Assessing the impact of variability on the performance of the X production line

Wout Temmink

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Author: Wout Temmink
Email: w.w.temmink@student.utwente.nl

University of Twente
Postbus 217
7500 AE Enschede

Faculty: BMS
Department: IEBIS

Supervisors at University of Twente:
Dr. M.C. van der Heijden
Dr.Ir. J.M.J. Schutten

Supervisor Company Y
S. Sloot

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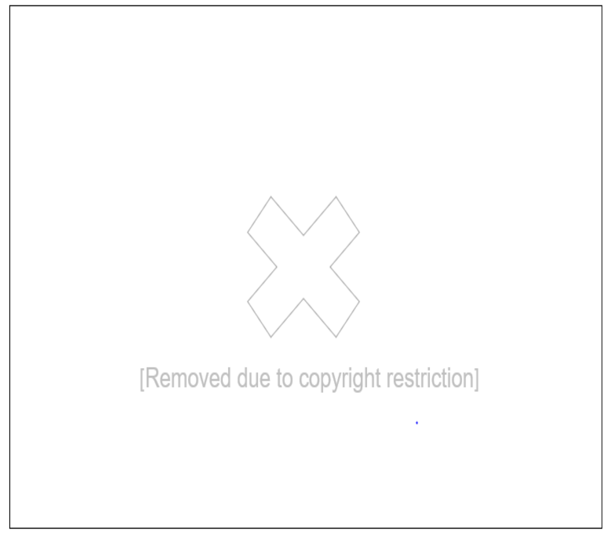

Preface

The following report is the result of my graduation period at the manufacturing department at Company Y. The report will mark the end of my bachelor industrial engineering and management at the University of Twente.

First and foremost, l I would like to thank everyone that helped me with conducting my research and writing this report. In particular, I would like to thank Steffan Sloot and Matthieu van der Heijden my supervisors at Company Y and the University of Twente respectively. Without their insights and feedback this would not have been possible.

Furthermore, my gratitude goes out to all the employees at Company Y that assisted me with my research. A special thanks goes out to Pascal Oonk, for all the verification and validation he assisted me with.

Lastly, I would like to thank Elsbeth my friends and family for all the support they gave me throughout the duration of my graduation period.

Wout Temmink

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Management summary

Company Y is a production plant with its own R&D development center that is currently producing electrical switchgear products that are used throughout the entire power grid. The production process of one of their main products, the highly customizable X Medium voltage switch gear system is not always performing up to standard. Evident from the fact that their desired KPI goals are not always attained, the two main KPI's used to evaluate the performance of the production line are takt and on time to promise (OTP).

The X production line is a complex system that can be divided into two sections; the standard section and the special section. The purpose of the standard section is to equip the X with its standard functionalities, whilst the purpose of the special section is to add extra secondary features. Research indicates that the special section of the production line is the reason for the production line not performing well at times.

Both sections consist of a set of production tasks, these tasks all have their own purpose and whilst all the X systems pass through the production tasks located in the standard section, only certain systems pass through some of the production tasks located in the special section. Naturally this causes there to be a lot of variability in the utilization of these production tasks. From research it is clear that the special section starts performing inadequate when the utilization of its tasks is higher than 60-80%. The inadequate performance is the result of a combination between relatively high utilization and the various sources of variability that are causing the production line issues.

The main research goal is: gaining quantitative information on the influence of different sources of variability on the performance of the special section. Researching this will enable the possibility to effectively study the effects of alternative production line lay-outs on the performance of the production line, and in the process the effects of these sources will hopefully be lessened. The root causes for variability can roughly be divided into three categories namely:

- Rework
- Process time variability
- Production order mix

A Rework occurs when a X system does not comply with the strict safety and quality standards set by Company Y. If the first time yield decreases from the current level of around 96.36% to 92%, throughput times and WIP levels spiral out of control, thus affecting the performance of the production line negatively.

Process time variability is a big black box that represents the difference between the amount of time planned for a certain production step and the actual time needed to complete set production step. The difference is caused by among others: components not being industrialized, non-industrialized components are components that have an unknown processing time and raw material requirement. The variability in process time results in the bottleneck shifting from the standard section to the special section. Furthermore, personnel cannot be effectively scheduled throughout the production line, since the amount of hours needed according to the post-calculation can sometimes be three times the amount of hours planned for in pre-calculation.

The production order mix encompasses all the variability that is caused by the different types of X systems that are being requested by customers. For example, one month Company Y could be required to make no X systems of type A whilst in the next month, they are required to make several hundreds of them. This results in the fact that balancing the X production line is very hard, and that effectively making use of production resources at hand every month is difficult.

To lessen the effects of the sources of variability mentioned above and thus improve the performance of the production line, the following 4 main recommendations are made to Company Y.

1. Company Y should consider changing the lay-out of their production line from their Original configuration to the X 500B configuration. The X 500B is more resilient to variability, evident from the fact that the standard deviation of the average throughput time between different months (all representing different production order mixes) is reduced from 8.5 hours to 3.47 hours. In addition, the average amount of WIP is also reduced with 30%. Furthermore, an OTP improvement of 0.2%-1.5% is achieved with the alternative production line lay-out depending on the production order mix that month.

2. Company Y should actively try to reduce the amount of X components that are not industrialized, because non-industrialized components results in issues arising at the planning department and in the production line. The non-industrialized components are the main reason for the fact that the amount of hours needed (Post-calculation) is three times the hours planned (Pre-calculation) at certain tasks. This results in the planner not scheduling enough workers to deal with peaks in workload during certain months. This in turns results in systems spending more than a week to long in the production line and production tasks being barely utilized or over utilized. There is however a trade-off since industrializing all components would not make sense due to all the engineering hours needed for this. Company Y could however consider increasing the amount industrialized components by changing the threshold for industrialization. Currently the threshold for industrialization is: components that are used in roughly 5% of all systems, this could be changed to 3%.

3. Company Y should consider implementing a different way of monitoring the performance of the X production line. Instead of monitoring the X production line with the current high level KPI takt, Company Y should consider using a different KPI that is based on the total workload of a specific system, opposed to the amount of fields a system contains. Company Y could implement such a system, by logging the amount of hours planned for a system upon a system leaving the section. This would contribute to resolving the issue of having no clear insight into how many hours have been processed at the different production tasks in a day and will thus help with identifying inefficiencies.

4. One of the first things noticed during the graduation period at Company Y was a disconnection between the different departments at Company Y. And although this phenomenon is inherent to a company like Company Y, this is particularly problematic at Company Y because of the fact that the Sales department can sell a large array of X configurations that all have a large impact on the performance of the production line (Parente, 2002). There are several ways to combat the disconnection. One possible solution would be to use the multi stakeholder decision tool (MSDS-tool) developed by Cyriel van Oorschot (Van Oorschot, 2017). With the help of the MSDS-tool all stakeholders will be able to view the impact of their decisions on the performance of the production line, which will result in debate and better mutual understanding.

Contents

List of Acronyms

- **ETO:** Engineer to order (Meaning that a company is willing to develop a unique solution for a problem that a customer presents).
- **ATO:** Assemble to order (Most parts are stocked, and only have to be assembled)
- **MTO:** Make to order (Several parts still have to be ordered)
- **LLI:** Long lead time items (Items that require materials that have a long lead time)
- **OTP:** On time to promise (The percentage of products that are delivered upon time).
- **VSM**: Value stream map
- **DES:** Discrete event simulation
- **JIT:** Just in time
- **FTE:** Full-time Equivalent
- **SAD:** Simulation activity diagram
- **CAPEX**: Capital expenditure (Funds used by a company to acquire, upgrade and maintain physical assets such as property, buildings, an industrial plant, technology, or equipment) (Kenton, 2020).
- **KPI**: Key performance indicator

Definitions

- **Takt:** In lean terminology Takt is defined "the rate at which a finished product needs to be completed in order to meet customer demand" (ISIXSIGMA, 2020). At Company Y, the term Takt is used as a measure of output, the Takt stands for the number of fields that are produced in a day.
- **Field:** A field is a term used to specify the amount phase groups a single X system consists of. A X can consist of 1 to 5 fields depending on the type of X.
- **Frame:** Frame is the term used for the outer casing of the X system.
- **Baan:** Baan is the ERP-system used at Company Y
- **Production task:** is a frequently used term for a production step.
- **Workload:** The amount of time a specific X product requires at a Sub.
- **X typical:** A specific X configuration that is often requested by a customer like for example Enexis.

Chapter 1: Real world problem

Section 1.1: Background of the company

Company Y Corporation is a large multinational with locations in the United States, Ireland, China and the Netherlands. Company Y Worldwide is currently employing almost a 100.00 people with an annual turnover of more than x. This research will be conducted at Company Y; Company Y currently employs around 700 people. The focus of Company Y is to produce solutions for the EMEA-region (Europe, the Middle east and Africa). Company Y is currently producing products that are used in all levels of the power grid.

Company Y 's product portfolio falls within the Power distribution division (PDD). More specifically within the Electrical solutions and services (ESS) division; this division focuses on the production of medium and low voltage switch gear systems and motor control systems (Company Y, 2019). This division offers complete project solutions to companies, even going as far as to engineer to order (ETO) certain customer requests. The subject of this research will be with one product included in this division, namely the X. The X is a medium voltage switch gear system that is unique because it offers customer specific solutions, in addition to lifelong service deals. The medium voltage switch gear system market is quite saturated, so it is important for Company Y to stand out.

Company Y has a strong hierarchal management structure. Furthermore, the staff at Company Y is divided into departments that all have their own area of expertise. I will be conducting my bachelor thesis at the manufacturing engineering department.

Section 1.2: The X product

As previously mentioned, the focus of this research will be the X. The X was introduced in the year 2002, and it was and still is unique, in its safety, durability, environmental and user friendliness. It was one of the first mid-voltage switch gear systems that was able to operate without the usage of the highly toxic SF-6 gas. After 18 years the X has arrived in the maturity phase of its lifecycle. Because of this, competing on production cost has become increasingly more important.

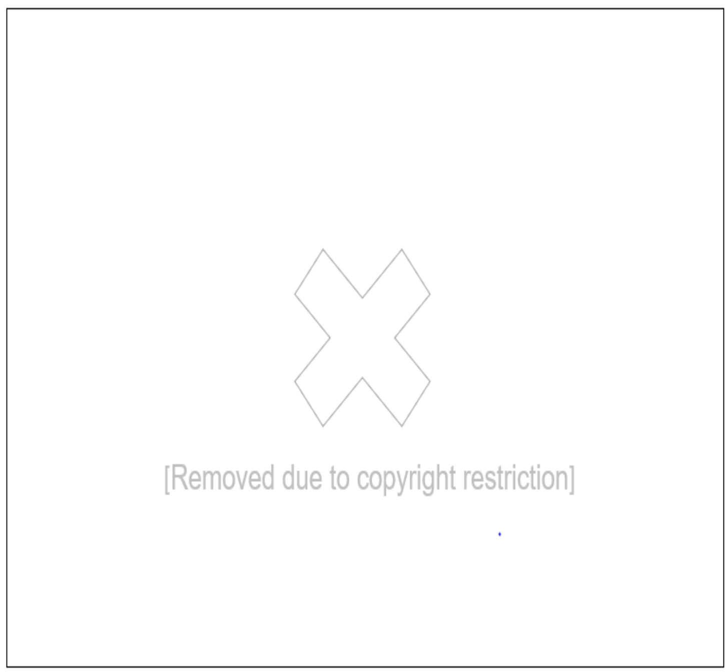


Figure 1: An example of a X Ext. system (Company Y, 2019)

Figure 1 is an example of a X. The entire structure is called a X system. A X system consists of a certain number of frames. These frames are joined with the help of a coupling point. The X in Figure 1 consists of 2 frames. A frame then contains a certain number of fields, the term field is important to remember because the number of fields produced in a day (the Takt) is the main KPI used to monitor the performance of the line. The system in Figure 1 consists of two frames both containing two fields. A field basically refers to a phase group. X systems all contain a certain amount of phase groups. The more phase groups a system contains the more circuit breaks it can make generally.

Currently the X product portfolio is viewed from two different perspectives, which has to do with the fact that the different departments are operating in their own bubble. One way of viewing the X is from an inventory management perspective. This perspective is invented by the Supply Chain department at Company Y.

This perspective proposes to divide the X into three different categories, based on how their raw materials are stocked. These three categories are: the basic, the plus and the special. The basic products are all assemble to order (ATO), which means that their raw materials are stocked at the production line at all time. The plus products are all make to order (MTO), which implies that their raw materials are not stocked at all time. This means orders have to be placed before production can start. Upon arrival, these raw materials are kept in the warehouse. The products and their Bill of materials are however, registered in the ERP-system. Meaning the supplier and the lead times are known. Lastly the special category, these products are engineered to order (ETO). The process of manufacturing these products is unknown. The material requirement is not known as well, and suppliers still have to be found, these products frequently fall in the long lead time items (LLI) category.

On the other side of the spectrum we have the perspective used by the manufacturing department. The manufacturing department looks at the X from a production perspective. They divide the X in two main categories namely, the standard and the special. The division is made based on the frequency at which that X configuration is produced. The perspective chosen in this research is derived from the manufacturing perspective. We will split up the portfolio into two categories namely the standard and the special. The standard product will go through a certain group of production steps that are all part of the main line, before going to expedition. The special on the other hand, will enter the special section, after passing through the main line.

Section 1.3: The X production line

The subject of the research will be the X production line. In this part of the research a short introduction to the production line will be given, further information can be found in chapter 2. The X production line can be divided into two sections namely the standard section and the special section. The standard section is configured in a line, with a flow from start of production to expedition. Whilst the special section is configured in a cell structure. The difference in structure between the two sections results in various issues, like the fact that the total production cannot be monitored with the help of one KPI. The difference in lay-out can however be motivated when we investigate the product structure of the X. X systems entering the special section are allocated to a specific cell based on their configuration.

Every order that enters the production line is accompanied with an information binder; in this binder information can be found regarding the configuration of the order. A step in the production process can only commence when the information binder is passed on from the previous production step. The introduction of the information binder is however not considered the start of production, which seems counter intuitive. The standard section of the production line is output oriented; its performance is judged on its achieved takt levels in a day i.e. the number of fields produced. Initial research indicates that the standard section of the production line is mostly well organized and optimized, according to most of the stakeholders. In the special section of the production line secondary functionalities are added to the standard X. Some of these functionalities are industrialized, which means their processing times and raw material requirement are known. The special section of the X production line is currently being overhauled. The project is called the X 500, and its goal is to improve the performance of the special section. More specific, the X 500 project seeks to achieve a couple of goals namely, scaling up the special section, creating a line configuration instead of a cell configuration and trying to create more buffer space (Hek, 2019). More information on the X 500 project can be found in Appendix A.

Section 1.4: Problem identification

Section 1.4.1: Problem statement

The X production line at Company Y is a complex ever-changing environment; changes are even being made during my graduation period. The initial problem and the reason I was contracted by Company Y was: a lack of insight into the inner workings of the X production line, and the solution of a simulation model was suggested. This suggestion was made because the head of the manufacturing department mentioned that he had trouble convincing his colleagues at the other departments of new ideas, because his claims lacked quantified data. An example of such an idea is changing the lay-out of the production line. The second reason stemmed from the fact that a previous intern had made a simulation model for the planning department. The model sought to give more insight into the effects of sequencing and planning control (Salomons, 2019), and the head of the manufacturing department wanted a model that was tailor made for his own department.

During the first few weeks spent at Company Y, the production levels were low compared to the average level of last year. During these weeks, the production line was performing well: production goals were met and the on time to promise (OTP) was about x%. However, the X production line was not functioning up to these standards at higher production levels. Evident from historic data and interviews. Last year the takt was about 65 systems per day in certain months, which is high compared to the current takt of 40. The high production level caused the production line to perform subpar evident from a.o. a low OTP of x%. This became the starting point for my problem cluster.

Section 1.4.2 Scope of the research

Before the problem can be further dissected, a proper scope must be delineated. Looking at the total order process, from the initial order to eventual expedition puts the production process in perspective. A X typically has a lead time of 6 to 8 weeks, about 2 of these weeks are reserved for production. The planning department starts scheduling orders solely based on their promised delivery date. They do this by using a Just in-time (JIT) policy. Every order is scheduled based on their throughput time that consists of their processing times in the ERP-system Baan, and some rules of thumb and common sense. Since our research will be conducted at the manufacturing department only the production process will be considered. Which means problems considered should fall within the portfolio of the manufacturing department.

