experiment in a graph. After analyzing these graphs, we show the real values for the interesting experiments. After that, we determine the relevant best experiments in more detail.

Results experiments

So, first we can see below the experiments shown in a graph per output value. Since the number of experiments is too high to see all results in detail, we decided to zoom in on the best experiments per output value. After, we can see which experiments are interesting to investigate, the real values are displayed in a table. For all configurations per experiment number, we refer to Appendix B. For all results per experiments, we refer to Appendix C.

We look at the six output values and how the experiments score on them. We do not show all experiments since that gives us a chaotic overview of the results. For all detailed results, we refer to Appendix C. So, we decide to look the best experiments per output value. After looking at the output values separately, we search for overlapping experiment numbers. If so, we can conclude that these experiments are candidate to be the best experiment.

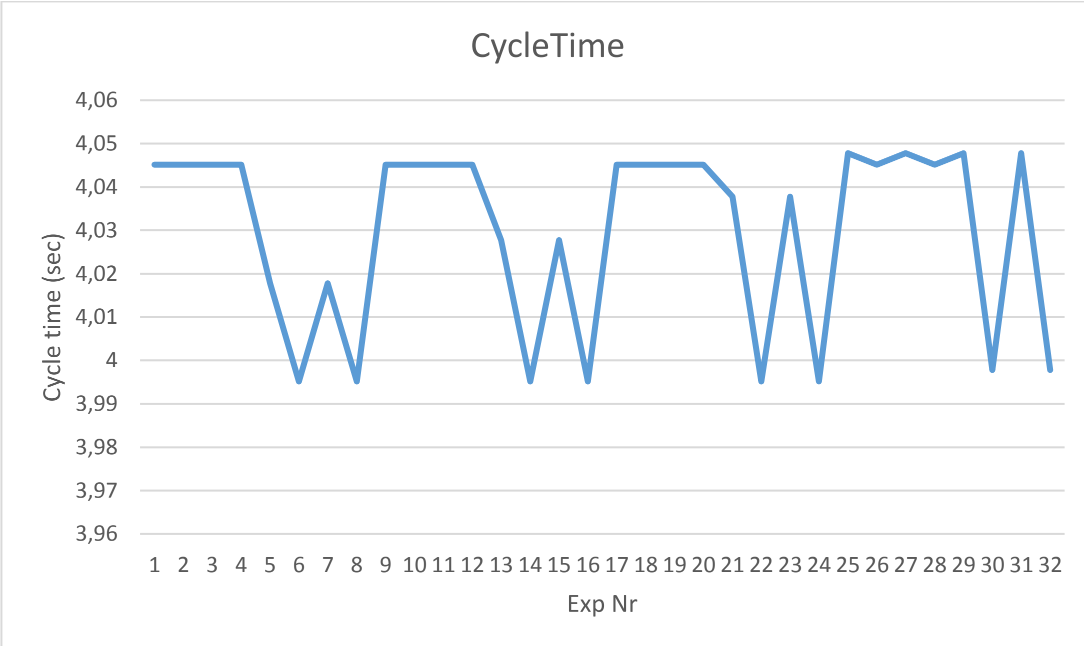

Figure 5.1. Average cycle time per experiment based on the computations of the simulation model with a simulation time of one week, where the flattened peaks occur due to the boundaries of the input.

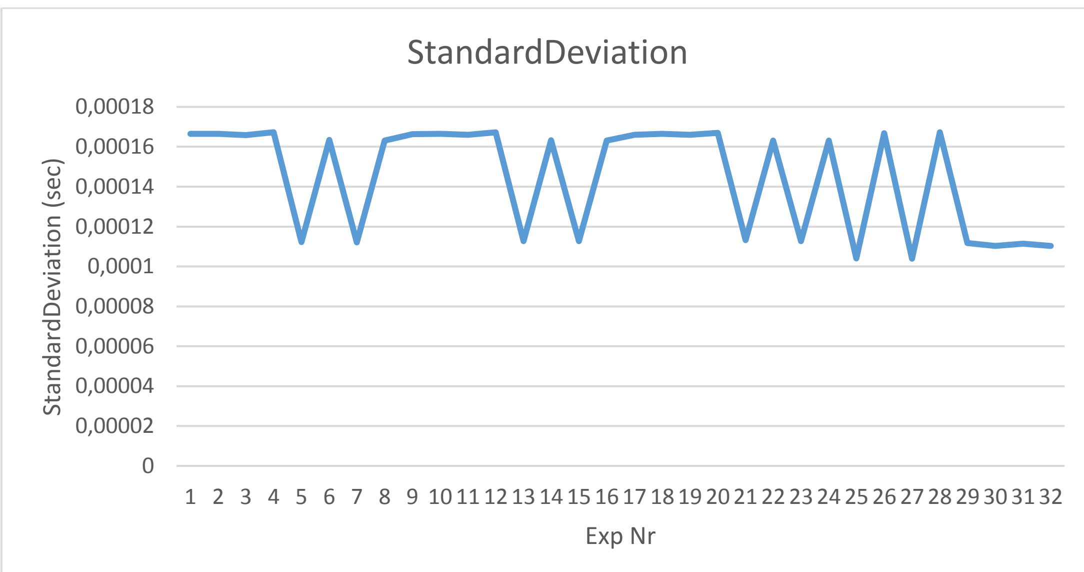

Figure 5.2. Standard deviation of the cycle time per experiment based on the computations of the simulation model with a simulation time of one week.

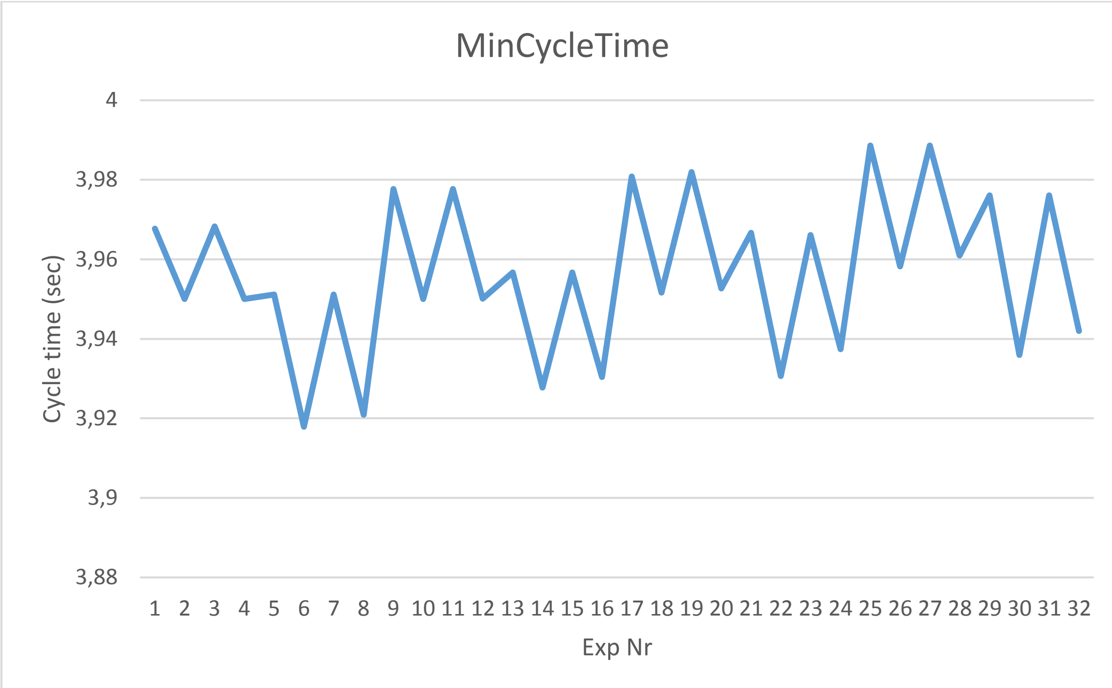

Figure 5.3. Minimal cycle time, lowest CycleTime(2), observed per experiment based on the output of the simulation model with a simulation time of one week.