For example, issues identified with the sales strategy will not be relevant in this research, since the manufacturing department will not be able to effectively change this. The portfolio of the manufacturing department consists of the following elements: maintaining production line efficiency, establishing KPI's and making sure these KPI's are attained and creating business cases for replacement of manufacturing tools etcetera. (Company Y, 2018). This means the focus will not be on problems like, material availability, product innovations information systems and scheduling. But the focus will lay on production line optimization, by balancing the line and dissolving bottlenecks. Viewing problems from one perspective does have the disadvantage that the researcher might lose track of the larger scope of the issue.

Section 1.4.3: Problem cluster

With the scope delineated and the problem identified. We can start dissecting the problem with the help of a problem cluster. Some of the relations shown in Figure 2 will be explained in more detail below.

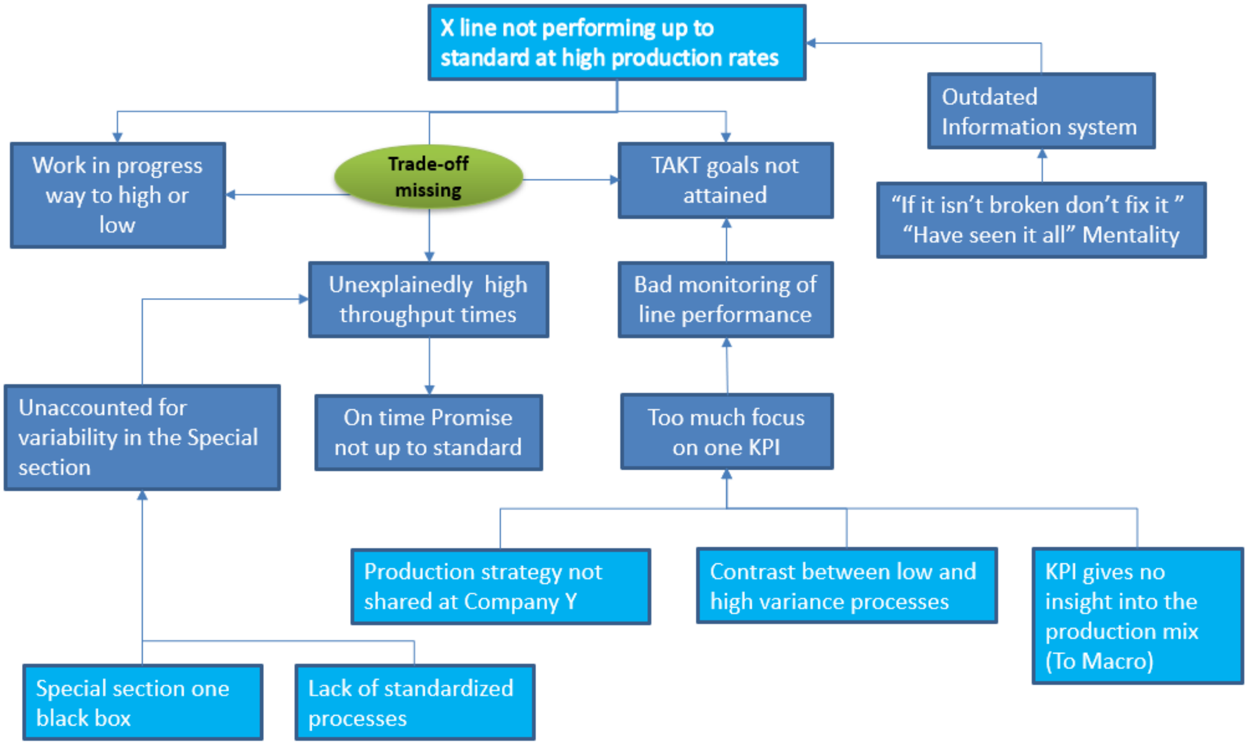


Figure 2: Problem cluster

The first sign of the line not performing up to standard is the fact that the takt goals are not met. At the beginning of each planning period, takt goals are set for each day in that period. These takt goals are used to evaluate the performance of the production line on a day to day basis. Secondly the WIP is too high or low at certain production steps. If the WIP is high, throughput times will quickly get out the hand. Whilst low WIP levels can cause problems like low utilization. Thirdly, the throughput times tend to be unexplainably high. The trade-off between these three phenomena's is easy to explain with the help of Little's law (Winston, 2004), but Company Y does not use consider this relation when waking decisions.

Takt goals are not met because production line performance is badly monitored among other reasons. This is caused by too much focus on one KPI, namely the takt. The first issue with this being that the KPI takt is to high level. Since the takt only specifies the number of fields that are produced in a day. Thus, not specifying the kind of orders that are being produced. This is an issue, since different X configurations have different workloads. The second issue being that the production strategy is not shared throughout the entire production line, evident from the fact that the standard and special sections are configured in different ways. Thirdly the contrast between the low variance processes located in the standard section, and the high variance processes located in the special section. One of the reasons for this disparity is the product-mix. Since tasks performed in the standard section are similar in workload for most of the different X systems, whilst the workloads for the different X configurations in the special section differ substantially. The unexplainably high throughput times mentioned above, result in a bad production plan adherence and thus a low OTP rate. Since the unexpected throughput time means that products spent more time in the line than planned for. This indirectly results in a low OTP-rate since the products are planned according to a JIT strategy. The unexplainably high throughput times are caused by the effects of various sources of variability in combination with a high utilization. These sources are largely unaccounted for, because of a lack of industrialized processes in the Special section, and the fact that this section is treated as a black box planning wise.

Section 1.4.4: The Core problem

A lack of quantitative information on the influence of different sources of variability on the performance of the special section of the X production line at Company Y.

The core problem was selected for various reasons. First, this core problem tackles several issues by looking at multiple sources of variability. This can be a benefit since we can solve multiple issues at once. But this can also be an issue, since the problem can quickly become big. Proper scoping throughout the duration of this research is therefore important. The second reason for picking this specific core problem, was hearing the needs of the X 500 project stakeholders. The X 500 team identified variability as a problem and was looking for ways to reduce it. The third reason is that the special section of the X production line can be considered as a black box in its current form. Not a lot is known about the way specific parts of the production line perform and interact. Mapping out the special section and modeling it will therefore be a helpful extension to existing research. This also ties into the desire, expressed in the initial interview at Company Y by the head of the manufacturing department. Most importantly, finding out the influence of variability on the production line will enable us to make the right choices when looking to improve the performance of the line.

Section 1.5: Report outline

With the core problem identified we can start our research. In this section a quick overview of the structure of the research will be given, and the research questions that need to be answered for the core problem to be solved will be stated.

- **Chapter 2** will define the current situation.

  What is the current situation at the X production line at Company Y?

  a. *What is the exact relation between production line performance and the output level at the X production line?*
  b. *How does the X product structure look?*
  c. *How are the different production tasks organized and connected to each other, and which can be considered as a bottleneck?*
  d. *What are the different sources of variability affecting the performance of the X production line?*

- **Chapter 3** will contain literature research needed for the successful completion of the simulation study.

  What is the best way to conduct simulation study given the specific conditions of a manufacturing system like the X production line at Company Y?

- In **Chapter 4** the conceptual model that defines the contents and the objectives of the simulation model is specified.

  How can we turn the X production line described in chapter 2 into a Simulation model that is sufficiently accurate for our purposes?

- In **Chapter 5 we** will conduct experiments that hopefully give insight into the impact of variability and the best way to deal with it.

  How do the identified sources of variability affect the performance (of the Special section) of the X production line?

  What is the best way to improve production line performance by lessening the impact of variability?

- The contents of **Chapter 6** will summarize the contents of the previous chapters by answering the core problem. In addition, an overview will be given of all the possible solutions Company Y could use to solve the core problem and improve the performance of the production line. The following problem will be solved:

  A lack of quantitative information on the influence of different sources of variability on the performance of the special section of the X production line at Company Y.

  In addition, the following question will be answered:

  What can the manufacturing department do to improve the performance of the production line?

Chapter 2: The X production line

In chapter 2 of this research we will research the current performance of the production line in detail. By doing this the following research question and its sub questions will be answered:

What is the current situation at the X production line at Company Y?

a. The question: What is the exact relation between production line performance and the output level at the X production line? Will be answered in section 2.1.
b. The question: How does the X product structure look? Will be answered in section 2.2.
c. The question: How are the different production tasks organized and connected to each other, and which can be considered as a bottleneck? Will be answered in section 2.3.
d. The question: What are the different sources of variability affecting the performance of the X production line? Will be answered in section 2.4.

The result of chapter 2 will be the starting point for the conceptual model that will be created in chapter 4, and it will also motivate the use of simulation modelling in this research.

Section 2.1: Current performance production line

In chapter 1 the observation was made that the (special section of the) X production line is not performing up to par. In this section we will quantify these claims. As mentioned before the total X production line is currently assessed solely based on the attained takt. The term takt is derived from the indicator takt time commonly used in lean philosophy. Takt time is defined as:

$$Takt\ time = \frac{Available\ production\ time\ per\ day}{Amount\ of\ fields\ scheduled\ in\ a\ day}$$

Equation 1: Takt time

For the X production line this implies the following: the line operates in shifts, currently one shift a day is used. However, two shifts are sometimes used. A shift starts at 7.30 and ends at 16.00 with several breaks that add up to one hour. Meaning that the available production time is 7.5 hours. If for example the planning department decides to schedule 50 fields a day then the takt time has to be 9 minutes, this means that every 9 minutes the production of one field should start in order for a takt of 50 to be realized.

In Figure 3 the average takt levels during 2020 (January-April) and during 2019 are shown. The output levels in 2020 are lower because of seasonal demand and the ongoing COVID-19 pandemic. Before we can find the relationship between output level and production line performance, the indicator used to measure the performance has to be defined. Production plan adherence is currently used to measure the extent to which the takt is attained:

$$Production\ plan\ adherence = \frac{Actual\ amount\ of\ fields\ started\ in\ a\ day}{Amount\ of\ fields\ scheduled\ to\ start\ in\ a\ day}$$

Equation 2: Production plan adherence

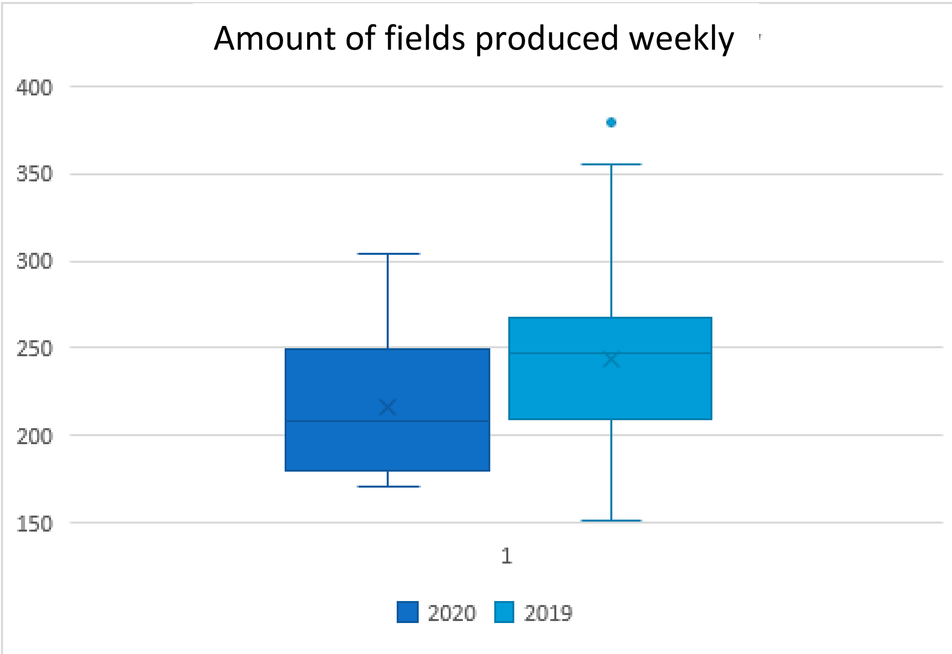


Figure 3: Weekly output (takt) levels for 2019 and 2020

During 2019 the average output level was 244 fields per week, which coincided with an average production plan adherence of the total production line of x. However, during weeks in 2019 the adherence was even lower. During these weeks, the takt was higher than 300 or many X Extendable (Ext.) /Specials were being produced. If we compare this to 2020, we can come to interesting conclusions. The average output in 2020 is 217 fields per week, which coincided with a production plan adherence of x. Which suggests that there is a correlation between output level and production line performance. The correlation between these two variables is not strong, which has to do with variability Like for example stock outs, machine breakdowns and the amount of shifts used. Further analysis is included in Appendix B.

The OTP being subpar is already mentioned in the problem cluster. One of the reasons for this is that the OTP is closely related to the production planning adherence. Since not starting production on time combined with an JIT policy, results in broken promises. Last year the overall OTP was x, whereas the goal set for that year was x. This suggests that the line is performing fine. However, the OTP of the X Ext was x, which means that the special section of the X production line performs worse than the standard section since all X Ext. visit the Special section. Data on the OTP of the total special section is not kept; the OTP of the X Ext is therefore used as an indicator. These OTP levels become really problematic if you take into account the long-term OTP goal pursued by Company Y of x.

After evaluating the total production line, we will now evaluate the separate sections. The standard section is monitored by assessing the takt attained by the individual tasks defined in section 2.3. Evaluating these tasks will not be interesting, since these tasks are already mostly well optimized. The special section on the other hand is judged as a whole, based on the KPI capacity.

$$Capacity = \frac{Hours\ available\ for\ all\ the\ orders\ processed\ in\ month\ x}{Hours\ used\ for\ production\ during\ month\ x}$$

Equation 3: Capacity

First the process behind the calculation of the capacity is interesting to look at. The finance department releases an initial estimation of the number of hours that should be used for production in that specific month, somewhere in the middle of that month. The supervisors and the team leaders responsible for the day to day performance of the line have then already assigned workers to the different tasks but will use this estimation to make sure the hours spent do not get out of hand. At the end of the month they return the number of hours used to the finance department. Where after the actual hours that were available for production are calculated by looking at the orders that were finished during that month, and a final assessment of the capacity is made during the next month. From this description we can conclude that feedback and estimations are given too late. This shows in the average capacity of x attained in 2019, which is low compared to the goal of x%. Low capacity is caused by variability that will be further discussed in section 2.4. More analysis can be found in Appendix B.

From the current performance analysis, we can deduce that the production line is not able to attain the goals set. In particular the special section when output levels are high. The analyses will form the basis for our modeling objectives. Effects of the improvements made to the X production line will be measured with the help of the KPI's defined above.

Section 2.2: The X product

After having assessed the current performance of the production line, the product processed on the line can be researched. As explained in chapter 1, the X is a complex product that is highly customizable. In this section we will give an overview of its product structure, and a selection of X types that should be included in this research will be made. This selection will be made because including all configurations is almost impossible and inefficient. The selection will be made with the help of the Sales team and the manufacturing engineers.

In Figure 4 the product structure is given graphically. There are four types of X systems namely: Extendable, Block, Fused and Metering. The fused and the metering panel will not be included in this research due to their relatively low frequency compared to the Extendable (Ext.) and the Block. The main difference between the Block and the Ext. is that the latter can be ''coupled''. Coupling is done in the special section, and the goal of the process is to connect several frames to each other. This allows for more customizability. During 2019 approximately 45% of the systems processed were Ext. and 55% of the systems were Blocks. Every non-coupled X system consists of one frame, each frame than contains a certain number of fields as mentioned before. The average amount of fields per frame during the year 2019 was 2.6 fields. All X systems that enter the Special are considered special. Whilst all X systems that do not enter the special section are considered standard. More detailed information on the X product structure can be found in Appendix C.

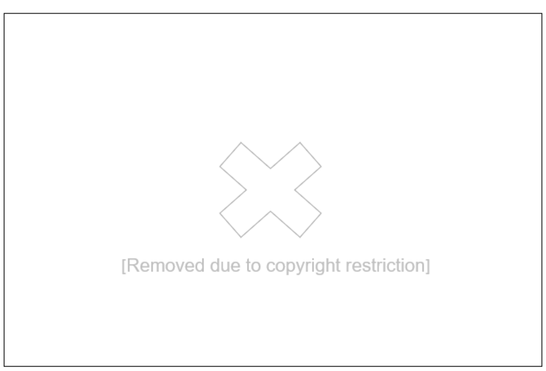


Figure 4: Different types of X included in this research.

Section 2.3: The current production line

Section 2.3.1: Overview of the production line

The performance of the production line and the products produced on the line are analyzed, which allows us to study the production line in more detail. As already mentioned in section 1.3, the production line can be divided into two sections. These sections consist of so-called production tasks. Production tasks are a collection of processing steps that are all grouped together in the ERP-system Baan under the same task number. In this section we will describe these tasks in more detail; specifying the nature of the activities and the tools used and give information on how they are connected to each other. For a graphical overview see Figure 5. Deviations from the standard production process are not shown in Figure 5 although they are mentioned in the text. This is done to keep the Figure readable. Furthermore, a more extensive overview of the line is given in Appendix D.

1. Subs various components (5319)

At the Subs various component task, the information binder is introduced, for some people this task is the start of the line. At this task, a variety of front modules are manufactured that are put into the X system at later stages of production. The Subs section consists of 4 to 5 identical workstations at which one worker can manufacture front modules. Where after the information binder travels to the Frame pre- assembly 1 task.

2. Frame pre-assembly 1 (5316)

At the Frame pre-assembly 1 task an appropriate frame is selected, and some minor activities are performed. After that, the frame and the information binder are sent to Frame pre-assembly 2.

3. Frame pre-assembly 2 (5322)

Here the frame is mounted on a cart with the help of a crane, and some more minor activities are performed on the frame further preparing it for eventual assembly. From this task the information binder and in theory the frame travel to the Bosch-line, in reality this is not the case, but we will explain this in more detail below.

4. Bosch-line (5321)

The Bosch-line can be viewed as a mini production line on its own, that consists of several sequential processing steps all executed by one worker. The fields first introduced in section 1.2 are assembled here. Towards the end of the Bosch-line the fields are mounted into the frame with the help of a crane, this process is called the marriage. The frames needed for the marriage are in theory always present at the Bosch-line, since the information binder should travel with the frame from the Frame pre-assembly 2 task. In practice however the information binder is often moved to the Bosch-line ahead of the frame. From the marriage onwards the information binder will stay with the system, for this reason the Bosch-line is considered to be the real start of production by many. The Bosch-line is also the most labor-intensive part of the line, 10 to 12 workers are needed to operate all stations. The system and the information binder are then brought to the Various component task.

5. Various components (5323)

At the Various components task the front modules prepared at the Subs task are built into the X block systems. The front modules prepared for the X Ext. system are assembled in the special section, although the assembly process for the Block and the Ext. are the same. This seems illogical so I asked if this was done due to capacity constraints at the various component task. The team leader responsible for this task assured there is enough capacity, exploring this statement might thus be interesting. From the various components task the system travels to primary testing.

6. Primary testing (5353)

Good quality is one of the X's selling points, because of this X systems must go through 2-3 testing stages depending on its type. The first test is called Primary testing; here a visual check and a high voltage test are performed on all the systems. Visual inspection requires a worker to go through a checklist, making sure that all the primary parts are correctly assembled. The high voltage test is performed by well trained workers, this step is dangerous, so it has to be performed in one of the two testing cells. Important to mention is that the primary testing station is one of the two stations that can send systems to the rework section if a quick fix is not possible. More about this rework section in section 2.4. From the primary testing task, the system is passed on to the Final assembly task.

7. Final assembly (5325)

At the Final assembly section the X system is closed with the help of some sheet metal, and to make sure some compartments of the frame are airtight glue is added. The glue then must dry for approximately 2 hours, where after a leakage test and some minor activities can be performed. From here the flow of the X splits in the following three directions:

1. The standard X Block will be passed on to the Secondary testing task.
2. The special X Block will be brought to the Electrical finishing task.
3. The X Ext. is passed on to the Remote finishing section.

8. Secondary testing (5356)

At the Secondary testing task all the secondary components of the X system are tested, to make sure these are also up to standard. The Secondary testing task is also able to send systems to the rework section. Some of these tests also involve high voltages which means these tests also must be performed in testing cells, currently there are 14 testing cells available for Secondary testing. Successfully tested systems are passed on to the End of line assembly task.

9. End of line assembly (5332)

Here the last assembly tasks are performed like the mounting of doors and covers, before the system is sent to expedition.

10. Electrical finishing (Special section) (X Block) (5326)

As explained the special X block systems are passed on to the Electrical finishing task, here extra features are added to the system like current transformers or voltage transformers. Before workers can start assembling, the systems have to be hoisted on a workstation by one of the two available cranes. After these extra features are added, systems are either passed on to the Chimney and plinth task, or to the Secondary testing task. Although certain systems also visit the plinth section first, the reason for this deviation is not clear.

11. Remote finishing (Special section) (X Ext.) (5327)

The X Ext. systems are all passed to the Remote finishing section from the Final assembly task as explained. Here the front-modules prepared at the Subs various components are built into the system among others. Apart from this the Remote finishing and the Electrical finishing tasks are very similar. X Ext. systems are then sent to the Measurement & coupling task in certain cases or they are sent to the Chimney and Plinth/Secondary testing task.

12. Measurement & Coupling (Special section) (5329)
In the Coupling section X Ext. are coupled together. Coupling requires a track and a special crane; systems are hoisted onto the track where after coupling can take place. Currently there is only one track and crane available. After coupling systems are taken to the Chimney and plinth task or they are sent to the Primary testing task.

13. Chimney and plinth (Special section) (5328)
The special X Block flow and the X Ext. flow meet up again at the Chimney and plinth task, here a chimney or a plinth are assembled onto certain configurations. Where after Special X blocks are sent to the Top-unit task immediately. Whilst the coupled X Ext. systems need to be tested again since a coupled system also needs to pass the high voltage test. Which means certain X Ext. will pass through primary testing a second time before being sent to the Top-unit task.

14. Top unit assembly (Special section) (3712)
The last task in the special section is the Top-unit assembly. Here a top unit is occasionally placed on top of the Special X Block and the X Ext. passing through. This depends on the wishes of the customer, since certain options require extra space in the form of a top unit. The mounting of the Top-Boxes takes place physically at the Electrical finishing task or the Coupling task depending on the type of X, whilst the hours are industrialized under the task 3712. Both flows than resume the standard process by being passed on to the Secondary testing task.

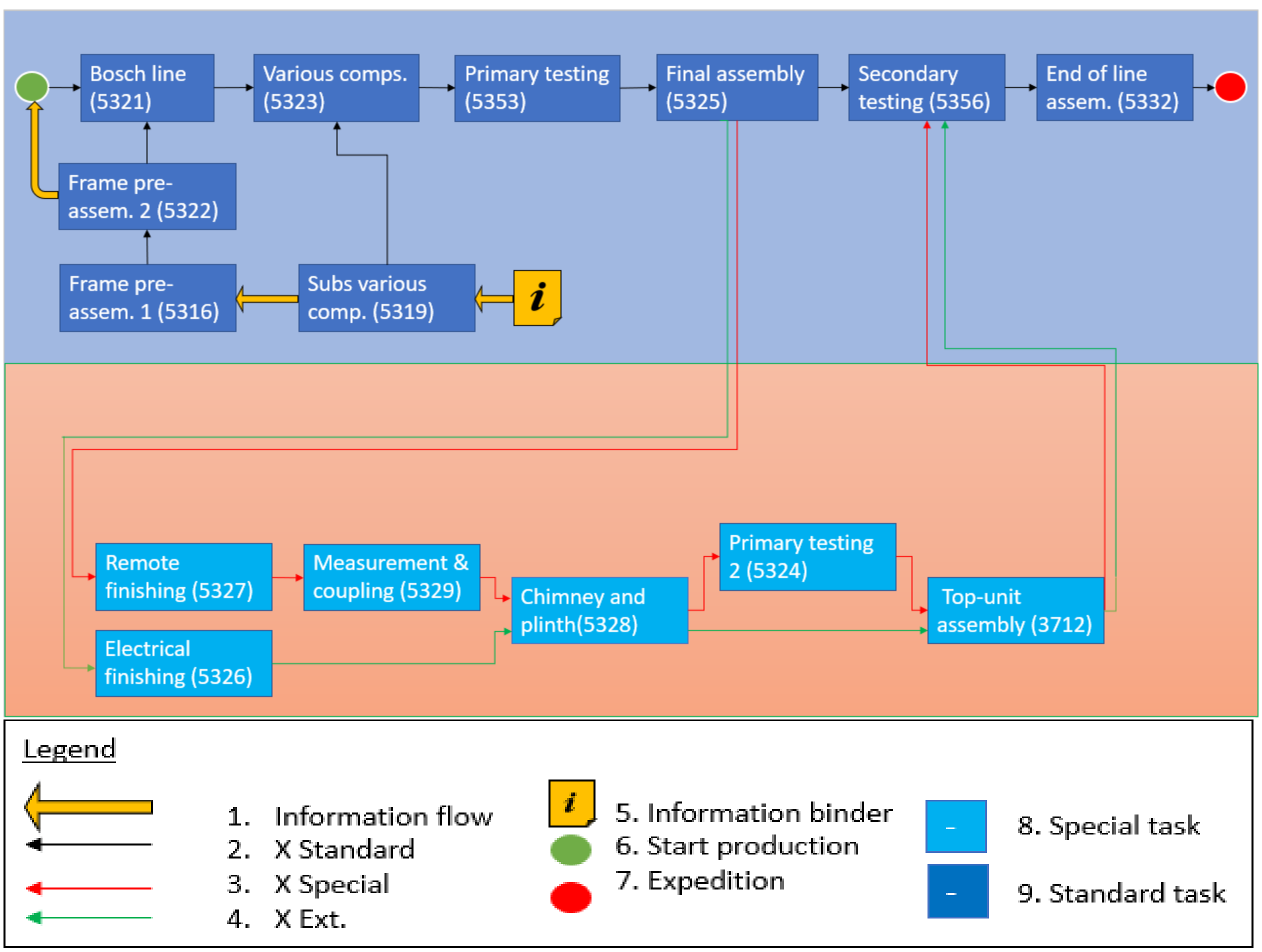


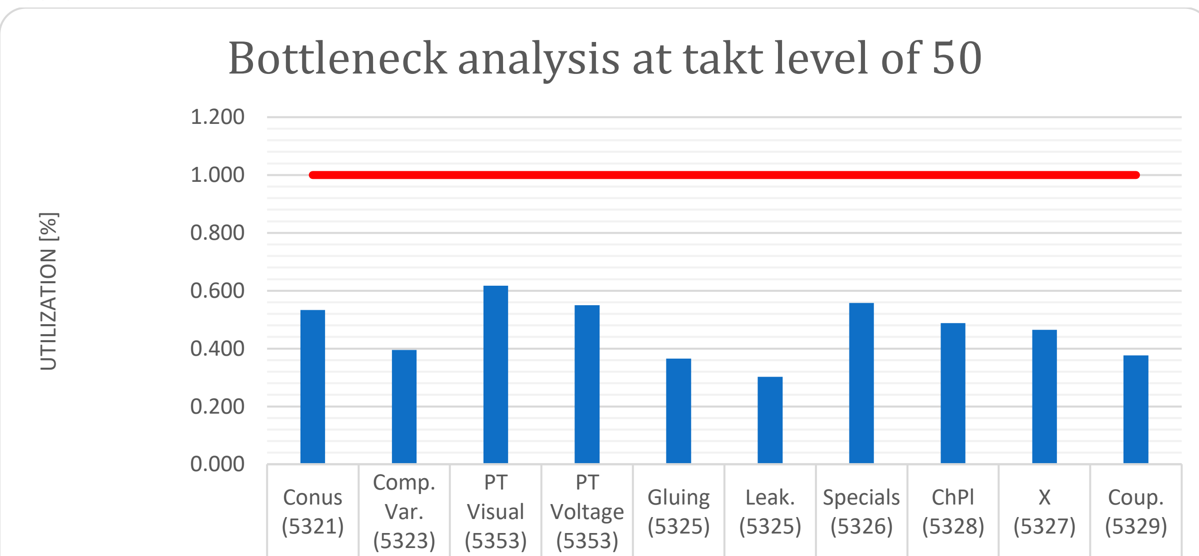
Figure 5: Overview of the X production line

Section 2.3.2: Bottleneck analysis

In section 2.3.1 an overview of the X production line is given, it specifies what it is that happens in the line and how it is done. This enables the possibility to study the line in more detail and identify potential bottlenecks. The bottleneck analysis will form the basis for the experiments that will be conducted. The bottleneck analysis will assess the adequacy of the capacity of several production steps at different output levels, by comparing the capacity of the steps to the theoretical workload they would have to process. The capacity of the steps considered is calculated in the following way. All the steps considered in the bottleneck analysis consist of a certain amount of identical workstations, and with the assumption that a workstation is equal to one full-time equivalent (FTE) we can express the capacity of a step in an amount of available processing time in minutes per day. This assumption can be made because although several people can work at one station. Generally, this does not happen because the slight increase in processing time does not cover the cost of an extra FTE.

The theoretical workload mentioned above is calculated by translating a certain output level into an amount of processing time per processing step, by considering the average product-mix over the year 2019. For example, 20% of all systems produced in 2019 had to be coupled, which implies that at an output level of 50 systems, on average 10 systems have to be coupled. The amount of systems that have to be coupled is then multiplied by the average cycle time at the coupling step according to Baan, resulting in the theoretical workload.

All production tasks have already been identified in section 2.3. An overview of all the production steps of which a production task exists, and their exact average cycle times can be found in Appendix D. The average cycle time of ta step in the standard section is specified for a system containing one field up to a system containing five fields. For processing steps located in the special section the average cycle times are specified per system, due to the possibility that not all fields inside a system are given an extension when they enter the special section. Two possible output (takt) levels will be considered in the following analysis, a takt level of 50 and 75. This choice was made because a takt level of 50 coincides with a production day without performances issues, similar to the past few months. Whilst a takt level of 75 coincides with a production day plagued by performance issues similar to several weeks in 2019.



	Conus (5321)	Comp. Var. (5323)	PT Visual (5353)	PT Voltage (5353)	Gluing (5325)	Leak. (5325)	Specials (5326)	ChPl (5328)	X (5327)	Coup. (5329)
Utilization	0.534	0.395	0.617	0.549	0.365	0.302	0.558	0.488	0.465	0.377
Max utlilization	1	1	1	1	1	1	1	1	1	1

Figure 6: Bottleneck analysis at a takt level of 50 fields.

In Figure 6 an overview of the amount of available FTE and thus workstations are given. In addition to the amount of FTE and thus workstations needed to attain a takt of 50. In Figure 6 only a selection of steps is reviewed. This selection is made with the help of the manufacturing engineers and frequent visits to the production line. There are several reasons for why a step can be excluded from the analysis, for example: The secondary testing step is excluded because it currently only uses half of its stations even at higher output levels. Whilst the majority of the Bosch-line is excluded from this overview, since the Bosch-line does not suffer a lot from variability.

Figure 6 shows that at a takt level of 50, there are no real utilization problems. This is in line with the conclusion that was made at the end of section 2.1, since the conclusion was made that the production line is able to perform well at lower takt levels. Another conclusion that was made at the end of section 2.1 was that the production line does not function well at higher takt levels. In Figure 7 an overview of the number of workstations needed at a takt level of 75 is given.

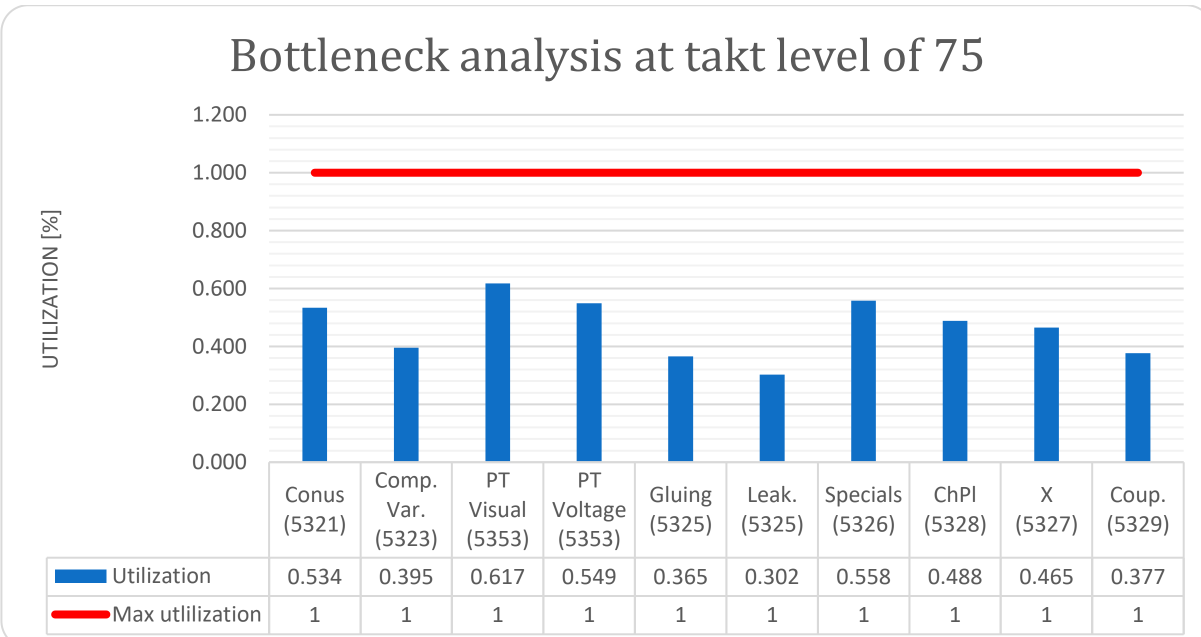


Figure 7: Bottleneck analysis at a takt level of 75 fields.