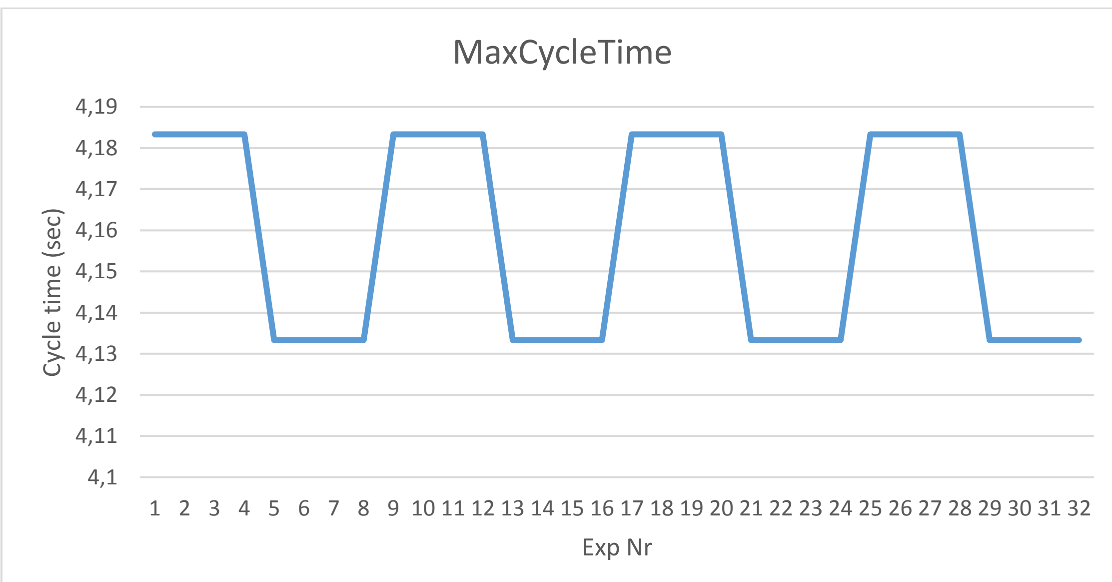

Figure 5.4. Maximal cycle time, highest CycleTime(2), observed per experiment based on the output of the simulation model with a simulation time of one week, where the flattened peaks occur due to the boundaries of the input.

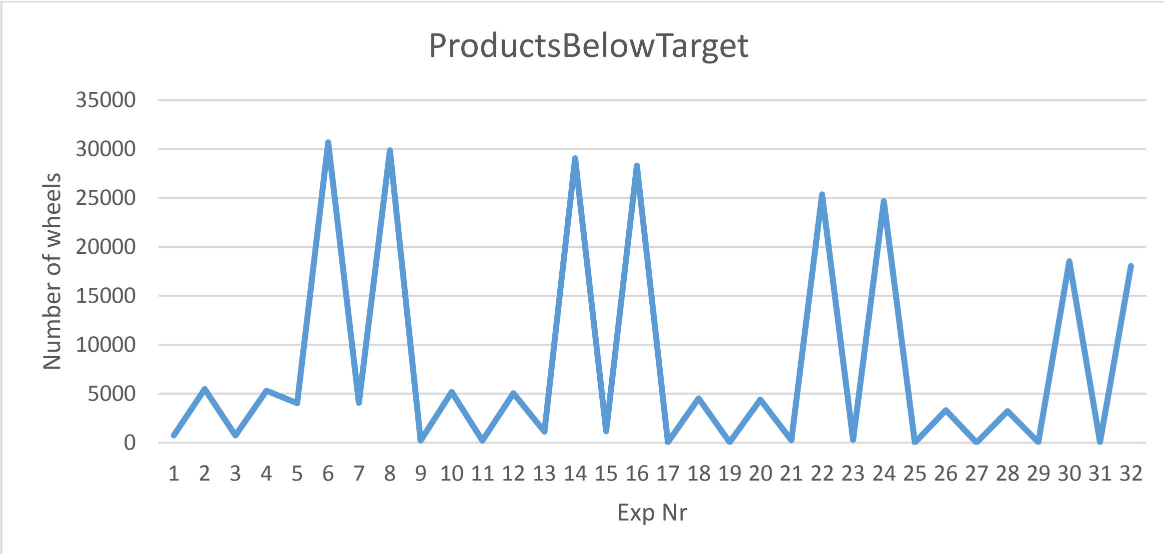

Figure 5.5. Number of products below the target of 4.000 seconds per experiment based on the output of the simulation model with a simulation time of one week.

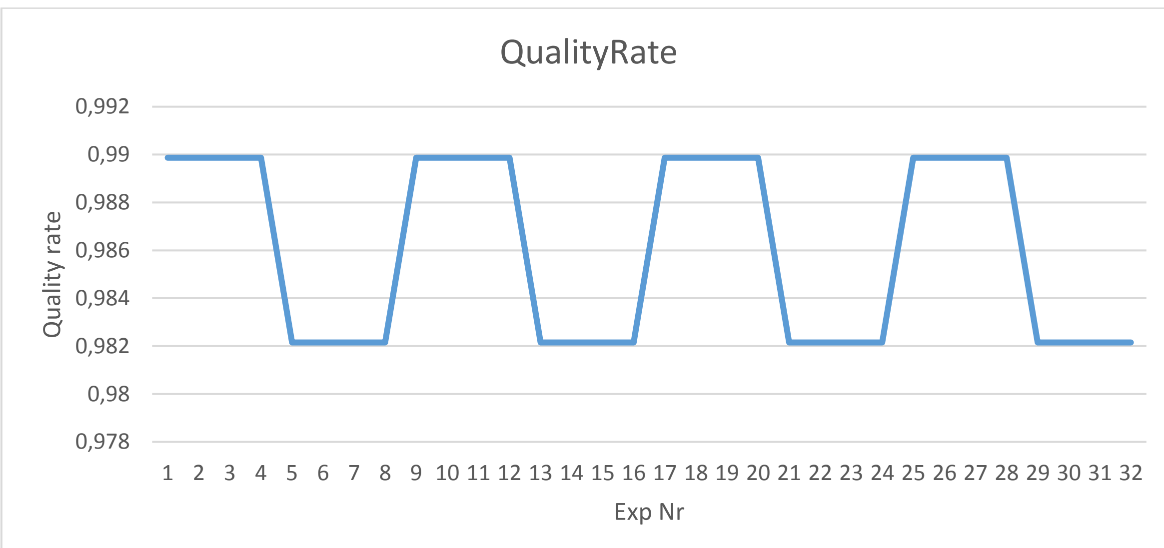

Figure 5.6. Quality rate per experiment based on the computations of the simulation model with a simulation time of one week, where the flattened peaks occur due to the boundaries of the input.

When we look at the graphs above, we can quickly see that experiments 6, 8, 14, 16, 22, 24, 30 and 32 have the lowest cycle time. Furthermore, they relatively also have the lowest minimal cycle time and highest number of products below the target of 4.00 seconds. However, based on quality and maximal cycle time we can see that these experiments have not the best performance. So, when also taking into account the quality rate and maximal cycle time combined with the other KPIs, we cannot determine a clear best experiment or set of experiments. However, when looking over a longer period of time the average cycle time is the most important KPI, therefore we choose to look at the experiments mentioned above more deeply. Besides these KPIs, we can see in the Figure 5.2 that for all experiments the standard deviation is relatively negligible. Therefore, we can say that the system is stable. Below in Table 5-1, we show per experiment the output values of these experiments. In Table 5-2, we can see the corresponding configurations per experiment.

Table 5-1. Output values of the best experiments shown per experiment.

Experiment	Cycle time (sec)	Min cycle time (sec)	Max cycle time (sec)	Below target	Quality rate
6	3,995168872	3,917883991	4,133333333	30693 (48.0%)	0,982152403
8	3,995168768	3,920885469	4,133333333	29890 (46.7%)	0,982152403
14	3,99516882	3,927717855	4,133333333	29082 (45.4%)	0,982152403
16	3,995168716	3,93040971	4,133333333	28312 (44.2%)	0,982152403
22	3,995168924	3,930660119	4,133333333	25384 (39.7%)	0,982152403
24	3,995168664	3,937425245	4,133333333	24685 (38.6%)	0,982152403
30	3,997779748	3,935979811	4,133333333	18556 (29.0%)	0,982152403
32	3,997779754	3,941957295	4,133333333	18066 (28.2%)	0,982152403

Table 5-2. Configurations of the best experiments, with the experiment number corresponding to the number in Table 13.