From Figure 7 some interesting conclusions can be made. All the production steps are functioning at almost maximum utilization; the Specials step even has a utilization of over 80%. This becomes even more problematic if we factor in the fact that the theoretical workloads assume no variability. In the standard section of the line this assumption will not have large consequences since the production steps are similar for all the different X configurations that pass through it. For the special section however, this assumption becomes a problem, since the processing times of the systems that enter this section can differ widely. In addition to the amount of systems that enter this section in a day. Furthermore, the special section should never be fully utilized because some of the capacity should be reserved for ETO products. ETO products still need to be engineered and assembled; assembly is done in the special section. Time that is needed for assembly is not considered in the planning process; the planner just assumes that there is always enough capacity for these ETO products.

In conclusion, we can state that at higher takt levels the capacity of the Specials and the X Ext. steps is not sufficient when variability is considered. This implies that scaling up these stations could be helpful to combat the impact of variability on the performance of the production line.

Section 2.4: The sources of variability

Now we have a better understanding of the product, the production line, the performance of the line and its possible bottlenecks we can start looking at the reason for the lacking performance. As mentioned in section 2.3 variability has a significant impact on the performance of the production line at all output levels, but especially at higher output levels due to the fact that the production line is operating at max. utilization during these days. Variability is identified to be the main cause for the lacking performance of the line. The production line suffers from two types of variability; variability that is inherent to the process and variability that is not inherent to the process.

First, we will discuss the variability that is inherent to the process. As previously mentioned, the X is a very complex product that leaves a lot of room for customization. And since different configurations require different processing times at the same production step, it is important to consider the impact of these different configurations. Certain configurations even contain parts for which no time is specified at all, or parts that have their assembly time specified but not at any particular production task. More about these configurations in the not inherent section. An overview of the X product structure is given in section 2.2. The different possible product mixes will be the first source of variability considered. The source is incorporated by feeding different months of the Orderbook to the simulation model.

Another aspect of the inherent variability are the fluctuations in demand, it is a known fact that X's are ordered more often just before or during holidays. It is furthermore expected that the demand will grow over the coming years, due to the fact that the EU is banning the use of medium voltage switch gear systems that function with the help of SF-6 gas. The demand fluctuations will be incorporated in the model, by testing the performance of the line at different output levels.

Now we have discussed the sources of variability that are inherent to the process we can go over the sources that are not inherent to the process. The total impact of all the sources of variability that are not inherent is measured as a difference between the total amount of production hours planned and the total amount of production hours used. The total difference over the last year, between the hours planned for production (Pre-calculation) and the hours used for production (Post-calculation) is over x hours, which is equal to x% of the total (Pre-calculation) hours. In order to further analyze the reasons behind this difference in Pre and Post calculation, the total amount of hours will be split up into two categories namely: the hours lost in the rework section and the hours lost in the production line. This distinction is made purely based on the way data is (and more importantly is not) documented in the production line. For example, data on time lost due to raw material not being available is only documented in the rework section.

Before diving deeper into the hours lost in the rework section, an overview of the rework process will be given. There are two ways to solve defects with quick fixes or with reworks. Quick fixes are used when product defects can be solved within approximately 15 minutes; these are than resolved in the production line itself, and they will be incorporated into hours lost in the production line. Reworks are the more time-consuming tasks; these can only be identified at the testing tasks. From the testing tasks these systems requiring a rework are sent to the rework section. The total amount of fields requiring a rework last year was x, this relative to the total output of x fields last year. This results in a first-time yield (FTY) of x% over the entire line. Reworks are incorporated in the model by using the FTY as a rejection percentage at the testing sections. The average workload in the rework section is approximately 8:15 hours per day, which roughly corresponds to one FTE per day. This is in line with reality since the rework section is always occupied by one mechanic. In Appendix F an appropriate distribution is fitted onto the rework data, which will be used in the simulation model.

When a X system leaves the rework system, the mechanic responsible for the rework will specify in an excel file the reason for which the system entered the rework section and the amount of time required for the rework. From multiple stakeholder interviews it became clear that the documentation process is not flawless, which means the data set is not perfect.

An overview of all the reasons for which a system can enter the rework section is given in Table 1. In total there are 11 different possible reasons, these are grouped into three categories namely Equipment, Raw material and Process errors. These three categories were identified with the help of a literature study and interviews with stakeholders. **Process errors** are caused by the Personnel, and it is an important source according to interviews with stakeholders. **Equipment** has a significant influence on product defects according to stakeholders, since information systems are also viewed as equipment. Furthermore, although **raw material** availability and quality falls outside the scope of the manufacturing department, neglecting it is not possible, because of the large impact it has on the performance of the production line. As mentioned, these three categories will be implemented into the model as a cumulative rejection rate at the Primary and Secondary testing tasks. The most common reason given for a system entering the rework section is Error recovery after testing. This reason encompasses all the mistakes that were not previously noticed at other places in the production line.

Table 1: Reasons systems are sent to rework section and their ratios

Task	Meaning	Cumulative [%]	Category
901	Mistakes due to insufficient knowledge	29.8%	Process errors
902	Mistakes due to imprecise processing	31.5%	Process errors
904	Error recovery after testing	71.8%	Process errors
909	Extra processing due to later deliveries	73.7%	Raw material
912	Internal raw material errors	73.9%	Raw material
914	External raw material errors	84.6%	Raw material
915	Work instruction error Sales	85.2%	Equipment
916	Work instruction error Mech. Engineering	89.3%	Equipment
917	Work instruction error Elec. Engineering	92.6%	Equipment
918	Work preparation error	94.1%	Equipment
999	Error caused by machine/material breakdown	96.9%	Equipment
Other	other old 9-codes	100.0%	-

Now that we have discussed the hours lost in the rework section, we can start to discuss the number of hours lost in the production line. The hours lost or gained in the production line are registered at a production task level. The registration process operates in the following way: First a theoretical processing time is set (Pre-calculation), this time is equal to the time registered in Baan. Then after production has taken place the actual processing time is documented (Post-calculation). The theoretical and actual processing times differ for several reasons. Firstly, the process efficiency of the mechanic greatly impacts the difference. Secondly the fact that many configurations are not industrialized, resulting in hours not being coupled to the right task has a big impact on the difference. And lastly all the so-called quick fixes have a big impact on the difference. The fact that there are so many potential reasons for a difference in processing time makes it so that there is no way to effectively reduce the difference, since there is no information on the nature of these reasons. Distributions have been fitted on these differences, the result of this can be found in Table 2. More information on the distribution fitting process can be found in Appendix F.

Table 2: Variability in processing time.

Task	Distribution	Param. 1	Param. 2	LB(Hr.)	UB (Hr.)
5316 Frame pre-assembly 1	-				
5319 Subs various components	-				
5321 Bosch-line	-				
5322 Frame pre-assembly 2	-				
5323 Various components	-				
3712 Top Unit	Lognormal	$\mu = 0.098$	$\sigma = 0.604$	1	15
5325 Final Assembly	-				
5326 Electrical Finishing	Exponential	$\lambda = 0.561$		0.01	25
5327 Remote Finishing	Exponential	$\lambda = 0.561$		0.01	15
5328 Chimney Plinth	Exponential	$\lambda = 0.302$		0.13	10
5332 EOL assembly	Gamma	$\alpha = 2.381$	$\beta = 1.214$	0.08	10
5329 Coupling	-				
5353 Primary Testing	Lognormal	$\mu = 0.218$	$\sigma = 0.629$	0.3	10
5356 Secondary Testing	Lognormal	$\mu = 0.731$	$\sigma = 0.801$	0.36	22.5
Rework	Exponential	$\lambda = 1:54$			

Section 2.5: Conclusion

Chapter 2 sought to answer the research question: ***What is the current situation at the X production line at Company Y?*** And its multiple sub questions. The first conclusion that can be made is that the production line is not performing up to standard at higher output levels. The reason for this being that the high utilization at the Specials (5326) and the X Ext. steps (5327) becomes a problem when we take in to account the sources of variability present in the X production line. One of these sources comes from the complex structure of the X. Another source is a result of the many deviations X workers take from the standard process. All the sources fall into one of the following two categories inherent and non-inherent variability. Due to the complex nature of both the X and its production line it is clear a simulation model is needed to further analyze the impact of the identified sources of variability.

Chapter 3: Conducting a simulation study

From the previous chapters of this research, it became clear that the core problem could only be solved with the help of a simulation model. Conducting a simulation study is a complex process however, and knowledge regarding how to conduct one is lacking. Thus, the following research question has to be answered:

<u>What is the best way to conduct simulation study given the specific conditions of a manufacturing system like the X production line at Company Y?</u>

In the following chapter the framework presented in Figure 8 will be explored further, detailing the best way to conduct a simulation study from this point onward.

Section 3.1: The framework

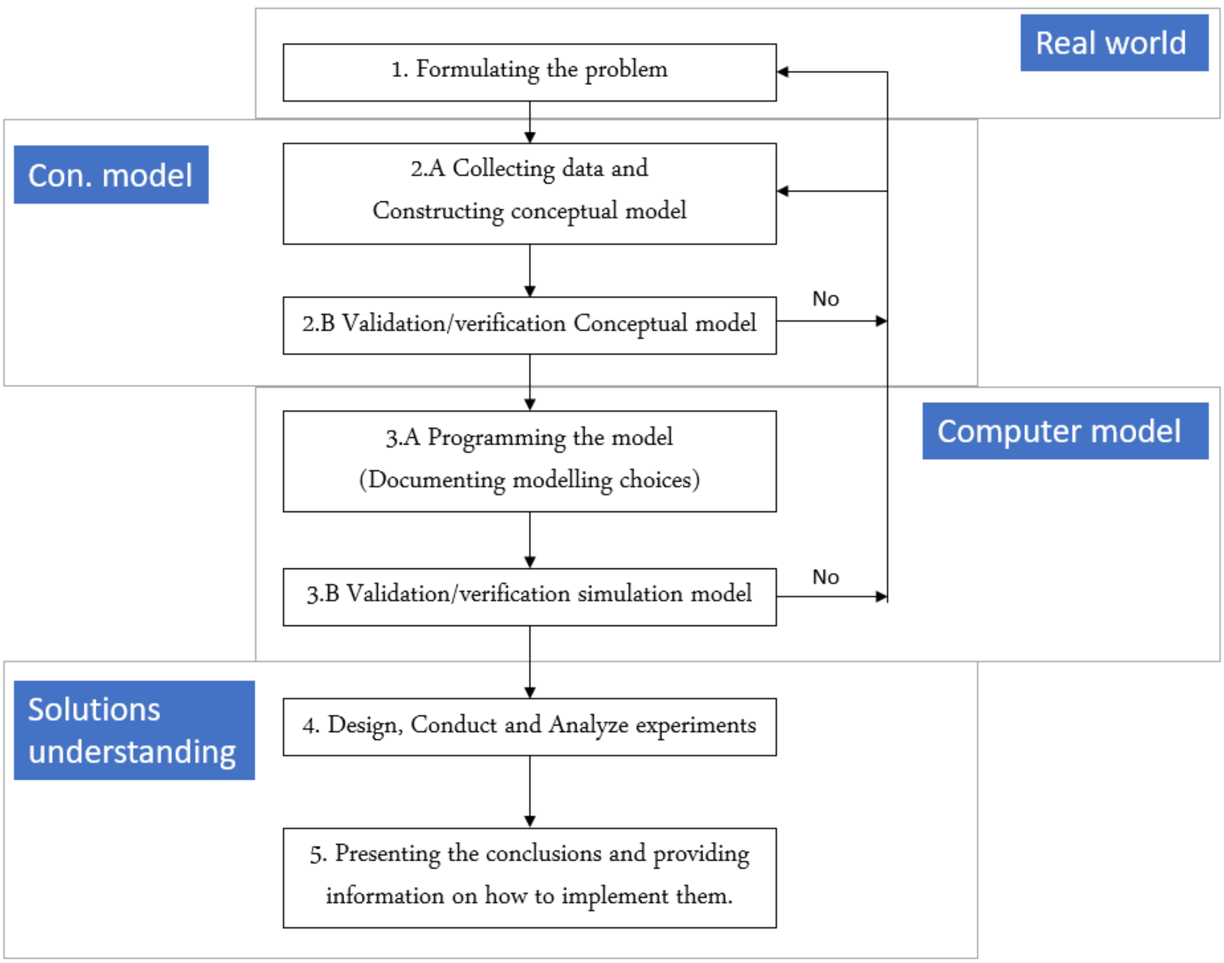


Figure 8: Overview of all steps that must be taken in a simulation study (Robinson, 2004), (Law, 2003).

The first step and part of the second step have thus already been completed since a core problem is identified and some of the conceptual modelling has already been done. Which means steps 2-5 still have to be executed. First, we will look into how the limited time available should be divided over the steps. The best way to allocate your time over the different simulation study steps is (Heavey, 2006)

- 40% of time should be spent on conceptual modeling, experiment design and input data preparation.
- 20% of time should be spent on the modelling itself.
- 40% of time should be spent on conceptual/computer model validation and verification, experimentation, interpretation and implementation.

The second step of a simulation study is conceptual modelling and data collection, and although some of the conceptual modelling has already been done, we will first start defining the concept of conceptual modelling. “Conceptual modelling is the process of abstracting a model from a real or proposed system” (Robinson, 2008 p1). And it has been described the most important activities of a simulation study (Van Der Zee, 2007). Modelling a manufacturing system is difficult since they are often very complex. This complexity is caused by the many factors influencing the performance of these systems (Hernandez-Matias, 2008). The conceptual modelling framework used in this research will therefore be a combination, of the framework proposed by Robinson and the framework proposed by Hernandez-Matias (Robinson, 2004; Hernandez-Matias, 2008).

1. <u>Objectives</u>

A. Organizational aims and Modelling objectives

Before we can start defining the modelling objectives, we have to define the organizational aims, since these aims will form the basis for the modelling objectives. The aims specify what Company Y hopes to achieve. The modelling objectives will form the basis for the criteria upon which our simulation model will be validated. It will also function as a basis for experimentation and criteria upon which we can judge the success of our study (Robinson, 2008). The modelling objectives are an overview of all the data, the researcher hopes to extract from the simulation model.

B. General project objectives

The general project objectives of this research will be organized along a selection of the criteria proposed by Robinson (Robinson, 2008). These objectives will provide insight into the purpose of the model.

- Timescale: The time available for the simulation study.
- Flexibility: The extent to which the real world, upon which the model is based changes during and after the study.
- Visual display: The extent to which visual representation is needed.
- Ease-of-use: Specification of the intended users, and their knowledge of modelling software.

2. <u>Inputs and outputs</u>

Defining our inputs and outputs will be part of our preliminary experiment design, since these lists will define all the experimental factors, and output measures. The experimental factors are the factors that will be changed to achieve the modelling objectives. These factors should thus be related to the modelling objectives. After the experimental factors are established, determining their ranges becomes the next objective. The range specifies between which values the experimental factors can change (Robinson, 2008). The process of establishing these experimental factors is iterative since new factors could pop up throughout the duration of the simulation study. The factors used to measure the results of these tests are the responses. These responses can be viewed as indicators that measure the extent to which the modelling objectives are achieved and should thus be a direct consequence of the modelling objectives.

3. Contents

A. The scope of the model

The scope of the model is meant to identify the boundaries of the model, which factors will be included, and which will not (Robinson, 2008). A general overview has already been given in chapter 2. However, in order to effectively document these modelling decisions another tool needs to be used. The best tool for this is the one proposed by Robinson. This tool organizes all components along four main categories and specifies whether it is included/excluded and the reason for the inclusion/exclusion. To improve the tool proposed by Robinson further, these main categories are then further divided into subcategories as suggested by Hernandez (Hernandez-Matias, 2008). An example of such a Table can be found below:

Table 3: Scope of the research (Robinson, 2008; Hernandez-Matias, 2008).