Experiment	Crawl Height (mm)	Distance SubStation2.1	Distance SubStation4.1 (mm)	Waiting
6	0	1	25	True
8	0	1	29	True
14	1	1	25	True
16	1	1	29	True
22	2	1	25	True
24	2	1	29	True
30	3	1	25	True
32	3	1	29	True

So, we can see that the cycle times are very close to each other, but there are some slight differences. For example, we can see that the lowest average cycle time corresponds to experiment number 24. However, on the other KPIs experiment 24 has not the best performance. Based on the minimal cycle time, experiment 6 has the best performance. This experiment has also the best score on the number of products below the target of 4.00 seconds. On the maximal cycle time and the quality rate, all eight experiments have the same performance. Further, we can see that experiments 30 and 32 have relatively higher average cycle time and lower of the products below the target. Since the differences are small, we decide to use experiments 6, 8, 14, 16, 22 and 24 for the next analyses. When looking at the configurations of these experiments, we can see that the crawl height and distance of the SubStation4.1 have an influence on the minimal cycle time and therefore the number of products below the target. However, the SubStation4.1 height differences in outcome are minimal and therefore considered as negligible. Further, we can see that the distance SubStation2.1 is reduced in all of the experiments. This also holds for the waiting factor which is always equal to true which means that there is no waiting time.

5.1.1. Bottleneck analysis

Now that we know the best experiments, we can perform a bottleneck analysis. For this bottleneck analysis we use the best experiments as concluded from the previous section. The tool "BottleneckAnalyzer" within PlantSimulation is used to determine which station or stations can be defined as bottleneck during the experiment. Below in Table 5-3, we can see the contribution per station as bottleneck per experiment.

Table 5-3. Bottleneck analysis of the best experiments.

Experiment	SubStation2.1 station	SubStation4.1 station	SubStation10.2
6	76.76%	0%	23.24%
8	73.08%	7.40%	19.52%
14	68.41%	0%	31.77%
16	66.23%	5.66%	28.11%
22	58.98%	0%	41.02%
24	57.55%	4.01%	38.43%

From the table we can see that when reducing the distance of the SubStation4.1 station, it results in a two bottleneck situation. Further, reducing the crawl height shows us that the bottleneck contribution of the SubStation10.2 decreases. A more thorough interpretation and conclusion is discussed in section 5.5.

5.2. Sensitivity analysis

In this section, we perform a sensitivity analysis regarding the cycle time target. We take the best experiments mentioned above and look on how much Product A are below or equal to the target. Currently, within Company X this cycle time target is set on 4.00 seconds. Within this sensitivity analysis, we vary this target from 3.92 till 4.10 seconds with steps of 0.01 seconds. In Table 5-4, Table 5-5, Table 5-6 and Table 5-7, we can see per cycle time target the performance in terms of number of products below this target and within the parentheses we can see the percentage of Product A that is below the target. Further, we see in Figure 5.7 the lapse per experiment in terms of percentage of products that is below the target versus the cycle time target.

Table 5-4. Sensitivity analysis part 1, with target of 4.10 to 4.06 seconds based on the out of the simulation model with a simulation time of one week.

Exp	4.10	4.09	4.08	4.07	4.06
6	63869 (99.8%)	63684 (99.5%)	63383 (99.0%)	62873 (98.2%)	61811 (96.6%)
8	63869 (99.8%)	63684 (99.5%)	63383 (99.0%)	62873 (98.2%)	61810 (96.6%)
14	63869 (99.8%)	63684 (99.5%)	63383 (99.0%)	62873 (98.2%)	61811 (96.6%)
16	63869 (99.8%)	63684 (99.5%)	63383 (99.0%)	62873 (98.2%)	61810 (96.6%)
22	63869 (99.8%)	63684 (99.5%)	63383 (99.0%)	62873 (98.2%)	61811 (96.6%)
24	63869 (99.8%)	63684 (99.5%)	63383 (99.0%)	62873 (98.2%)	61810 (96.6%)

Table 5-5. Sensitivity analysis part 2, with target of 4.05 to 4.01 seconds based on the out of the simulation model with a simulation time of one week.

Exp	4.05	4.04	4.03	4.02	4.01
6	59587 (93.1%)	56076 (87.6%)	52908 (82.7%)	45858 (71.7%)	39135 (61.2%)
8	59579 (93.1%)	56043 (87.6%)	52811 (82.5%)	45634 (71.3%)	38674 (60.4%)
14	59587 (93.1%)	56070 (87.6%)	52843 (82.6%)	45552 (71.2%)	38319 (59.9%)
16	59579 (93.1%)	56037 (87.6%)	52749 (82.4%)	45332 (70.8%)	37873 (59.2%)
22	59581 (93.1%)	56005 (87.5%)	52512 (82.1%)	44606 (69.7%)	36326 (56.8%)
24	59573 (93.1%)	55974 (87.5%)	52417 (81.9%)	44397 (69.4%)	35903 (56.1%)

Table 5-6. Sensitivity analysis part 3, with target of 4.00 to 3.96 seconds based on the out of the simulation model with a simulation time of one week.

Exp	4.00	3.99	3.98	3.97	3.96
6	30693 (48.0%)	23532 (36.8%)	13665 (21.4%)	8093 (12.6%)	2961 (4.6%)
8	29890 (46.7%)	22246 (34.8%)	12233 (19.1%)	6658 (10.4%)	2128 (3.3%)
14	29082 (45.4%)	20522 (32.1%)	10008 (15.6%)	4542 (7.1%)	1188 (1.9%)
16	28312 (44.2%)	19368 (30.3%)	8958 (14.0%)	3746 (5.9%)	852 (1.3%)
22	25834 (39.7%)	14993 (23.4%)	5572 (8.7%)	1825 (2.9%)	336 (0.5%)
24	24685 (38.6%)	14177 (22.2%)	5000 (7.8%)	1510 (2.4%)	245 (0.4%)

Table 5-7. Sensitivity analysis part 4, with target of 3.95 to 3.92 seconds based on the out of the simulation model with a simulation time of one week.

Exp	3.95	3.94	3.93	3.92
6	807 (1.3%)	104 (0.2%)	7 (0.0%)	0 (0.0%)
8	478 (0.7%)	43 (0.1%)	1 (0.0%)	0 (0.0%)
14	227 (0.4%)	23 (0.0%)	0 (0.0%)	0 (0.0%)
16	128 (0.2%)	8 (0.0%)	0 (0.0%)	0 (0.0%)
22	57 (0.1%)	3 (0.0%)	0 (0.0%)	0 (0.0%)
24	30 (0.0%)	1 (0.0%)	0 (0.0%)	0 (0.0%)

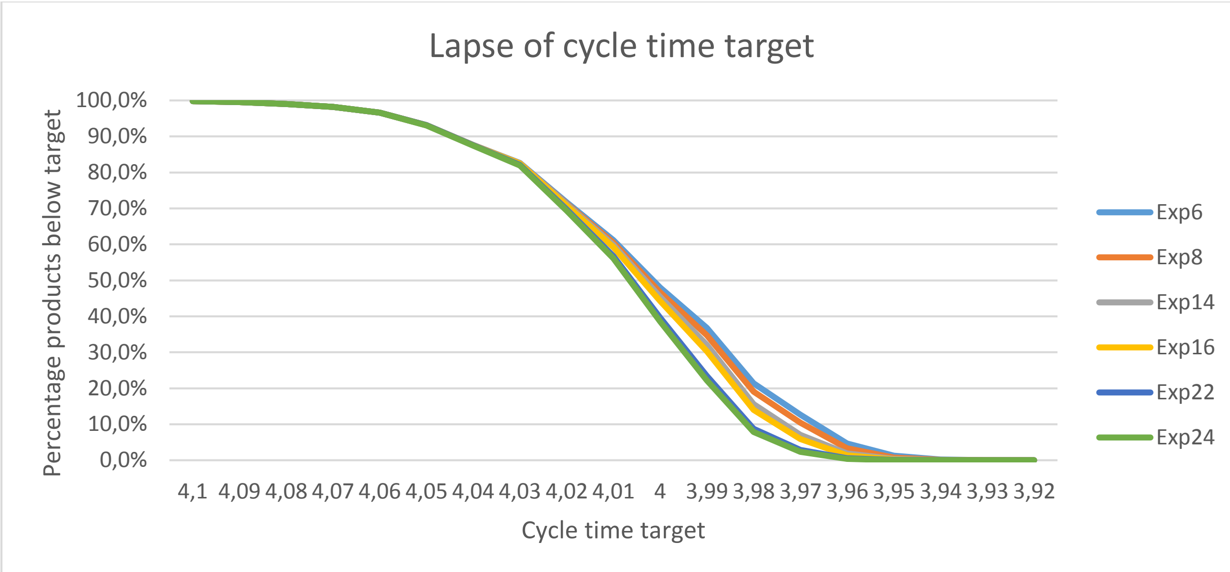

Figure 5.7. Lapse of the cycle time target - sensitivity analysis, based on the out of the simulation model with a simulation time of one week.