Component	Include/Exclude	Justification
Entities (Specific parts in the factory, like for example forklift trucks).		
Activities (These are the machine, the processing stations etc.)		
a. Manual operation		
Processing station	Include	Needed
b. Machine operation		
c. Transport		
Queues (Buffers waiting areas etc.)		
a. Delay		
b. Production buffer		
Resources (Staff and equipment)		

B. The level of detail

If the scope of the model dictates how broad the simulation study will be, the level of detail will dictate how deep it will go. Determining the level of detail will be done, by specifying for all the components we have selected at the scope of the model which details will be included. For example, if transport is included in the scope then a decision has to be made regarding transport times, will they be included as a constant or as a distribution for example. The tool used for this is a direct result of the tool identified above.

Table 4: Level of detail (Robinson, 2008), (Hernandez-Matias, 2008).

Component	Detail	Include/Exclude	Justification
Processing station	Capacity	Exclude	Not interesting
	Processing time	Include	Needed

Some of the components might require additional explanation, complex routing logic for example is hard to explain within the Table mentioned above. Activity cycle diagrams and logic flow diagrams are tools that can be used to model such components (Van Der Zee, 2007).

4. Assumptions/Simplifications

In the creation of the scope and the level of detail several assumptions and simplifications will have to be made (Robinson, 2008). In order to translate the real world into a conceptual model. The difference between a simplification and an assumption is: A simplification is made to enable quicker model use/development and an assumption is made when something is uncertain, and when there are certain beliefs about the real world (Robinson, 2008).
Validating and verifying the conceptual model will be **step 2.B** of a simulation study. This process requires the involvement of different stakeholders like the manufacturing engineers. Involving these stakeholders is only possible if the conceptual model is clearly defined. Clearly defining the conceptual model will be a metric upon which its quality is judged. Clearly defining a conceptual model is one of the most overlooked aspects of a simulation study (Robinson, 2020).

Specific metrics upon which the conceptual model is judged should be specified before the conceptual modelling is created (Robinson, 2020). Several papers were studied to construct a list that covers all the aspects of a good conceptual model (Robinson, 2004; Heavy, 2006). The first four criteria are very macro; they provide a general assessment of the quality. Whilst the last five criteria are meant to judge the specific modelling techniques used.

Table 5: Criteria upon which Conceptual model will be judged (Robinson, 2004), (Heavy, 2006).

Criteria	Description
Validity	A perception, on behalf of the modeler, that the conceptual model will lead to a computer model that is sufficiently accurate for the purpose at hand.
Credibility	A perception, on behalf of the clients, that the conceptual model will lead to a computer model that is sufficiently accurate for the purpose at hand.
Utility	A perception, on behalf of the modeler and the clients that the conceptual model will lead to a computer model that is useful for the purpose at hand.
Feasibility	A perception on behalf of the modeler and the clients, that the conceptual model can be developed into a computer model.
Resources	The ability of the method to allow elaboration of system descriptions.
Branching	The ability of the method to model complex branching logic.
Elaboration	The ability of the method to allow elaboration of system descriptions.
Communication	The ability of the method to communicate system information, especially to non-experts
State	The ability of the method to model state changes in a system.
Information	The ability of the method to model information flow in a system.

After the conceptual model has been created and is verified and validated, **step 3** the model design phase starts. The model design phase is an iterative process in which the conceptual model is translated into modelling language whilst still representing the real world (Gigch, 1991). In this phase the conceptual model will have to be updated constantly, since new assumptions might have to be made in order to translate the conceptual model in a computer model. Simulation logic can get very complex, in order to explain this complex logic Simulation activity diagrams (SAD) can be used (Heavey, 2006). The premise behind SAD is that complex events that occur in a DES are broken down into a sequence of actions.

As previously mentioned, several simulation models of the X production line already exist. Simulation model reuse should therefore be considered. “Simulation model reuse” can be interpreted to mean different things. Namely, reusing little portions of code, components, component design, model design or modelling knowledge (Robinson, 2004). Reusing previous models has huge benefits in theory, but there are some pitfalls, such as the validity/credibility of the previous models and the time it takes to familiarize oneself with the model.

In addition, the difference in model requirements between my model and the model selected for reuse should be considered (Robinson, 2004). Research states the simpler the code the better (Robinson, 2008). Reusing previous models might therefore result in a contradiction. Since force fitting certain components that are not specifically made for my purpose might save time but make the model more difficult.

Step 3.B of the simulation study is verifying/validating the simulation model. Verifying the simulation model basically means assessing whether the simulation model is built in the right way. Thus, judging whether the model and the data used represents the conceptual model in a sufficient manner. Proper model verification can only take place however, if the modelling language is understood, since the program Plant-simulation makes use of hidden assumptions. Some of the hidden assumptions that were identified are: Resource recapture, condition delayed entities, yielding control temporarily and conditions involving the simulation clock.

Model validation on the other hand, means checking whether the created simulation model is fit for its purpose. There are several methods for this; first we can compare our model to the other models that are already created. Comparing the results of previous models to the results of my model under similar circumstances could help validate certain parts of the simulation model (Mitre, 2020). Secondly, the model can be validated with historic data. Feeding the simulated production line a day of orders and checking whether it achieves the real world output is an effective way of validating the model. Lastly, we can make use of parameter variability sensitivity analysis; this technique basically implies that relationships between input and output parameters in the real world should also exist in the simulation model. A known bottleneck in the real world should also show bottleneck behavior in the simulation model for example.

After the simulation model is properly validated and verified, **step 4** experimentation can start. The goal of this step is to gain insight into the inner workings of the production line and compare the benefits of various decisions and policies (Sanchez, 2006). Experimentation can roughly be divided into three activities namely: finding suitable sample data to experiment with, setting the model parameters and searching the solution space (Robinson, 2004). The data needed for experimentation is the production order history in the case of our simulation study.

Setting the model parameters will be done with the help of the manufacturing engineers, first a baseline situation will be modelled for validation purposes. Setting the model parameters also requires determining a warm-up period, run length and a number of replications. For a non-terminating simulation like the one that is being conducted these settings are crucial. The warm-up period is important since the initial state of the simulation model is not in line with reality, because of the fact that the production line is never empty. There are several techniques that can be used for this purpose. But the most effective method is the Welch's graphical method. Welch's method entails that the researcher runs the simulation model, preferably with the most variability included. Where after the gradient of the output KPI's should be studied, Welch suggests picking a warm-up period with the naked eye that makes sure that data is only gathered after the KPI's become stable (Law,2005). Furthermore, it is important to pick this warm-up period conservatively, to make sure no undesired effects show up in the results. Most of the literature suggests that the run length should be a lot higher than the warm-up period. From the literature research we concluded that the run length of the simulation should be at least 10 times higher than the warmup period (Law, 2005). The number of replications is also very important to determine, since not using enough replications will make the eventual results useless from a statistical point of view. The method proposed by Robinson to determine the number of replications needed will be used. Robinson states that the number of replications should be picked in such a way that the point estimates of the KPI's fall within a (1-Alpha) confidence interval Robinson (2004) From literature it became clear that a confidence level of 5% is sufficient (Robinson,2004; Law,2005). Now that the model parameters have been set information on the performance of the production can be gathered. This basically means that the solution space has to be searched. Sanchez gives an overview of all the different experimental designs possible (Sanchez, 2006). The experimental design most useful for our simulation study is the 2^(k-p) resolution fractional factorial design (RFFD). Because it is suitable for experiments that include relatively many experimental factors that can only take a few different values (Sanchez, 2006). Which is perfect for our study since the objective of the research is to find the influence of several sources of variability on the performance of the production line.

A short summary of the RFFD design will be given here, but for a more detailed description Sanchez should be consulted (Sanchez, 2006). The design matrix below is an example of a 2^(7-4) fractional factorial design matrix, a design point is a specific combination of factors values (Sanchez, 2006). The columns here refer to the different sources of variability. The idea behind the design is that certain interactions between factors are not considered, instead an extra experimental factor is added.

Des. Pt.	X_1	X_2	X_3	X_4 (1,2)	X_5 (1,3)	X_6 (2,3)	X_7 (1,2,3)
1	−1	−1	−1	+1	+1	+1	−1
2	+1	−1	−1	−1	−1	+1	+1
3	−1	+1	−1	−1	+1	−1	+1
4	+1	+1	−1	+1	−1	−1	−1
5	−1	−1	+1	+1	−1	−1	+1
6	+1	−1	+1	−1	+1	−1	−1
7	−1	+1	+1	−1	−1	+1	−1
8	+1	+1	+1	+1	+1	+1	+1

Figure 9: Example of a 2^(7-4) fractional factorial design matrix (Sanchez, 2004)

After the experiments are conducted that look into the effects of variability, certain possible solutions will be tested in **step 5**. The best solutions than have to be presented and an implementation plan has to be written. The implementation plan specifies how Company Y should interpret the solution and how they could use the solution to improve the performance of the production line.

Section 3.2: Conclusion

Chapter 3 sought to answer the following question: What is the best way to conduct simulation study given the specific conditions of a manufacturing system like the X production line at Company Y? The result of the literature study documented above is a clear roadmap that can be used to guide the process of conducting a simulation study.

Chapter 4: The Conceptual model

In this chapter the conceptual model of the simulation study will be defined. The conceptual model will be documented along the framework that was set out in chapter 3. The research question that will be answered in this chapter is:

How can we turn the X production line described in chapter 2 into a Simulation model that is sufficiently accurate for our purposes?

Section 4.1 will define the objectives of the simulation study as well as the inputs and outputs that will be used to study the effects of variability. Section 4.2 will give an overview of the content of the simulation model; it will describe the scope and the level of detail at which the production line will be modelled. Section 4.3 will give a list of all the assumptions/simplifications that were made during the construction of the conceptual model, and lastly section 4.4 will describe the verification/validation process that the conceptual and simulation model went through.

Section 4.1: Objectives

Section 4.1.1 Modelling objectives

Organizational Aim

The overall aim is to improve the performance of the X production line and especially its special section, by lessening the impact of various high impact sources of variability. This should be evident from an increase in OTP of 5% in certain periods.

Modeling Aims

- Mapping out the influence of several sources of variability on the performance of the X production line, especially its special section. (A need)
- Finding possible solutions that would mitigate the effect of variability on the performance of the X production line, especially its special section. (A need)
- Creating a tool with which the manufacturing engineering department can experiment. (A wish)

Section 4.1.2 General project objectives

- **Timescale**: The problem identification part of the simulation study was completed in module 11. Steps 2 to 5 still have to be completed, in the timeframe of about 10 weeks.
- **Flexibility:** The production line is an ever-changing environment, for the simulation model to be useful in the future it needs to be very flexible.
- **Visual display:** A simple 2D model will be sufficient (mainly due to time constraints and the fact that the client is familiar with the simulation software).
- **Ease-of-use:** For the experiment phase of this research it is useful for the model to be easy to use, since a lot of experiments will be conducted. Furthermore, the simulation model will only be available in a view only version after the graduation period has ended. This means that only simple interactive features can be implemented for further possible use.

Section 4.1.3: Input

In Table 6 an overview is given of all the inputs that will be used in the simulation study, these inputs are a direct result of sections 2.2-2.4. Additional elaboration on the values of the inputs production order mix and production line changes will be given below.

Table 6: inputs of the simulation model

Inputs	Aspect	Indicator	Value
Cause for rework			
	Raw materials	Impact on First time yield [%]	12.90%
	Equipment	Impact on First time yield [%]	12.20%
	Process errors	Impact on First time yield [%]	71.70%
Production order Mix			
	-	Months from the Orderbook	Specified below
Process efficiency			
	-	Process time variability	Table 2
Production line changes			
	Layout of the line	-	Specified below
	Sequence of processing steps	-	Specified below
	Buffer	Buffer size	Specified below
	Workstation	Number of workstations	Specified below

First the input production order mix will be explained further. For this research 4 different months from the orderbook in terms of production order mix have been selected. These months will be used to research the effects of the production order mix on the performance of the production line. The months have been chosen such that all different scenarios that can occur at the X production line can be researched. Information on the specific characteristics of these product mixes can be found in Appendix G.

Now that all the sources of variability have been mapped out, the potential production line changes can be specified. The manufacturing engineer's portfolio allows them to change one of the following factors: The layout of the line, the sequence of the production steps, the place and size of buffer spaces and the number of workstations at a processing step as can be seen in Table 8. The potential values of these changes are incorporated in a set of scenarios. The entire list of scenarios can be found in Appendix H. Due to time constraints only one of these scenarios can be tested with the help of simulation. Some of the other scenarios will however be discussed again in chapter 6. The X 500 scenario was picked to be studied further with the help of a simulation model, since it is an ongoing project, that is created to improve the special section. The scenario also seems to be the most promising solution to the problems currently experienced. Before we can explain why this is the case, X 500 has to be explained further. X 500 is a project that proposes to change the lay-out of the special section. However, it is currently still a concept, an exact plan specifying the lay-out of the new special section is still missing. With the help of the manufacturing engineers several concepts were created that can be viewed in Figure 10 and 11.

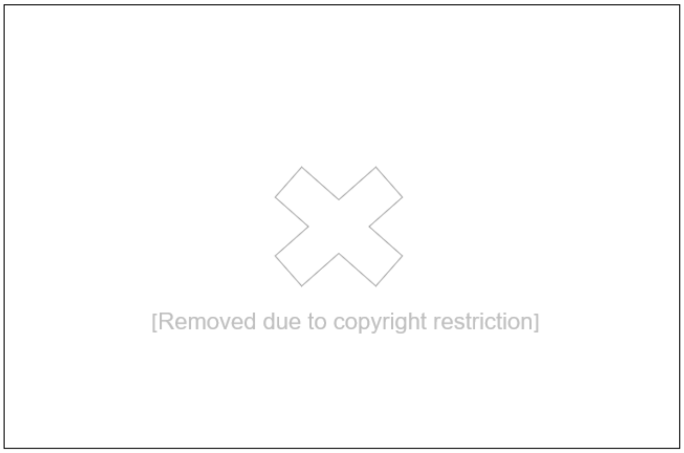


Figure 10: Overview of the new production line X 500A.

The first concept that was drafted is called the X 500A. It proposes to merge the Electrical finishing, the Remote finishing and the chimney and plinth section into one big section. Furthermore, all the top-units are coupled to the systems at the new Special 500 section.

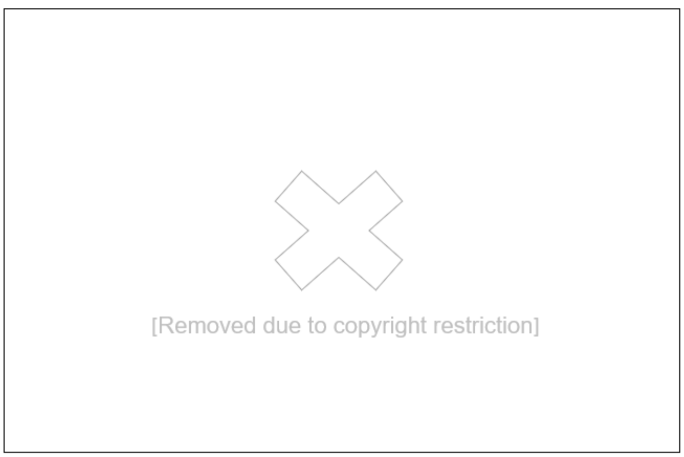


Figure 11: Overview of the new production line X 500B.

The second concept that was drafted is called the X 500B. It proposes to merge Electrical and Remote finishing section into one big section, whilst keeping the Chimney and plinth section autonomous. The X 500A and X 500B concepts are very similar in most aspects, the main difference is the degree at which the tasks are being merged. Important to mention is that the total amount of workstations in the entire special section will not change between alternatives.

These alternative lay outs have several expected benefits. Firstly, the fact that there are a lot of workstations available that are all able to perform all the tasks that are now specified at the Electrical finishing, Remote finishing and Chimney and plinth will make the line more resistant to the impact of different product mixes. Since X Ext. and X Block specials systems can now be assembled in the same section at the same stations. Secondly it will make the section more transparent, since the Special 500 task will have one big buffer space instead of multiple smaller spaces, which will allow team leaders and workers to quickly view the total amount of WIP in the special section. Having one big buffer space will also make the implementation of policies like First in first out (FIFO) easier. Thirdly, it will allow the planning process to be more accurate. In the current situation workers are operating at multiple tasks while being assigned to one, and certain activities are performed at task A while the hours are being booked under task B. In the new situation this will not be the case anymore because these tasks are all merged into one.