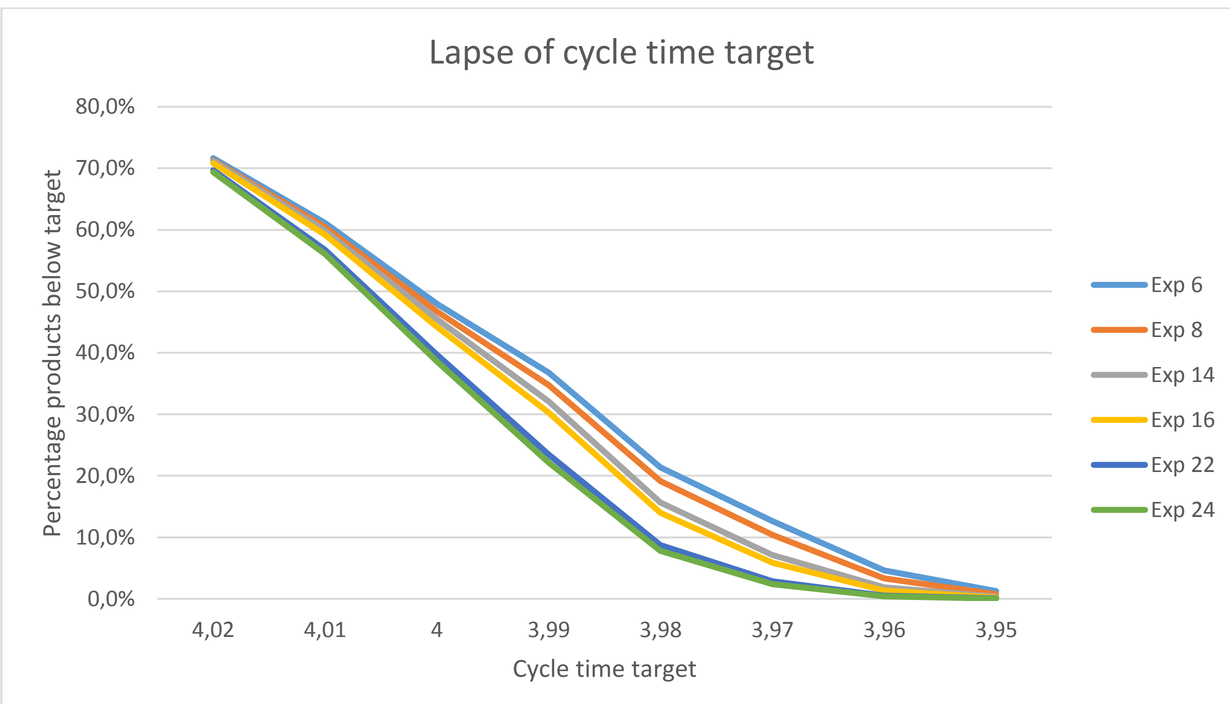

Figure 5.8. Zoom of the lapse of the cycle time target, based on the out of the simulation model with a simulation time of one week.

From the tables and Figure 5.7, we can see that with a relative high target the percentages are equal or very close to each other. Since some targets show us no or almost no difference, we zoom in on the interesting area. This can be seen in Figure 5.8**.** From 4.03 seconds and lower, we see that a partition takes place. Experiment 6 and 8 stay on the highest level in terms of performance. When reaching the target of

3.94 seconds almost no difference can be identified, because nearly all products are produced with a cycle time above the target. From these outcomes we can say that if reaching the cycle time target is its major concern, Company X should set the crawl height on 0.

5.3. Consequences supply chain

In order to analyze the consequences for the next steps in the production process, we first need the to define the current situation. This means that we need the current inventories of help materials that are needed for both the curing and packing department as indicated in blue in Figure 1.5. Further, we define three possible scenarios for analyzing these consequences. Within these scenarios, we also evaluate it for both one press (MACHINE X). We chose experiment 8 to be the best experiment to analyze, because reducing the SubStation4.1 height does not influence the average cycle time despite it takes costs to implement it. Therefore, the consequences for the supply chain are evaluated based on experiment 8.

5.3.1. Help materials

First, we need per step the materials that are needed to fulfill this step. We divide the steps into two main processes: curing and packing. Per process, we make a list of all materials needed and how many there are currently on hand within Company X. Further, we need the cycle time of such a help material before it is returned and can be considered as ready for use.

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Curing process

For this process two main help materials are needed, namely heat-proof plates and blocks in which the plates are placed. The Product A are placed between these plates and stacked on top of each other. Then these stacked plates are placed on the blocks. In Figure 5.9**,** we see schematically how the Product A are placed between the blocks. These blocks are put in the oven for their curing process. After the Product A are baked, they have to cool down for a several hours. In Table 5-8, we can see how many of these help materials are currently available. Besides that, the total throughput time of this part, till cooling down, of the process is 41.5 hours.

Table 5-8. Help materials and other information for curing process (Saint-Gobain Abrasives Database).

Material	Amount
Heat-proof plates	35260 pieces
Blocks	197 pieces
Plates/block	215 pieces/block
Throughput time	41.6 hours

Packing line

In this step of the process no new help materials are needed. The blocks with plates arrive at the packing line after cooling down and waiting to be ready for packaging. After the blocks are unloaded they can be considered as done and ready for a new cycle. The total throughput time of this packing process is 4.3

hours. Further, the packing line consists of three identical lines where the Product A are packed. About 661 plates can be unloaded within 1 hour.

5.3.2. Scenario analysis Machine X

For analyzing the consequences for the help materials, we define three scenarios. We consider a(n) best case, average case and worst case scenario. We describe each scenario and indicate the number of products expected based on the best experiment as can be seen from section 5.1 taking into account the corresponding quality rate. In addition to this analysis, we compare this with the old situation.

- **Best case scenario:** Within this scenario, we consider the minimal cycle time obtained from the best experiment. This means that we use, by rounding to three decimals, 3.921 seconds as cycle time. Further, we observe a quality rate equal to 0.982. This scenario gives us an indication if the machine is working optimally and implementing all described improvements. With optimal working is meant that all split times reach their lowest possible time. So, with this scenario we can see if the system could handle such a decrease in cycle time.
- **Average case scenario:** Within this scenario, we consider the average cycle time obtained from the best experiment. This means that we use, by rounding to three decimals, 3.995 seconds as cycle time. Besides that, the quality rate of this experiment is also 0.982. This scenario gives us an indication that is quite realistic, because it takes into account the stochastic character of the pressing process and the proposed improvements. So, with this scenario we can analyze if the system could handle quite a realistic increase in number of products.
- **Worst case scenario:** Within this scenario, we consider the maximal cycle time also obtained from the best experiment. This means that we use, by rounding to three decimals, 4.133 seconds as cycle time. Next to that, the quality rate of this scenario is also 0.982. So, this scenario gives us an indication if the system is performing worse than it should be despite of the planned improvements. So, with this scenario we can analyze how the system handles such a relative high cycle time.

Before analyzing the impact of these scenarios, we need the number of products that are produced per period of time. In Table 5-9, we can see per scenario the number of products that are produced assuming a constant production time without stops. Since in reality the machine experiences stops and maintenance, we have to adapt the number of products. In order to compute this, we use the quality rate and overall equipment effectiveness computed over the period of December 2018 till January 2019. We can do this, because at Company X the quality rate is computed on a later point in time than the OEE. The actual OEE is equal to 78.2%. We can see the number of products produced taking into account the OEE in Table 5-10.

Table 5-9. Number of products per period of time without OEE per scenario.

Scenario	#Products/hour	#Products/shift	#Products/day
Best	918	7345	22035
Average	901	7209	21627
Worst	871	6968	20905

Table 5-10. Number of products per period of time with OEE per scenario.

Scenario	#Products/hour	#Products/shift	#Products/day
Best	727	5819	17457
Average	724	5711	17134
Worst	690	5521	16562
Current	670	5356	16068

Now that we have all information, we can analyze the impact of the several scenarios. Further, we compare the three scenarios with the current situation based on the average cycle time as we can find in chapter 2. Further, when we add up the throughput times of both process steps as described in section 5.3.1. we obtain a total throughput time of 45.8 hours. Since the plates and blocks are also used by the other presses, we also need that information which we keep the same in order to analyze the impact of improved productivity of Machine X.