Section 4.1.4: Output

To measure the performance of the production line, and judge the effectiveness of our proposed changes in experiments the following outputs are needed:

- Distribution of the throughput time per system (and per field) of the X production line. This measure is chosen because it of its connection with the OTP. The throughput time will be measured for different types of installations.
- Distribution of the WIP (in fields) of the production line. This measure is chosen because it shows the degree to which the production line is operating in a smooth flow. In addition, it also gives an indication about the degree to which the production line can handle a certain output level. The amount of WIP will be measured at different buffers to identify bottlenecks.
- The average utilization of the different production steps of the X production line. This measure is chosen because it shows the degree to which a production steps needs more/less capacity or can handle more/less total workload, again helpful for identifying possible bottlenecks. But also, for identifying steps that are underutilized.

Section 4.2: Content

Section 4.2.1: The scope of the model

In this section of the research we will specify which parts of the real world are included in the simulation model and which are not. A detailed overview of the scope can be found in Appendix I. However vital modelling choices will be discussed below.

Firstly, the production steps that are included in the simulation model are specified in Appendix K, some notable production steps excluded from the scope are the metering section, the fused section and the frame supermarket. The fused and metering section are omitted from the scope, because a X system rarely passes through these sections (< 1% of the systems). Whilst the frame supermarket is omitted from the scope because frames are almost always available and retrieving them from the supermarket takes a negligible amount of time. Secondly, personnel operating the workstations is not included in the scope for several reasons. The first one being a lack of modelling time. Modelling individual workers requires a lot of time in terms of programming but also in terms of research, and the inclusion of these workers will not be vital for solving the core problem Secondly, the benefit of including individual workers will be minimal due to the fact that without the inclusion of other factors like movement of systems and storages, the movements of the workers can't be modelled in detail. Instead the assumption is made that every workstation is equal to one worker. Furthermore, equipment like forklift trucks and cranes used in the production line are not modelled. The main reason for this is the fact that the software does not facilitate this. In addition to the fact that equipment is never cited to be a huge issue.

Section 4.2.2: The level of detail

In this section of the conceptual model the level of detail at which elements of the simulation model will be defined is specified. A detailed overview of all the elements and their level of detail can be found in the Appendix J. A few key choices will be discussed below.

The X product is the most important element of our simulation model. As explained a X system consists of a certain number of frames, each frame than consists of a certain number of fields. Systems can contain front modules and top units. All the information on a specific system is kept in information binders; these binders accompany the X system from the beginning of the Bosch-line to expedition. The frames are incorporated into the model as an object since the so-called Marriage of the fields to the frame is an important step in the production line. Whilst the fields are incorporated into the information binder object since the paths of the fields and the information binder are identical. Front-modules are not modeled as separate objects, because these are always available at the assembly stations. The processing steps all consist of a certain number of workstations, these workstations operate in shifts as outlined in chapter 2. Overtime however is excluded since it is hardly used in the production line. In addition to the fact that there is no clear protocol for when to use it.

Section 4.3: List of simplifications and assumptions

Section 4.3.1: Simplifications

- New production orders arrive before the start of production at 7:30 AM in one batch and are released based on the cycle time required that day.
- New production orders are started in the order at which they arrive in the released order buffer.
- The workers in the line operate in one shift, setup time is assumed to be zero. The workers receive three breaks that are exactly 15 min, 30 min and 15 min respectively.
- The throughput time of a system is calculated by finding the difference between the creation time of the information binder, and the time at which the information binder passes through the expedition station.
- The WIP is measured as the amount of systems present at the end of each hour.
- Utilization is tracked as the relative amount of time a station is processing a production order, data is gathered over the entire simulation run length.
- X systems can overtake each other in the production line at almost all production steps, except for the steps that consist of one workstation. This can happen due to the fact that at many production steps, production stations are configured in a parallel manner.
- Individual workers will not be modeled; instead, products that have to be processed will be given a processing time at the station.
- Travel between stations will not be modelled because it is a process that does not influence the performance of the production line.
- Cranes and other equipment used in the X production line are not modeled.

Section 4.3.2: Assumptions

- Deviations from the standard process that are not documented are not considered.
- WIP is only stored at the indicated buffer spaces.
- A maximum of one worker can operate one workstation.
- Systems have a deterministic drying time of 90 minutes, whilst in reality certain activities are performed on the systems before the 90 minutes are up sometimes. In addition, during hot days the drying time is shorter.
- Only production orders that are scheduled for that specific day can be started. Orders scheduled for the day after cannot be started.

- There are several data samples of 20 days, which is one month of the orderbook. If for example the run length of the simulation is 10 months, the scheduled orders in day 1 are the same as the scheduled orders in day 21.
- Products that are not finished before the end of the day or the start of a break, remain at the station to be worked on at the next start of production.
- If a system occupying a workstation cannot move on to the next station due to the fact that it is occupied the station is considered blocked, meaning that no new orders can be processed on the station.
- The assumption is made that only one order can be processed at one station, whilst in the production line this might not always be the case.
- Production orders cannot be rescheduled. Production orders that are still in the released order buffer at the end of the day remain there and are seen as back-log for the next day.
- Top-units and front-modules are always available on time at the assembly stations.
- No work is carried out outside the shift times, (e.g. overtime is not an option).
- Buffers at certain stages are made larger at higher takt levels.

Section 4.4: Verification and Validation

In the following section we will discuss the validity of the conceptual model and the simulation model that were created, and we will verify the accuracy of these models. Verification and validation will be done along the framework that was outlined in chapter 3. The verification and validation process was conducted with the help of the manufacturing engineers.

Section 4.4.1: Conceptual model

First, we will shortly discuss the validity of our conceptual model since the conceptual model forms the basis for the simulation model. The validity of the conceptual model is deemed to be sufficient for several reasons. The first reason being that the conceptual model is a very complete representation of the Special section, which is vital given the goal of the research. Furthermore, the sources of variability have been researched in depth. The research has limitations however. Due to the fact that important data on failures at specific tasks in the production line is missing or the fact that many components have not been industrialized. However, since the sources of variability have never been studied at this depth before. We can assume that the model will be able contribute to solving the core problem and to improving the performance of the production line. In addition, knowing which data is missing can lead to new initiatives.

Furthermore, the conceptual model is accurate enough to represent the inner workings of the production line at certain key processing steps in the special section, like the coupling section and the Top-Box section. Thus allowing us to study the behavior of the line in more detail. When discussing the validity of the conceptual model is it important to mention its credibility. The credibility of the model was established with frequent interviews with not only the manufacturing engineers but also with other stakeholders. A credible model is very important at Company Y, since several students already tried to improve the performance of the production line but failed to effectively do this to due to the models having sub optimal credibility among other reasons. Lastly the conceptual model can realistically be turned into a simulation model. This assessment could be made because the researcher and the stakeholders at Company Y are familiar with the simulation software used. The conceptual model was created with the limitations of the software considered, and by making assumptions and simplifications whenever necessary.

Section 4.4.2: Simulation model

After the conceptual model was created the modelling process could start, the resulting model can be found in Appendix L. After the modelling process was completed the validation and verification process of the simulation model was started. The simulation model will be validated in the following two ways: validation with historic data and validation with previous models. Validation with historic data is one of the main strengths of the model. First the results of the validation with historic data will be discussed. Firstly, the amount of WIP that was present in the line during the models run length was deemed to be representative according to the manufacturing engineers. Furthermore, comparing the high OTP in 2020 of around x% to the OTP achieved by the simulation model of around 90% also suggests that the model performs quite similar, the relatively large difference of x% difference of present will be explained below.

First the concept behind OTP will be explained again, where after the differences between the simulation model and reality will be explained. An OTP hit takes place when a system spends more than a week to long in the production line, since systems are scheduled according to an JIT policy plus an extra buffer of one week. The first difference between reality and the simulation model is that at several points in time abnormally large buffers build up at the Various component and the Primary testing tasks. These abnormally high buffers are caused by particular days in the orderbook that contain an abnormally high workload at these tasks. This leads to one of the limitations of the simulation model. Namely the fact that these buffers would not be that high in reality, because of the fact that the team leaders in the production line are very dynamic in the way they assign their workers to the different tasks, which means that problems caused by particular mixes are often mitigated. These particular mixes are however rare, which means they do not have a very large impact on the performance of the overall production line over a longer period. Another difference are the occasionally high through-put times. Certain systems have throughput times that are significantly higher than any throughput time encountered in reality. This is caused by the fact that the simulation model contains no rule that decides which system takes precedence over another system. Whilst in reality a team of experts meets every other day, to make sure that a system that spends too long in the production line receives priority over other systems. These differences all contribute to the difference in OTP mentioned above.

The simulation model was further validated with previous models created by Steffan Sloot and Tim Salomons (Salomons, 2019; Sloot,2017). Although the models have different purposes, they can still be useful for validation purposes. The model created by Steffan Sloot (2017) only contains the standard section of the production line. The model has very similar performance, apart from some of the effects that are caused by abnormalities in the product mix. The model created by Tim Salomons (2019) contains the entire production line but lacks important detail and makes some key assumptions like the exclusion of the Top-Box and part of the primary testing section. The standard section of both lines does however perform quite similar if we exclude the control methods that were introduced in his research.

Verifying the simulation model was done with extensive visual checks, which included checking whether systems moved the way we expected them to move. In addition to this utilization of the different production steps was checked, to make sure they were included in the paths of the different systems. Furthermore, buffer sizes and total WIP levels were closely monitored to make sure no abnormalities appeared.

Chapter 5: Most effective way to reduce the impact of variability

Chapter 5 is arguably the most important chapter of the entire research, because it will answer the main research questions. In section 5.1 the structure of the experiments that will research the impact of variability will be discussed where after the results of these experiments will be discussed in section 5.2. Section 5.2.1 will contain analysis on the impact of rework and process time variability, whilst 5.2.2 will contain all the analysis on the impact of different orderbook months, whilst section 5.2.3 will try to answer the research question:

<u>How do the identified sources of variability affect the performance (of the Special section) of the X production line?</u>

Section 5.3 will discuss the experiments needed to compare the performance of the different production line lay-outs. Section 5.4 will contain all the results of these experiments and will try to answer the following research question:

<u>What is the best way to improve production line performance by lessening the impact of variability?</u>

Section 5.1: Experimental design impact of variability

First the warm-up period, the run-length and the number of replications have to be calculated. The warm-up period was determined to be a 100 days and the total run-length of a replication was determined to be a 1000 days. In addition, the minimum number of required replications was determined to be 6, more information on these figures can be found in Appendix N.

Secondly an overview of all the different input parameters is given in Table 7, these input parameters are a direct result of section 4.2. X2 refers to the different types of possible production order mixes, a high output level refers to an output of 64 fields per day, whilst for all the other months the output is 50 fields. High % of specials refers to a month where the ratio of special system is around 60%, and a low % of specials refers to a month where the ratio of special system is around 40%. X3 refers to the processing time either being deterministic if X3 is false, or variable if X3 is true.

Table 7: Experimental factors

Experimental factor	*Description*	*Range*
X1	First time yield %	70-100 %
X2	Production order mixes (Months from the Orderbook)	⟨High output level, High % Specials, Low % Specials, Low % Specials ratio alternative scheduling⟩
X3	Process time variability	⟨False, True⟩

The input parameters are chosen in such a way that the research question mentioned above can be answered with the help of a set of scenarios that can be found in Table 8. The reasoning behind the selection of these specific scenarios is given below.

Table 8: Experimental design

Scenario	X1	X2	X3
1	100%	High % Specials	False
2	96.37%	High % Specials	False
3	100%	High % Specials	True
4	96.37%	High % Specials	True
5	96.37%	Low % Specials	True
6	96.37%	Low % Specials Alt. Scheduling	True

The first scenario will function as a baseline situation with which we can assess the performance of the other scenarios. The outputs with which the performance of the scenarios is assessed are specified in section 4.1.4. The baseline scenario does not contain any variability, and the month with a relatively high % of specials is selected as input, because that month is the most representative when looking at the year 2019. The impact of reworks and process time variability is studied by comparing the performance of scenarios 2,3 and 4 to the performance of scenario 1. Scenarios 5 and 6 are used to study the impact of different production order mixes on the performance of the production line. The impact of the different production order mixes is studied with all the other sources of variability enabled. Additional experiments not mentioned in Table 8 will be conducted to determine the general effects of the input parameters. Furthermore, additional experiments will be conducted whenever necessary to further study an effect that is identified throughout the research.

Section 5.2: Results of impact of variability

In the following section the impact of the identified sources of variability on the performance of the production line is discussed. The impact of these sources was researched by executing the experiments mentioned in Table 8, among others.

Section 5.2.1 Impact of Reworks and Process variability

First the performance of the production without any sources of variability considered is analyzed. Without any variability the production line performs excellent as expected, see Figure 12 (scenario 1). However, in the initial experiments the Primary and Secondary testing tasks are the bottlenecks. This is evident from the fact that the average utilization of most of the production steps is around 50%, whilst the utilization of the testing tasks is around 80% exact figures on the utilization of production steps can be found in Appendix M. These findings stand in contrast with the initial assessment of the production line’s bottleneck. A reason for this is that the processing times specified in Baan are not a good representation of reality. When verified with the manufacturing engineers this turned out to be true. Another reason for the shift in bottleneck could be the fact that there are relatively many X Ext. being produced during the selected month. These systems have a high workload at the Primary testing sections compared to the X Block systems. For example, a X Block 2 fielder has the same workload as an X Ext. 1 fielder, whilst a 2 fielder contributes twice as much towards reaching the output KPI. This suggests that the KPI takt is not an effective way to measure the performance of the production line. With the base scenario fully analyzed we can start to look at the impact of variability on the performance of the production line.

Figure 12 gives an overview of the impact of variability on the performance of the production line in terms of the average throughput time per system over the entire run-length of the simulation. From the experiments the conclusion can be made that the average throughput time per system steadily increases upon introducing more sources of variability. This is in line with what one would expect. However, upon enabling all variability the bottleneck again shifts, this time from the testing sections to the Electrical and Remote finishing section. This shift seems counter intuitive since reworks cause the workload at the testing section to increase significantly. However, examining the distributions describing the process time variability shows that the processing times at the testing sections are often overestimated. On the other hand, processing times at the Electrical and Remote finishing sections are underestimated or missing frequently. This explains the shift in bottleneck and means that our initial estimation of the bottleneck was correct.

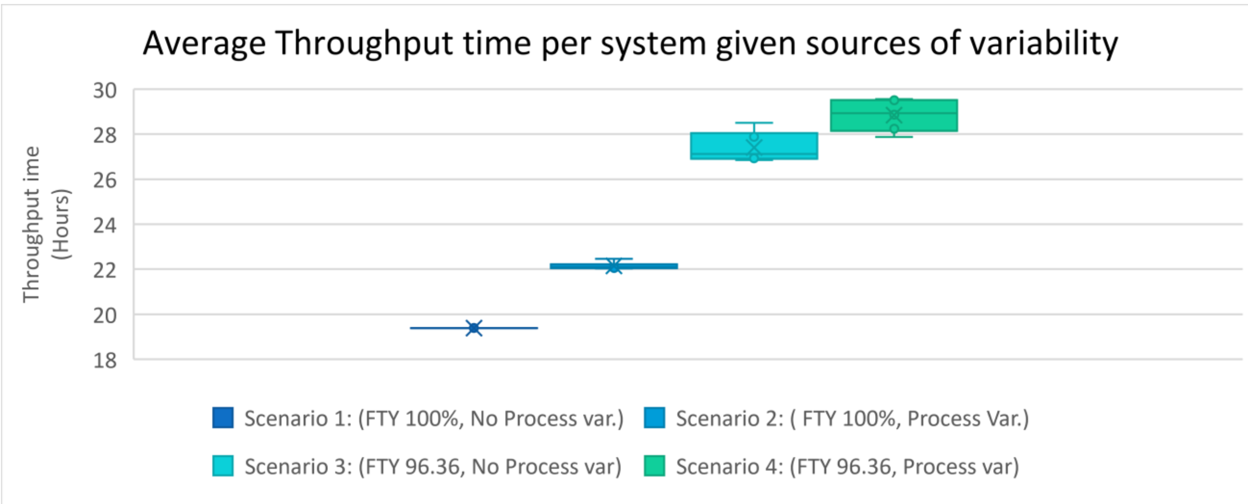
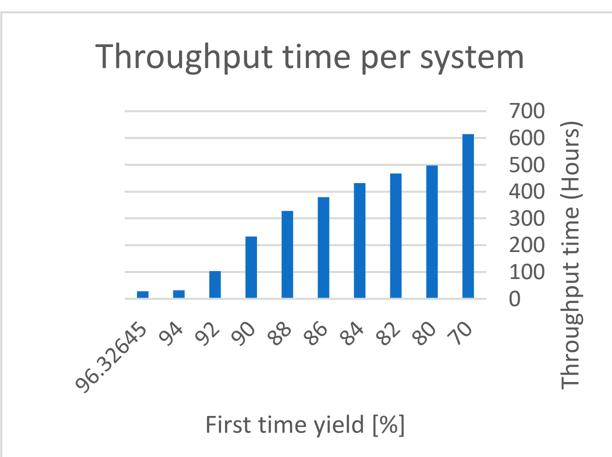


Figure 12: Average throughput time per system

Further researching the impact of Reworks on the performance of the production line is interesting, since information on the impact of the FTY % on the performance of the production line can be valuable. Therefore, additional experiments looking into the impact of the FTY% were conducted. From Figure 13 we can clearly see that both the WIP and the average throughput time spiral out of control when the FTY% is decreased slightly. The different departments at Company Y should therefor make sure that the FTY stays up to par, by for example making sure that the quality of the raw materials used is good.



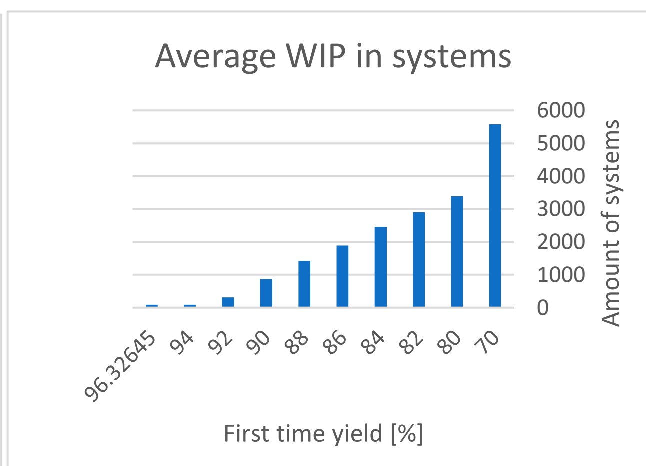


Figure 13: Rework sensitivity analysis

Section 5.2.2: Impact of product mix on the performance of the production line

As mentioned, the impact of the production order mix is analyzed by experimenting with three different months all with an output level of 50 fields. The results of these experiments can be found in Figure 14.

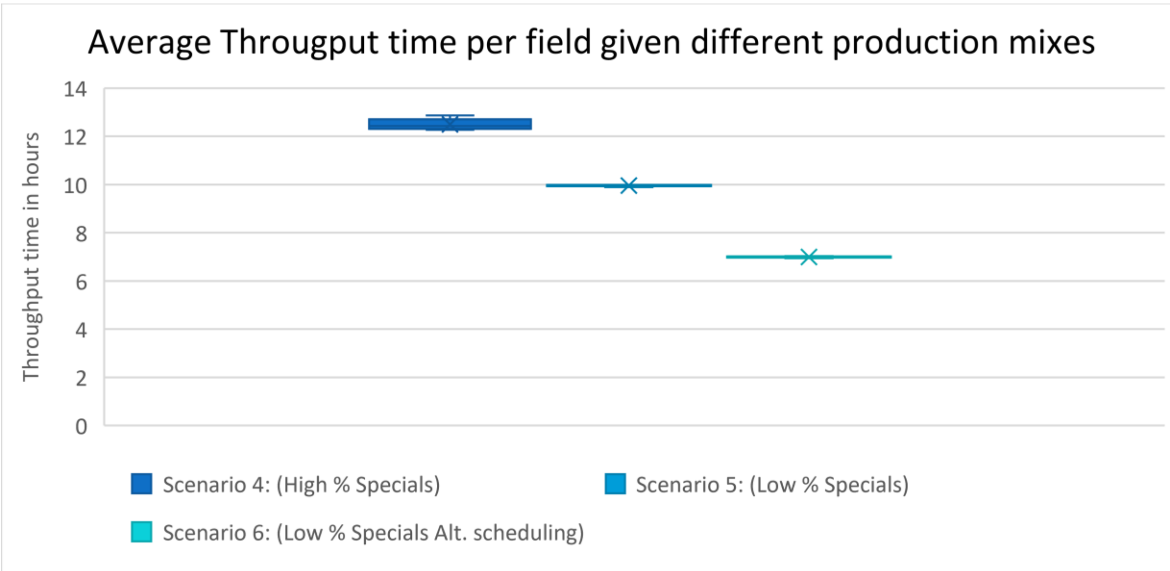


Figure 14: Average throughput time per system given the type of month.

From Figure 14 the conclusion can be made that the production order mix of a month has an enormous impact on the performance of the production line. Evident from the large discrepancies in average throughput time per field over the entire run-length of the simulation. Important to mention is the fact that the throughput time per field is considered instead of the throughput time per system. The reason for this is that in general the larger the system gets in terms of fields the greater the total workload for the production line. However, this does not always have to be the case as illustrated in the example given above regarding the Primary testing section.

Scenario 4 has the lowest average fields per frame of around 2.11 fields. This result in a relatively high average throughput time per field, although there are also other factors contributing to the relatively high throughput times. Namely the large amount of special systems that are being produced during that month. Furthermore, scenario 5 and 6 are very similar in terms of average amount of fields per frame and ratio of specials. This implies that the way orders are scheduled affects the average throughput time per field, since the only relevant difference between the two scenarios is the way the orders are scheduled. The main difference in scheduling between scenario 5 and 6 is the way X specials are scheduled throughout the month, in scenario 6 the specials are more evenly distributed over the duration of the month than in scenario 5. This hypothesis was further investigated by mixing up the sequence of orders in scenario 4. From these additional experiments it became clear that the sequence at which orders enter the line has a big impact on the throughput time. This conclusion was already made in previous research conducted by Tim Salomons, but Company Y has still not implemented any scheduling policy (Salomons, 2019).

Further analyzing the effects of the different production order mixes is done by looking at the utilization of various processing steps. The experiments show that certain stations are barely needed during scenario 6, whilst they are almost over utilized during scenario 4. Exact figures on the utilization can be found in Appendix M. This becomes a problem when we consider the way workers are assigned in the X production line. As mentioned, the planner at Company Y assigns workers to tasks purely based on the output level that is scheduled for that month. This means no attention is paid to the actual workload a task has to process during that month. This means that the planner should start planning based on workload, and that the special section should be more flexible in dealing with different workloads.

Section 5.2.3 Conclusion on impact of variability

- Due to the fact that the processing times of the Primary and Secondary testing tasks are overestimated, process variability causes the bottleneck to shift from the testing tasks to the Electrical and Remote finishing task (Explained in section 5.2.1).
- The more variability added to the production line, the worse it performs. Furthermore, the variance in average throughput time is huge. By taking variability into account, average throughput times per system increase by more than a day (Explained in section 5.2.1).
- A decrease in fields per frame results in a substantial increase in throughput time per field, due to the fact that the workload at a production step does not increase linearly upon increasing the amount of fields per frame linearly (Explained in section 5.2.2).
- Due to the effects of different production order mixes, planning based on output (takt) levels is not viable. Furthermore, the workload at certain production steps does not increase linearly as the number of fields per frame increase linearly, which again suggests that the current KPI is suboptimal.
- Electrical and Remote finishing both become bottlenecks, when the ratio of X Ext. is higher than 40%, and the ratio of specials is higher than 60% which is not uncommon (Explained in section 5.2.2).
- The first time yield percentage should be around 96% or higher, since a FTY lower than that results in WIP levels and Throughput time getting out of hand (Explained in section 5.2.1).

Section 5.3: Experimental design alternative production line layout

First an overview of all the different input parameters that are needed to study the impact of an alternative production line lay-out is given in Table 9. Table 9 is an extension of Table 7 with the addition of the experimental factor lay-out of the production line.

Table 9: Experimental factors

Experimental factor	*Description*	*Range*
X1	First time yield %	70-100 %
X2	Production order mixes (Months from the Orderbook)	⟨High output level, High % Specials, Low % Specials, Low % Specials ratio alternative scheduling⟩
X3	Process time variability	⟨False, True⟩
X4	Lay-out of the production line	⟨Original, X500A, X500B⟩

Table 10 contains all the scenarios that are needed to research the best production line lay out. Below the selection of these specific scenarios will be explained.

Table 10: Experimental design

Scenario	***X1***	***X2***	***X3***	***X4***
7	96.37%	High % Specials	True	X500A
8	96.37%	Low % Specials	True	X500A
9	96.37%	Low % Specials Alt. Scheduling	True	X500A
10	96.37%	High % Specials	True	X500B
11	96.37%	Low % Specials	True	X500B
12	96.37%	Low % Specials Alt. Scheduling	True	X500B
13	96.37%	High output level	True	Original
14	96.37%	High output level	True	X500A
15	96.37%	High output level	True	X500B

Scenarios 7-12 will be used to find out which of the production lines performs the best given different months from the Orderbook. Whilst scenarios 13-15 will give insight into the performance of the Original production line at higher output levels vs. the performance of the X 500A and X 500B at higher output levels.

Section 5.4: Results

As mentioned in section 5.3, there are two different alternative lay outs of the production line that both have advantages on paper. Their performance is compared to the Original production line, at different output levels and with different months of the orderbook.

Figure 15 shows the results of experiments 7-12, there is a significant difference in performance between the X 500A/X 500B line compared to the Original line in terms of Average throughput time per system over the entire run-length in the month with an high % specials. However, both alternative lines perform marginally worse in months with low % of specials. From these results we can conclude that the alternatives perform better in months with a relatively low average amount of fields per frame of around 2.11 fields/frame and a high ratio of special systems of around 64%. They perform worse in months with high amounts of fields/frame of about 3.03 fields and a relatively low ratio of special of about 45%. According to historic data the month with a high % specials is a better representation of an average month over the last year, which suggests that the alternatives are a worthwhile improvement. However, the last few months have shown a trend that suggests that the ratio of special systems is decreasing steadily, and the average amount of fields/frame is increasing steadily.

In terms of lessening the impact of variability on the performance of the production line, the X 500A and X 500B both perform substantially better than the Original line in terms of the standard deviation of the average throughput time per system over the entire run-length. The standard deviation of the average throughput time per system over the entire run-length for the Original line is about 8.5 hours, whilst for the X 500A line this is only 3.47 hours and for the X 500B line this is only 3.62 hours. The standard deviation of the average throughput time per system over the entire run-length is the standard deviation between the average throughput times over the entire run-length of the simulation of the different production orderbook months. It is an interesting measure because it basically states to what degree the performance of the production line is dependent on the production order mix of that month.

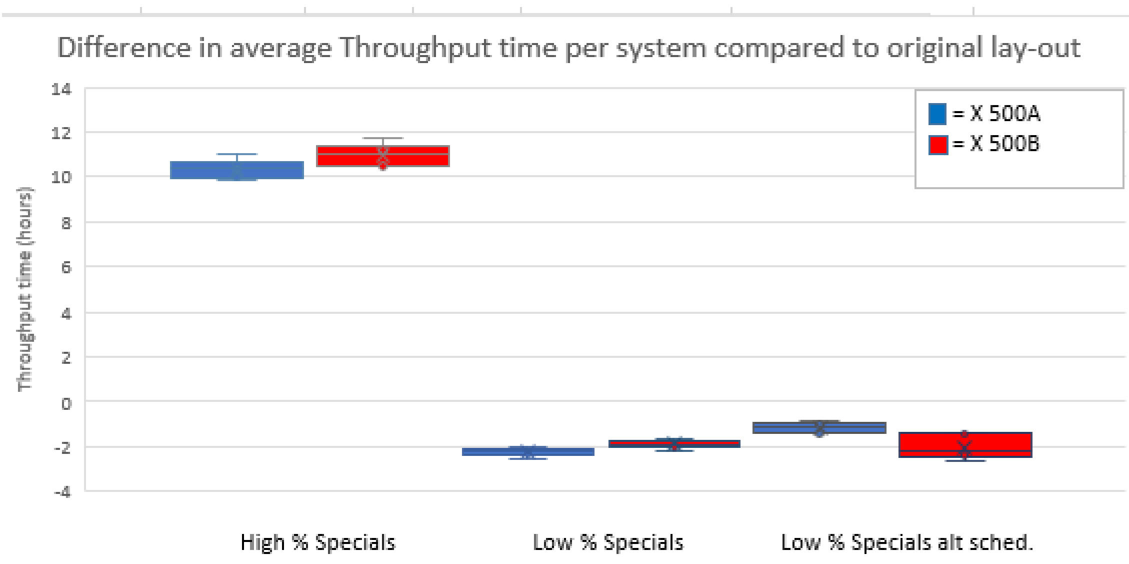


Figure 15: Improvement in Throughput time due to different layout relative to the Original production line

In terms of WIP both the X 500A and X 500B production lines also perform substantially better in terms of the average amount of WIP in the production line. On average the amount of WIP in the alternative production line is about 30% less, further analysis is included in Appendix M. Another important factor to look at is the performance of both the X 500 production lines compared to the Original line at a higher output level, since this is another one of the sources of variability that was identified. From experiments 13-15 the conclusion can be made that both the X 500's production lines do not perform substantially better than the X Original line, however the spread of the X 500 B is considerably smaller which suggests that the X 500 B line does perform more reliable under the influence of variability at higher takt levels.

The fact that the X 500B production line does not perform substantially better than the Original production line is further supported by the fact that the OTP is only improved by 0.2% to 1.5% depending on the type of month.

Section 5.4.1: The most efficient production line lay-out.

From analysis it became clear that the X 500A and X 500B production line both perform substantially better than the Original line in months where the average fields/frame is relatively low, and the special ratio is high. However, they perform worse in months where the average field/frame is relatively high, and the special ratio is low. This phenomenon can be explained when looking at the strengths of the Original lay-out and the X 500B lay-out as outlined in section 4.1. The Original production line consists of various tasks that all have their own capacity and buffers, this means the Original production line is able to quickly handle X systems that only have to visit some of the tasks in months where the ratio of specials is low. The fact that the capacity of these tasks is relatively low, does however mean that the individual tasks are worse at dealing with variability in workload. The X 500B lay-out on the other hand is great at dealing with variability in workload, whilst it performs worse in months with a low ratio of specials since all specials have to pass through the same buffer and task. Furthermore, both the X 500 lines perform substantially better in regard to the standard deviation of the average throughput time, which means both alternatives do handle variability a lot better. In addition, the average amount of WIP in both the alternatives is considerably lower. The experiments suggest that the X 500B line is the best alternative under the assumption that the average amount of fields per frame does stay around 2.4 fields and that the ratio of specials is on average around 60% which is realistic according to some of the manufacturing engineers.

Chapter 6: Conclusions and Recommendations

With all the experiments finished, insight into the influence of different sources of variability can be given in section 6.1, by doing this the core problem will be solved:

<u>A lack of quantitative information on the influence of different sources of variability on the performance of the special section of the X production line at Company Y.</u>

After more information is given about the influence of variability, information on how to lessen the impact of the aforementioned variability can be given in section 6.2, by answering the following research question.

<u>What can the manufacturing department do to improve the performance of the production line?</u>

Where after some of the recommendations for further research will be given in section 6.3.

Section 6.1: Conclusion

The impact of variability on the performance of the production line is large, but also complex to analyze since there are many sources that contribute to the performance of the production line. The main three sources that were identified are:

- Rework
- Process time variability
- Production order mix

Although the list is not fully complete, it is the best possible overview due to the fact that data on variability is not well documented at Company Y. Going over the sources listed above will give some insight into the influence of variability. The reworks can quickly become a huge problem, since a slight decrease in the FTY results in WIP and Throughput times spiraling out of control. The introduction of process time variability is responsible for a shift in bottleneck from the Primary and Secondary testing tasks to the Electrical and Remote finishing tasks among others.

Furthermore, the impact of the different production order mixes requires the planner to assign workers to certain tasks in the production line that are not needed, tasks can go from a utilization of 20% in one month to a utilization of 80% in the next month at the same output (takt) level. Obviously, differences are even more extreme on a weekly or even daily basis. Combining the effects of these sources results in a standard deviation in average throughput time per system of more than a day. Which means that in extreme cases systems spent more than a week in the production line. This means that Company Y is not able to reliably provide their customers with their products on time. Important to mention however is the fact that the production line is not the only reason for this fact, since production is only a small part of the order process in terms of lead time.

Section 6.2: Recommendations

- Company Y should consider implementing the X 500B production line, under certain circumstances. As mentioned, the X 500B production line functions superior in comparison to the original production line in certain months, which could result in a decrease in average throughput time per system of 33%. This does however depend on several factors. First of all, the number of fields per frame and secondly the number of specials that are produced in that month. This means Company Y should only implement the new production line if they know more about the way the market will progress. The X 500B does however perform way better in terms of dealing with variability, evident from a slight increase in OTP of 0.2% to 1.5% depending on the month and a decrease in standard deviation of the average throughput time between months. Which means that it might be an interesting option for Company Y although it does not always perform better than the Original production line in terms of throughput time.