At the other 8 presses approximately 4300 Product A are produced per hour. Per scenario, we can add up the number of Product A corresponding to the scenario. Further, we know that each plate can handle 7 Product A. We can divide the number of Product A produced per hour by 7 in order to know how many plates are needed per hour. In order to compute if the number of plates on stock is sufficient, we have to multiply it with the throughput time. The same is done for the blocks. We can see these values in Table 5-11.

Table 5-11. Help materials needed per scenario.

Scenario	Total products per hour	Total plates per hour needed	Plates needed per cycle	Blocks needed per cycle
Best	5027	718	32891	154
Average	5014	716	32806	153
Worst	4990	713	32649	152
Current	4970	710	32515	152

We can see that each scenario could handle the number of plates and blocks needed, since there are 35.260 plates and 197 blocks available. However, when we look at the packing line capacity, we see that they can handle only 660 plates per hour. When we multiply this with the throughput time of 45.8 hours, the packing line can handle only 30.281 plates per cycle. In Table 5-12, we can see per scenario the impact of this overdue work for the cycles which come afterwards.

Table 5-12. Impact on the packing line of improved productivity per scenario.

Scenario	Plates arriving minus plates handled / hour	Hours of work overdue	#cycles till the system is 1 cycle behind	#days till system is 1 cycle behind
Best	2610	3.9	11.6	22.1
Average	2525	3.8	12.0	22.9
Worst	2368	3.6	12.8	24.4
Current	2234	3.4	13.6	25.9

We can see that even in the current situation, there are capacity problems regarding the packing line. After approximately 22 days, we observe that the production process is one cycle behind. This backlog accumulates over time. However, since the current situation is also dealing with this backlog and an increase of productivity of Machine X does not influence this backlog that much, we can say that it is possible in terms of help materials overall and availability at the packing line.

5.4. Savings

In order to compute the savings of this project, we need to make an important assumption since otherwise it is very hard to calculate precisely the benefits of this project. The assumption that we make is that the time saved by reducing the cycle time on yearly basis is defined as the savings of this project. Subsequently, we can easily multiply the time saved with the hourly salary of an operator in order to compute the savings per year. So, as we know we can produce about 463,000 Product A extra per year and one wheel takes on average 3.995 seconds to produce. So, the time needed to produce these extra Product A is:

$$463000 * 3.995 = 1849685 \text{ seconds}$$

Which is equal to 513.8 hours of production. The costs of an employee are equal to 35.00 euros per hour. So, the savings of the improved cycle time are:

$$513.8 * €35.00 = €17,983$$

Since Machine X is not the only SubStation5.1, we could estimate the savings for X when implementing such adjustments to the other five MachinesXYZ. For this calculation, we make the assumption that the decrease in cycle time is relatively the same, thus 5.87%. For computing the savings, we follow the same procedure as above for Machine X. Since this results in the same savings, we can just simply multiply the savings of Machine X with 6 to obtain the total savings possible per year:

$$€17,983 * 6 = €107,898$$

Since, the total production days in one year is not equal to 365, which we assumed in this computation, we have to take a percentage of these amounts. Company X says that they have 250 days of production in a year. When we divide these 250 days by 365, we obtain a percentage of 68.5%. So, the real savings of Machine X are € 12,255 per year. With the computation as above, for all MachinesXYZ this is: € 73,533 per year. For the Product A, the same holds where we respectively obtain 317,220 and 1,903,322 Product A extra per year for Machine X and all MachinesXYZ.

5.5. Conclusion

In order to conclude this chapter, we first discuss the results of the experiments by answering the 11th sub question which is formulated as follows:

- *Which of these alternatives has the best performance?*

For answering this sub question, we executed various experiments of which all configurations can be found in Appendix B. For all results of these experiments, we refer to Appendix C. So, from the alternatives we obtained several results which could be candidate for the being the best experiment. Looking at the average cycle time, we can see that it is best to take the following actions:

- Pressing time SubStation10.2 to 1.1 seconds after performing thorough research on reducing it on all different types of SubStation2.1 and pressure.
- Crawl height of the SubStation10.2 to 0 mm.
- Moving down speed SubStation10.2 to 90% of its capacity.

- Buffer reduction of inlay stations to 0 seconds.
- Reduce the height of the SubStation2.1 station by inserting plugs such that the distance between the mold and the station is reduced.

These actions result in an average cycle time of 3.995 seconds. Furthermore, this experiment gives us the second lowest minimal cycle time and also the second highest number of products below the current cycle time target of 4.000 seconds. The best experiment, experiment 6, has a better performance but it is not worth it considering the costs of implementing the extra intervention. Only in terms of quality, these actions result in a higher reject rate. However, since this quality rate is slightly lower and based on an assumption that has to be tested in the future, we decide to take the experiment above as best experiment. Within this best experiment, we observe that the SubStation2.1 station now for about 73% of the time can be considered as the bottleneck within the system. The other bottlenecks are the SubStation10.2 and SubStation4.1 station. Financially seen, the improvement saves Company X 12,255 euros per year based on the saved hours multiplied by the employee costs per hour.

Also, the 12th sub question that is answered in this chapter and is formulated as follows:

- *How does this best alternative influence the inventory levels of help materials at the next production process steps?*

We used three scenarios to analyze these consequences based on the experiments. For each scenario we evaluated the impact on the curing and packing process. We observed that for each of the three scenarios an increase in productivity can handled in terms of help materials. However, for all scenarios the packing line would become a serious bottleneck in het system. Due to the fact that in the current situation the packing line is also dealing with backlog according to this analysis, we could conclude that such an improved cycle time is not that violent for the system on the condition that X analyzes and improves the productivity of this packing line.

A last interesting point that we can conclude from this chapter, is that Company X should consider if the current cycle time target is realistic or should be higher or lower regarding the cycle time improvements that could be passed through. With the current target and performing the best experiment, we observe that almost half of the products is produced within a time below 4.00 seconds. For example, if X decides to use a target of 4.05 seconds and implementing the improvements they could reach approximately 93% of the products below this target. In the other case, when they decide to lower it to for example 3.95 seconds, this percentage drops to only 0.7%.

All in all, we can conclude that there are serious possibilities to improve the pressing process. Since this is mostly based on a model, we also want to evaluate the options in reality. In the next chapter, we discuss the limitations of this research and mention options for further research.

6. Discussion

In this chapter we discuss the limitations of this research. These limitations occur due to time restrictions or other issues. Furthermore, we mention several options for further research relating to this research, but also some general issues. In chapter 8, we briefly come back at the options for further research.

6.1. Limitations

The first limitation that we have to mention is about the data used in this research. The data that we have used for the context analysis is based on a period of a year which shows us a good overview of the current performance. However, there are several reasons that these data are unreliable. The first issue is that within Company X there is not one consensus about how to compute several KPIs like the OEE. This could have distorted the analysis about the historical OEE. The second issue is that data are not always tracked and stored in the right way. Sometimes it is done manual and sometimes it is done automatically by software. Due to this inconsistency, differences between reality and used data occur.

A second limitation that we discuss is the fact that the simulation model used is partly based on assumptions. In order to perform the described experiments, lots of assumptions need to be made due to time restrictions of this research. For example, we did not take into account the short stops of the process, because it is quite hard to analyze the impact of the interventions regarding these short stops. The same holds for other stop-related assumptions like constant production. Since this is of no impact on CycleTime(2), we left it out. However, this does not show us the real process. Further, the affection on the quality rate by implementing plugs onto the molds is just an assumption and estimation. So, we cannot say exactly what this will do with the quality of the final Product A.

The third discussion point related to the research performed is about the scenario analysis as described in section 5.3. The data that are used in order to calculate the impact of eventual improvements is based on 2018. So, these data about the inventory of help materials is outdated and could therefore be incorrect. Due to these possible incorrect data, the outcomes of the impact calculations could be distorted. Furthermore, the total throughput time only give us an estimation of it, since it is hard to determine the time needed exactly. For example, the time to pack a certain number of products per hour is not always the same.

With this last sentence, we come to the fourth limitation of this research. This concerns the unpredictable behavior of several aspects of the research. First of all, the machine cycle times of all stations have a stochastic character. By means of a simulation we can reduce this variability to some extent, but not completely. In addition to that, we only simulate the pressing process. So, all kind of uncertainty within the next steps are not taken into account when computing the impact.

A fifth limitation to mention is that when investigating the options for improving the machine cycle time, we only focused on the primary improvement options. In this case primary means the direct options that are adjustable. When looking one step deeper into the machine, it could be the case that more improvements are possible. This is a more technical and engineering issue and therefore left out of this research.

6.2. Further research

In this section, we mention several options about possibilities of further research. These possibilities are both research as non-research related. We list them below with a short explanation per point.

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7. Implementation

In this chapter we discuss the implementation step performed after obtaining the results from the simulation model. First, we make an implementation plan in order to implement and control the improvement options regarding the production process. Next, we discuss the results of implementing the proposed interventions partly.

Recap

Before describing the implementation plan and the results of the testing phase, we give a small recap of what can be concluded from the previous chapters. We concluded that the best option for X to improve the cycle time is to adjust the crawl height and moving time of the SubStation10.2 plunger. Furthermore, they should reduce the distance between the mold and the SubStation2.1 station and make sure that there is no waiting time anymore. A last point of attention is that a reduction in pressing could be an option when investigating what reduction is possible without a loss in quality. Some of these adjustments have been implemented already and the intermediate results are analyzed in this chapter. Before this analysis, we made an implementation plan to maintain these improvements and other issues regarding the cycle time of Machine X.

7.1. Implementation plan

Now that we know which configurations and thus interventions should result in the best cycle time for Company X, an implementation plan is needed. This plan makes sure the interventions are implemented in the right way by the right people. Besides that, it is of at least equal importance that these interventions are assured for the future. In order to achieve this, we develop a checklist, a form that needs to be filled each hour and a long term roadmap in order to maintain the improvement.

Checklist and hourly form

Before an order is started, the operator that is working on Machine X should follow several steps stated in a checklist. First of all, he or she needs to make sure that the press time of the SubStation10.2 is set on 1.1 seconds. If on the order card another time is stated, he or she needs to ask the team leader what to do. Next, the operator should make sure that the crawl height is set on 0 millimeters. This can be done without asking a team leader or other superior. Furthermore, the moving time of the SubStation10.2 should be set on 90%. Also for this action no verification is needed from a supervisor. Besides these check actions, the standard already existing checks should be done like the speed of dividing the SubStation2.1 and the pressure of the SubStation10.2. Besides these checks done by the operator, an expert should frequently walk by in order to make sure everything is set in the right way and the machine is working as it should be. Below in Table 7-1, we summarized these checks for the operator.

Table 7-1. Checklist for operators before the can start an order.

Action	If not?
• **Check if press time is 1.1 seconds.**	• Check order card or ask team leader
• **Check if crawl height is set on 0 mm.**	• Set it on 0 mm.
• **Check if moving time on 90% of its power.**	• Set it on 90%.
• **Standard actions as known already**	• Check order card or ask team leader

Besides these checks that should be done, it is important to keep track of the cycle time on a regular basis. Therefore, it is important that an operator every hour registers the several performance indicators. We recommend Company X to register the date, time, cycle time of the press, cycle time of the SubStation10.2 plus rotation time and cycle time of the SubStation2.1 station plus rotation time. We chose these two stations in addition to the general cycle time since these are identified as the main bottlenecks before and after implementing the interventions. In this way, it can be quickly analyzed which station is the main bottleneck. In case, none of the two stations corresponds with the general cycle time the operator should report this to the team leader such that he or she can analyze how it is caused. Furthermore, an operator also should report it to the team leader if the cycle time is significantly increasing three hours in a row. In Table 7-2, a concept of this form with fictive numbers is shown.

Table 7-2. Example of filled form cycle times.

Date	Time	Cycle time	Cycle time SubStation10.2	Cycle time SubStation2.1 station
04/02/2019	10:10	4.01	3.95	4.01
04/02/2019	11:10	3.99	3.98	3.99
04/02/2019	12:10	4.01	4.01	4.00
04/02/2019	13:10	4.02	3.99	4.02
Etc.	Etc.	Etc.	Etc.	Etc.

Roadmap

In order to maintain the improvements on the long term, we develop a roadmap. In this roadmap, the actions that needed to be done are stated. Per action also is mentioned how often this has to be done and the deadline for this action. In the last column, we can find the people responsible for this action. By following such a roadmap, Company X can make sure that the actions are executed before the deadline. In Figure 7.1**,** we can find the roadmap. For the project team in the column of responsible people, we advise X to at least add the production leader, process expert and a person responsible for the data collection and analysis.

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Figure 7.1. Roadmap for implementing the adaptions at Machine X and other important issues regarding the consequences of the adjustments.

7.2. Results of implementation

Furthermore, we also implemented several interventions already during the end of the research. In this section, we briefly discuss the adjustments made and how these adjustments affected the cycle time. In addition to this, we also looked at the impact of the adjustments on the OEE with special attention to the short stops.

During the research, some improvements are already implemented in order to see if the cycle time can be reduced without an extra loss in OEE. However, due to a significant time that the press cannot be used only small adjustments are tested on Machine X. The speed of the plunger of the SubStation10.2 is adjusted such that is moves faster downwards. Further, the crawl height is adjusted to 0 millimeters. The other improvement options are not tested yet, due to the earlier mentioned stop time. In order to analyze if these adjustments result in a better cycle time and no extra loss on OEE, we first look at the minimal, maximal and average cycle time. In addition, we also compute the percentage of products below the target of 4.00 seconds. The data that is used as input for this analysis is extracted from the database within the period of one week, more specific from 07-02-2019 till 14-02-2019. Besides, we filtered the data with the same procedure as mentioned in chapter 4.

Table 7-3. Outcomes of the implementation testing phase in the period from 07-02-2019 till 14-02-2019 (Company X, 2018).

KPI	Value
Average cycle time	4.011 seconds
Minimal cycle time	3.960 seconds
Maximal cycle time	4.070 seconds
Products below target	49%

As we can see in Table 7-3, all KPIs are significantly improved in comparison with the old situation as indicated in Table 2-1 in chapter 2. It is not as good as the results from the simulation model, but this can be clarified by the fact that not all adjustments have been implemented already. Further, we can look at the minimal and maximal cycle time on bottleneck level. We can see in Table 7-4, that the SubStation10.2 station is significantly reduced with a maximal cycle time of 3.98 seconds which means that this station is always performing below the target. Besides this, we see that the SubStation2.1 station can be considered as the new bottleneck. This can be logically clarified by the fact that no adjustments have been implemented on this station already.

Table 7-4. Outcomes on bottleneck level showing the lower and upper bound of the machine cycle times and their bottleneck contribution measured over the period of 07-02-2019 till 14-02-2019 (Company X, 2018).

Station	Maximal cycle time (sec)	Minimal cycle time	Bottleneck
SubStation10.2 station	3.98 seconds	3.92 seconds	1%
SubStation2.1 station	4.07 seconds	3.96 seconds	99%

So, we can see that the cycle time can be reduced seriously with only two adjustments. In order to look at the bigger picture, we analyze the OEE in the same period as mentioned above. This gives us an indication if the (implemented) adjustments affect the OEE that much that a significant decrease occurs. Since, the measurement period is only one week we have to cautious when interpreting this OEE. It could be the coincidence that the OEE is lower or higher than usual due to other causes than the adjustments made. The OEE over the period of 2018 was approximately 78% as mentioned in chapter 2. The OEE as observed during the implementation testing period did not significantly deviate from the old OEE since it was mainly around 80% with some outliers downwards due to unexpected and planned maintenance.

So, overall we can say that the implemented adjustments have a very positive effect on the machine cycle time also known as CycleTime(2) and thus also on CycleTime(1) when measuring it over a period longer than one week in the near future. Furthermore, we observe a shifted bottleneck situation, since with the adjustment the clear bottleneck of the pressing process is currently the SubStation2.1 station with almost 100%. Moreover, the impact on the Overall Equipment Effectiveness is hard to determine in such a short testing period, but at first sight it seems that the OEE is not negatively affected. Therefore, we could say that the implemented adjustments could be defined as established implementations with the notification that X has to keep track of the results of these tested implementations in case the OEE will significantly decrease.

8. Conclusion and recommendations

In this chapter we formulate the final conclusion of this research. First, we answer the main research question. Subsequently, we give some general recommendations regarding the research performed. Next to that, we advise about further research that can be executed on various topics in the future.

8.1. Conclusion

Since Company X experience a serious loss in productivity due to inefficient machine cycle time at the pressing process, they want to identify the main bottlenecks and how to tackle them in order to improve their productivity. Currently, on average they produce one product in 4.242 seconds whereas the desired cycle time is 4.000 seconds. There could be a lot of factors that influence this cycle time, therefore we used a simulation model to see which adaptations or combinations of adaptations result in the best outcome for Company X. An increased productivity also causes an impact on the next steps in the production process. Within this research, we also computed the impact on these production steps in order to give X support to improve these processes in the near future. In order to come up with a well-founded solution for this problem, we answer the main research question as formulated:

"To what extent can the productivity of the pressing process, specifically at Machine X, within Company X be improved?"

8.1.1. Bottlenecks and solutions

Before coming up with quantified improvements for X, we need to define the bottlenecks as experienced currently at Machine X. After analyzing the data and executing several interviews, we can identify the following three main bottlenecks that affect the cycle time negatively:

- SubStation10.2 station at the Machine X.2
- SubStation2.1 station at the Machine X.1
- Waiting time of inlay stations

In order to tackle these problems, we identified per bottleneck what could reduce the machine cycle time. For the SubStation10.2 station, the time that the plunger moves down can be seriously reduced by adjusting two factors: the crawl height and the speed of the plunger. Further, the pressing time itself could be reduced after performing a more thorough analysis in order to be sure if the quality remains the same. For the SubStation2.1 station, we can reduce the distance between this station and the mold such that the time decreases the SubStation2.1 is spread onto the mold. The waiting time of the inlay stations is caused by the fact that the synchronization of the pressing process is not optimal. Let us know look at the summarized options of tackling the bottlenecks:

- **SubStation10.2 improvements:**
    - Increase the speed of the plunger such that the moving time reduces
    - Reduce the crawl height such that the plunger can immediately start pressing.
    - Reduce the pressing time after performing thorough research on effect on the quality of the wheel.
- **SubStation2.1 station improvements:** reduce the distance between the station and the mold on the table.
- **Waiting time improvements:** synchronize the pressing process such that all stations are well connected to each other

8.1.2. Cycle time and impact

Now that the bottlenecks and their corresponding solutions are defined, we can conclude what the best combination of solutions is for Company X regarding the cycle time. In terms of cycle time, we can say that X can reduce it with 5.87% by applying the following adaptions on Machine X:

- Reduce the pressing time of the SubStation10.2 to 1.1 seconds after performing thorough research on reducing it on all different types of SubStation2.1 and pressure.
- Reduce the crawl height of the SubStation10.2 0 millimeters.
- Reduce the moving time of the SubStation10.2 to 90% of its power.
- Synchronize the system such that waiting time is eliminated.
- Reduce the distance between the mold and SubStation2.1 station by making use of so-called "plugs".

This relative improvement is based on the average cycle time over a longer period of time. Since we are also interested in the extremes of the pressing process and how much products are produced below the cycle time target of 4.000 seconds, we can conclude that with the adaptations as mentioned above the following performance can be achieved:

- Average cycle time: 4.244 seconds → 3.995 seconds (5.87% reduction)
- Minimal cycle time: 4.060 seconds → 3.921 seconds
- Maximal cycle time: 4.413 seconds → 4.133 seconds
- Products below target: 46.7% of the products

Within this solution option, Machine X experience that the SubStation2.1 station can be considered as the new bottleneck, because about 75% of the time this station determines the cycle time. Also, the SubStation10.2 is still the number two bottleneck within the system. Besides the bottleneck contribution, we computed the impact on the curing and packaging process by achieving this new cycle time. We can conclude that the adaptions on Machine X are relative of no harm since even in the old situation it cannot be handled within the available time until a new batch of Product A arrives.

8.1.3. Concluding words

When returning to the central research question, we can improve the cycle time of the pressing process to an extent of 5.87% when comparing the old and new average cycle time of respectively 4.244 and 3.995 seconds. When we transfer this to number of products and money savings per year, it results in the following savings for both Machine X and a scenario of all six MachinesXYZ:

- **Only Machine X:**
  - Savings per year: *€12,255*
  - Extra Product A produced per year: *317,220*
- **All MachinesXYZ:**
  - Savings per year: *€73,533*
  - Extra Product A produced per year: 1*,903,322*

However, this approximately 6% improvement of the pressing process has consequences for the next steps in the production process. To that extent, the improvements results in a backlog of one batch after 23 days due to inefficiencies at the packing line. Although, in the old situation this backlog also is a problem but after 26 days. All in all, the productivity can be improved with almost 6% in terms of cycle time taking into account that backlog comes up earlier in time.

8.2. Recommendations

In this section, we give several recommendations to Company X regarding the research performed. Further, we summarize the options for further research as already explained in chapter 6.

8.2.1. Research recommendations

The first recommendation that we want to give to X is that they should implement the adaptions as proposed with a special notification for the pressing time of the SubStation10.2 which should be investigated more deeply. For investigating these options more deeply, we advise to use Design of Experiments as mentioned in section 3.3. By implementing these adaptions, they can also analyze the consequences for the short stops at Machine X. With these updated short stops, X can determine a new OEE which give them a good overview on where to put the focus on in the future regarding Machine X.

Secondly, we advise Company X to reconsider their target regarding the cycle time on Machine X. Currently this is set on 4.00 based on historical data and information. However, we can see in section 5.2. that less than half of the products reach this cycle time target. So, we would recommend X to define how much of the products should reach this target. Further, a dynamic target could also be an option. This means that the target moves along with the performance of the press.

A third recommendation what we would give to X is that they have to make sure that they keep track of the right cycle time. This is important because of several reasons. The first reason is that when showing the wrong cycle time, the analysis that one wants to perform regarding the cycle time of the press is based on wrong data. Further, a wrong cycle time displayed at the press could lead to taking to incorrect or unnecessary actions. In addition to this display, we advise X to investigate if sensors could be placed such that an automatic signal is sent. With the Industry 4.0 project in mind, this would contribute to the project overall.

Lastly, we observed that the bottleneck contribution of the SubStation2.1 station is about 75%. Since first this was much lower, we advise X to perform a profound analysis on only the SubStation2.1 station in order to reduce this bottleneck contribution. A corresponding advantage of reducing this SubStation2.1 station cycle time is that the overall cycle time also reduces. Following on this recommendation, we advise to X to continuously improve the production process such that the cycle times do not fall back into the old situation. Within this continuous improvement, we also advise to look at the possibility to expand these improvements to the other MachinesXYZ in the factory.

8.2.2. Further research

The first option for further research that we want to mention is to perform a profound analysis on the packing line, especially on the lines where the pancake Product A are packed. When analyzing the impact of the improved productivity at the pressing process on the next steps in the supply chain, we observed that the packing line is a serious bottleneck. Due to low efficiency or insufficient employees a backlog in het supply chain is created. In about 3 to 4 weeks, the production of pancake Product A is one batch behind. Therefore, it is strongly recommended to investigate how this packing department can be improved such that there is no backlog anymore, because even in the old situation with the cycle time of 4.244 seconds the packing line is not efficient enough.

The second recommendation we would like to give to X is that now that the loss due cycle time is minimalized, they should investigate on how to reduce their short stops, changeovers and set-up in order to reduce the OEE loss due to stops. They could make a good overview on how the short stops are distributed and which can be easily tackled. From this starting point, they could design a strategy on how to minimalize these stops in order to improve their pressing process.

The third recommendation regarding further research is that Company X could investigate the layout of their factory and some departments specifically. Currently, parts needed for creating the end-product are located all over the production plant instead of being at the location already where it is needed. Further, the warehouse of the SubStation2.1 ingredients is currently quite unorganized. The bags with these ingredients are placed on the floor instead of racks. So, we also advise to look how the warehouse can be improved. A last thing is that currently fork-lift trucks frequently do not drive optimally through the plant. Therefore, investigating on how to implement Automated Guided Vehicles (AGVs) within the factory could be interesting for X.

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Appendix A

Machine X.1

Time (sec)	Probability
1.05	0.020
1.06	0.395
1.07	0.503
1.08	0.082

Cavity Up

Time (sec)	Probability
0.63	0.0464
0.64	0.3993
0.65	0.1969
0.69	0.0073
0.70	0.1060
0.71	0.1824
0.72	0.0560
0.73	0.0056

Cavity Down

Time	Probability
0.80	0.0143
0.81	0.2718
0.82	0.5276
0.83	0.1758
0.84	0.0106

Station Up

Time	Probability
0.93	0.0479
0.94	0.2813
0.95	0.4393
0.96	0.2032
0.97	0.0283

Station Down

Time	Probability
0.65	0.0074
0.66	0.1448
0.67	0.4783
0.68	0.3286
0.69	0.0409

Station Forward

Time	Probability
1.29	0.0275
1.30	0.2322

1.31	0.2291
1.32	0.00453
1.33	0.0011
1.34	0.0016
1.35	0.0820
1.36	0.2374
1.37	0.1147
1.38	0.0080
1.39	0.0020
1.40	0.0047
1.41	0.0086
1.42	0.0054
1.43	0.0003

Station Backwards

Time	Probability
1.29	0.0334
1.30	0.3126
1.31	0.1796
1.32	0.0095
1.33	0.0039
1.34	0.1645
1.35	0.2412
1.36	0.0340
1.37	0.0002
1.38	0.0001
1.39	0.0055
1.40	0.0131
1.41	0.0024
1.42	0.0001

SubStation10.2 Station Down

Time	Probability
0.80	0.0027
0.81	0.0092
0.82	0.0212
0.83	0.1705
0.84	0.4502
0.85	0.2962
0.86	0.0492

SubStation10.2 Pressure built up

Time	Probability
0.25	0.0102
0.26	0.2835
0.27	0.5357
0.28	0.0842

0.29	0.0503
0.30	0.0361

SubStation10.2 Pressing

Time	Probability
1.29	0.2357
1.30	0.7643

SubStation10.2 Decompressing

Time	Probability
0.50	1.0000

SubStation10.2 Station Up

Time	Probability
0.37	0.0033
0.38	0.0425
0.39	0.4210
0.40	0.4773
0.41	0.0558

SubStation1.2

Time	Probability
2.66	0.0121
2.67	0.0355
2.68	0.0871
2.69	0.1544
2.70	0.1942
2.71	0.1863
2.72	0.1419
2.73	0.0919
2.74	0.0530
2.75	0.0270
2.76	0.0119
2.78	0.0047

SubStation2.2

Time	Probability
1.98	0.0018
1.99	0.0068
2.00	0.0198
2.01	0.0561
2.02	0.1090
2.03	0.1590
2.04	0.1701
2.05	0.1462
2.06	0.1127
2.07	0.0863
2.08	0.0617

2.09	0.0396
2.10	0.0194
2.11	0.0086
2.12	0.0031

SubStation3.2 Station

Time	Probability
2.16	0.0062
2.17	0.0176
2.18	0.0447
2.19	0.1018
2.20	0.1701
2.21	0.2127
2.22	0.1922
2.23	0.1394
2.24	0.0764
2.25	0.0307
2.26	0.0082

SubStation4.1 station

Time	Probability
2.50	0.0028
2.51	0.0048
2.52	0.0155
2.53	0.0399
2.54	0.0827
2.55	0.1292
2.56	0.1586
2.57	0.1600
2.58	0.1383
2.59	0.1069
2.60	0.0729
2.61	0.0433
2.62	0.0238
2.63	0.0126
2.64	0.0060
2.65	0.0027

SubStation5.1

Time	Probability
2.07	0.0203
2.08	0.0839
2.09	0.1438
2.10	0.1278
2.11	0.0680
2.12	0.0614
2.13	0.1172

2.14	0.1889
2.15	0.1399
2.16	0.0403
2.17	0.0062
2.18	0.0010
2.19	0.0007
2.20	0.0003
2.21	0.0002

Pick-and-place PCP-HP

Time	Probability
2.01	0.0001
2.02	0.0003
2.03	0.0025
2.04	0.0115
2.05	0.0377
2.06	0.0851
2.07	0.1427
2.08	0.1742
2.09	0.1728
2.10	0.1431
2.11	0.0974
2.12	0.0623
2.13	0.0368
2.14	0.0198
2.15	0.0095
2.16	0.0042

Pick-and Place HP-Belt

Time	Probability
2.38	0.0140
2.39	0.0378
2.40	0.0862
2.41	0.1579
2.42	0.2038
2.43	0.1916
2.44	0.1344
2.45	0.0805
2.46	0.0480
2.47	0.0265
2.48	0.0136
2.49	0.0056

Appendix B

Configurations of all experiments.

ExpNr	PressureHead	HeightHP	DistanceSubStation2.1	DistanceBL	Waiting	TableHeight	HeadPlungerDown
1	110	0	0	25	FALSE		90
2	110	0	0	25	TRUE		90
3	110	0	0	29	FALSE		90
4	110	0	0	29	TRUE		90
5	110	0	1	25	FALSE		90
6	110	0	1	25	TRUE		90
7	110	0	1	29	FALSE		90
8	110	0	1	29	TRUE		90
9	110	1	0	25	FALSE		90
10	110	1	0	25	TRUE		90
11	110	1	0	29	FALSE		90
12	110	1	0	29	TRUE		90
13	110	1	1	25	FALSE		90
14	110	1	1	25	TRUE		90
15	110	1	1	29	FALSE		90
16	110	1	1	29	TRUE		90
17	110	2	0	25	FALSE		90
18	110	2	0	25	TRUE		90
19	110	2	0	29	FALSE		90
20	110	2	0	29	TRUE		90
21	110	2	1	25	FALSE		90
22	110	2	1	25	TRUE		90
23	110	2	1	29	FALSE		90
24	110	2	1	29	TRUE		90
25	110	3	0	25	FALSE		90
26	110	3	0	25	TRUE		90
27	110	3	0	29	FALSE		90
28	110	3	0	29	TRUE		90
29	110	3	1	25	FALSE		90
30	110	3	1	25	TRUE		90
31	110	3	1	29	FALSE		90
32	110	3	1	29	TRUE		90

Appendix C

Results experiments.

Exp	CycleTime	StandardDeviation	MinCycleTime	MaxCycleTime	ProductsBelowTarget	QualityRate
1	4,04517	0,000166	3,967707	4,183333	727	0,989869
2	4,04517	0,000166	3,95	4,183333	5465	0,989869
3	4,04517	0,000166	3,968262	4,183333	718	0,989869
4	4,04517	0,000167	3,95	4,183333	5322	0,989869
5	4,01778	0,000112	3,951166	4,133333	4040	0,982152
6	3,995169	0,000163	3,917884	4,133333	30693	0,982152
7	4,01778	0,000112	3,951166	4,133333	4057	0,982152
8	3,995169	0,000163	3,920885	4,133333	29890	0,982152
9	4,04517	0,000166	3,977705	4,183333	197	0,989869
10	4,04517	0,000166	3,95	4,183333	5193	0,989869
11	4,04517	0,000166	3,977705	4,183333	202	0,989869
12	4,04517	0,000167	3,950113	4,183333	5056	0,989869
13	4,02778	0,000113	3,95667	4,133333	1126	0,982152
14	3,995169	0,000163	3,927718	4,133333	29082	0,982152
15	4,02778	0,000113	3,956681	4,133333	1146	0,982152
16	3,995169	0,000163	3,93041	4,133333	28312	0,982152
17	4,04517	0,000166	3,980855	4,183333	45	0,989869
18	4,045171	0,000166	3,951635	4,183333	4518	0,989869
19	4,04517	0,000166	3,981942	4,183333	45	0,989869
20	4,04517	0,000167	3,952681	4,183333	4399	0,989869
21	4,03778	0,000113	3,966656	4,133333	254	0,982152
22	3,995169	0,000163	3,93066	4,133333	25384	0,982152
23	4,037779	0,000113	3,96612	4,133333	260	0,982152
24	3,995169	0,000163	3,937425	4,133333	24685	0,982152
25	4,047773	0,000104	3,988611	4,183333	5	0,989869
26	4,04517	0,000167	3,958192	4,183333	3310	0,989869
27	4,047773	0,000104	3,988611	4,183333	5	0,989869
28	4,04517	0,000167	3,960985	4,183333	3204	0,989869
29	4,047778	0,000112	3,976111	4,133333	39	0,982152
30	3,99778	0,00011	3,93598	4,133333	18556	0,982152
31	4,047778	0,000111	3,976111	4,133333	38	0,982152
32	3,99778	0,00011	3,941957	4,133333	18066	0,982152