- One of the first things I noticed during my graduation period at Company Y was a disconnection between the different departments at Company Y. And although this phenomenon is inherent to a company like Company Y, this is particularly problematic at Company Y because of the fact that the Sales department can sell a large array of X configurations that have large impacts on the performance of the production line (Parente, 2002). There are several ways to combat the disconnection. One possible solution would be to use the multi stakeholder decision tool (MSDS-tool) developed by Cyriel van Oorschot (Van Oorschot, 2017). With the help of the MSDS-tool all stakeholders will be able to view the impact of their decisions on the performance of the production which will in turn result in debate, and better mutual understanding.
- From several experiments it became clear that the way orders are scheduled during a production month has a big impact on the performance of the production line. A lot of immediate gain could be made by making use of a sequencing algorithm. Implementing such an algorithm would be relatively low cost, and research showing how to best implement such an algorithm has already been conducted at Company Y by Tim Salomons (Salomons, 2019).
- The most impactful source of variance identified at Company Y were the different possible production mixes. The reason for this is the fact that depending on the type of X system, up to 60% of the system is not industrialized. Currently components are industrialized when they are implemented in roughly 1 out of 20 X systems. Which means that many of the components that enter a X system are not industrialized. According to some estimations up to 60% of the total portfolio, which in turn results in unexpected WIP levels and unexpectedly high throughput times as illustrated in section 5. Trying to lessen the impact of variability cannot be done effectively without looking for the root cause of the variability.

  I would therefore suggest Company Y to make sure more of their components are industrialized before implementing a new production line lay-out. Industrializing all their components would not make sense however, due to the large amount of engineering hours that would require. Company Y could consider industrializing all components that are used in at least 3% of the systems.
- The information binder system currently in use at Company Y is very outdated, and it has major drawbacks that have been outlined in this research. Digitalizing the information binder would allow several of the other scenario’s that have been constructed to improve the performance of the production line to be implemented. The impact of a change in information system was not fully researched due to time constraints.
- Company Y currently makes use of several so called ‘’Dummy’’ production task numbers that do not have any physical place linked to them namely 5333 and 5334. Both these task numbers occasionally have hours assigned to them that are therefore assigned to no particular station or task, assigning the hours to a task would decrease the amount variability in the process.
- Company Y should make sure that their ERP-system Baan is maintained, this is important because many processes depend on the accuracy of the data reported in the ERP-system. During the course of the research several errors were encountered in the documentation of data in the ERP-system. These errors were uncovered during the gathering of the production orderbook data. In addition to some of the documented data being outdated. Furthermore, Company Y should make sure that changes that are being made to key data is tracked and verified by someone else.

- Company Y should consider implementing a different way of monitoring the performance of the X production line. Instead of monitoring the X production line with the current high level KPI takt, Company Y should consider using a different KPI that is based on the total workload of a system, opposed to the amount of fields a system contains. Company Y could implement such a system, by logging the amount of hours planned for a system upon that system leaving the section. This would contribute to resolving the issue of having no clear insight into how many hours have been processed at the different production tasks in a day, and will thus help with identifying inefficiencies better.
- Company Y should make sure to keep the quality of their raw materials and their equipment the same, whilst also making sure that the amount of process errors is kept in check. Because research shows that small decreases in the FTY causes WIP levels and throughput times to get out of hand.
- Company Y could make big improvements in the way they document data in the production line. Barely any Information is gathered on errors or process inefficiencies, whilst there are relatively many of them. The fact that data is documented relatively scarcely is very strange when we look at the fact that the X has been manufactured for over 18 years. Restoring certain systems that were put in place by previous personnel working at Company Y, that have been removed due to costs would go a long way. Like for example, the whiteboards that were used to track raw-material shortages and information errors in the production line. More documentation would also provide some insight into the nature of the difference between Pre and Post calculation.
- Company Y should make sure their workers stick to the process as it was intended. The production line already has many sources of variability. Adding another source that is caused purely by the workers themselves will not improve the performance and will only make the process less clear. This includes placing X systems that are waiting for assembly in the appropriate buffer spaces and following the sequence of processing steps as they are defined in the ERP-system Baan.
- Company Y should re-assess the theoretical processing times in Baan of the testing sections.

Section 6.3: Recommendations for further research

- The distributions used to approximate the difference between pre-calculation and post-calculation are not statistically significant, due to the fact that there were not enough data points used for the distribution fitting process. Further research could expand the data set used, and increase the statistical significance of the chosen distributions.
- In Appendix H a list containing various scenarios is specified, testing these scenarios would give some of the recommendations mentioned in section 6.2 more credence. For example, initial research indicates that the information system is outdated. But quantitative data supporting the procurement of a new system is missing. Further research could look deeper into the effects of a new information system for example.
- The scope of this research is limited due to time-constraints and the fact that the research is conducted at the manufacturing department. Further research could investigate the entire order process from initial order to expedition, to find out whether the production line is the bottleneck in the entire order process.

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Appendix

Appendix A: X 500 Capex

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Figure 16: New overview of the X production line (Hek, 2019)

Appendix B: Current performance analysis

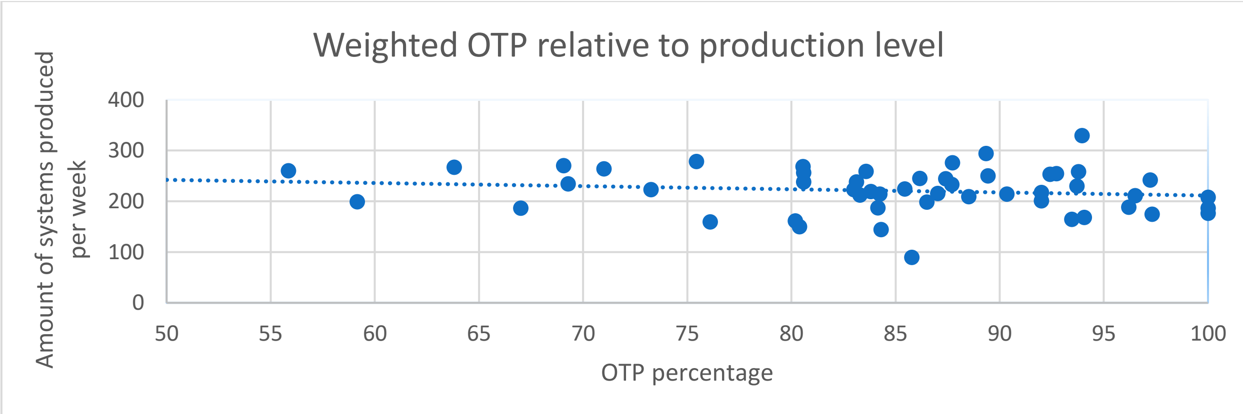

Figure 17: Weighted OTP vs. production level YTD

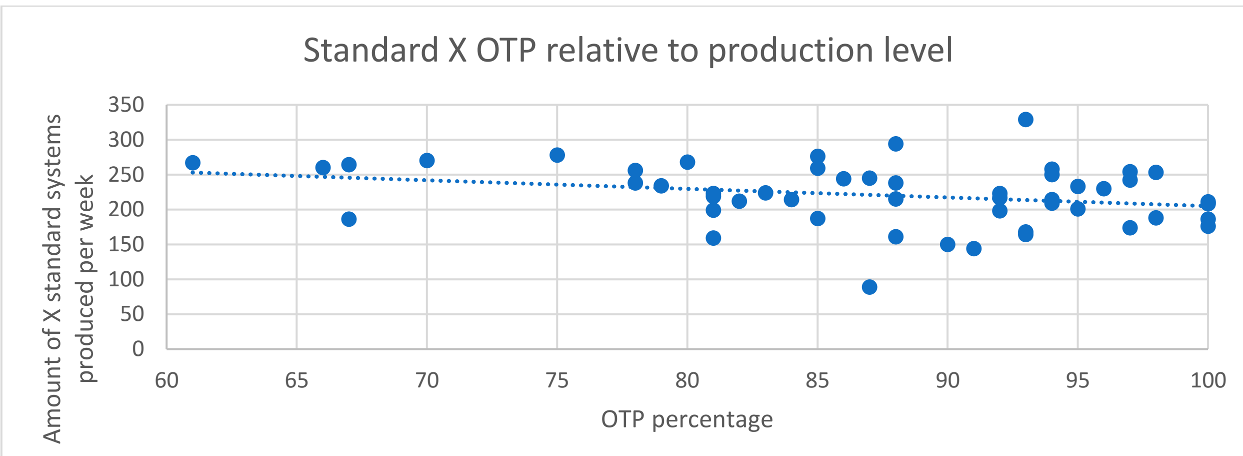

Figure 18: Standard OTP vs. production level YTD

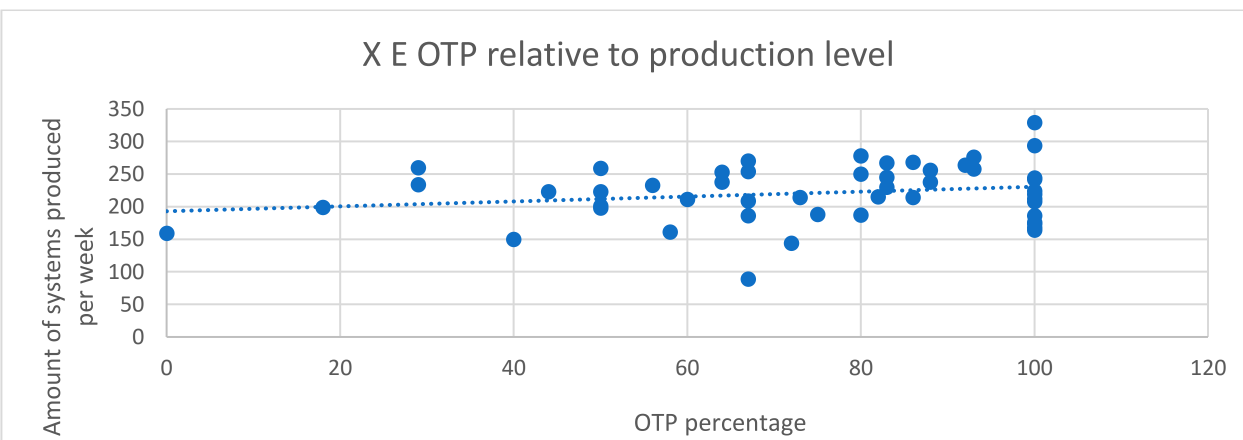

Figure 19: Standard OTP vs. production level YTD

As already stated, the relationship between the OTP and the production level does not show strong correlation. A reason for this is that during several periods of 2019 the production line operated in two shifts. In addition to the fact that overtime hours are used seemingly at random when the backlog of orders become too large. Of course the sources of variability also do not behave linearly; an increase in production level does not coincide with an increase in stock-outs all the time. For these reasons the relationship isn't very strong. Although we can observe that the spread of the points is a lot wider the higher the production level. Important to remember when viewing these graphs is the fact that the current OTP goal is 85%, and that the OTP pursued by Company Y in the long run is 95%. Reviewing these graphs with these goals in mind shows that the OTP needs to improve drastically.

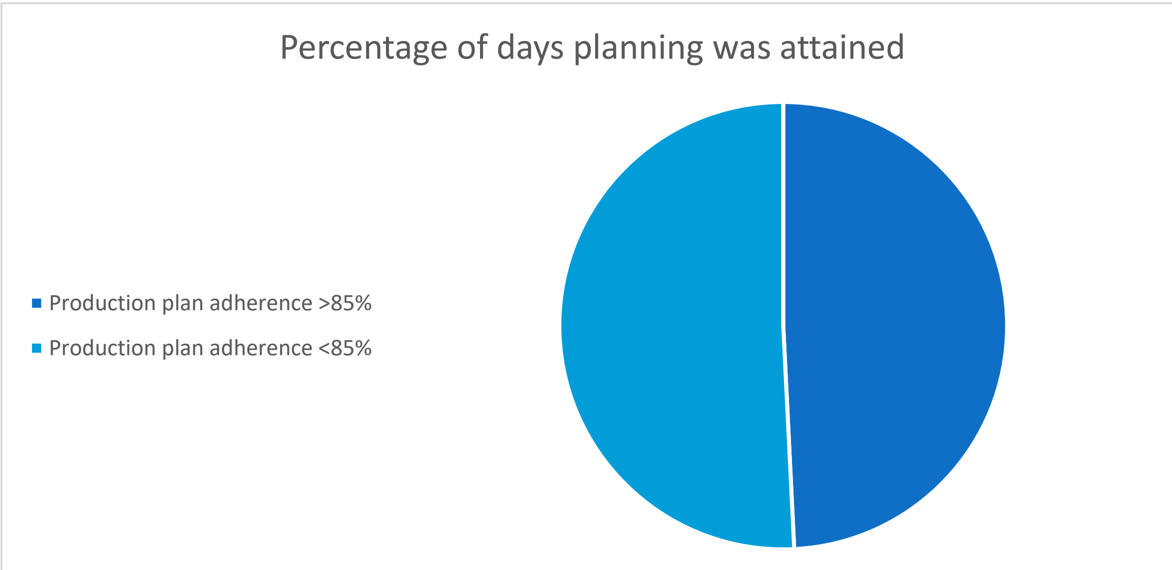

Figure 20: Pie chart showing the extent to which the production plan is not adhered to YTD

Figure 20 shows us the distribution of the days a production plan adherence of 85% was managed. More than half of the time an overall production plan adherence of 85% was not managed, this is one of the reasons for the OTP not being in order.

The capacity chart of the X E shows that the average capacity over the year 2019 was 75%. Whilst the first two months of 2020 show even worse results. Important to keep in mind when viewing this chart is that in 2019 10% of the hours made in the X Ext. section where not accounted for. Which if converted to man hours come down to a very substantial amount of resources.

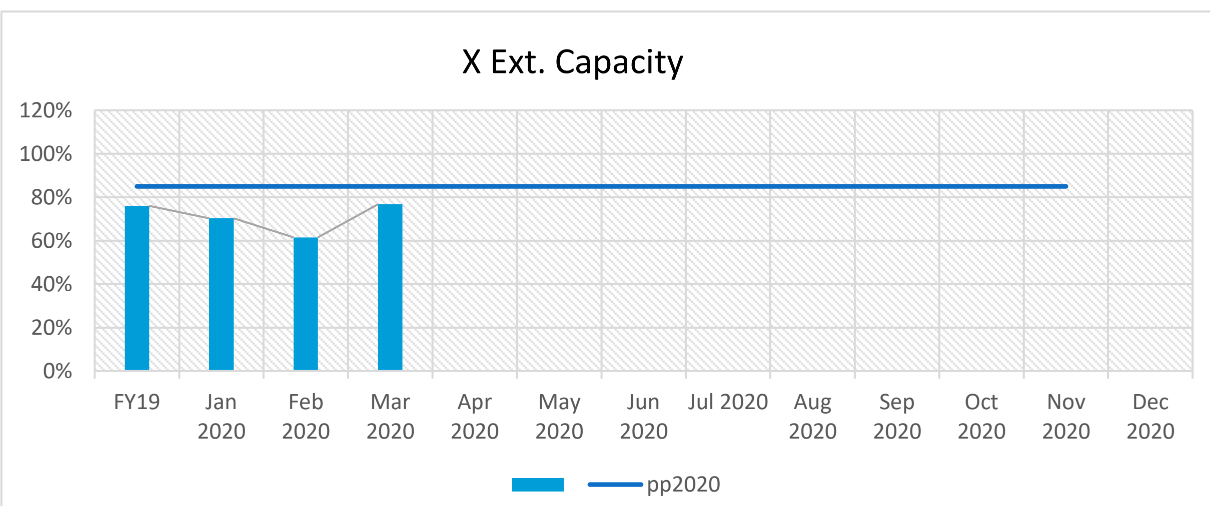

Figure 21: X Ext. Capacity

Appendix C: The X product family.

In the following section additional information will be given about the product structure of the X. Both the X Block and the X Ext. can be rated 12 kilovolt (kV) or 24 kV. The rated voltage specifies the amount of volt the system can handle. 33% of the systems currently processed are rated 12 kV and 66% are rated 24 kV. At this point the functionalities of the system still have to be specified. The two functions most frequently built are the load break switch (LBS) and the circuit breaker switch (CBS). The difference between the two being: the way they switch the current off. The LBS MEC 1 function is approximately picked 51.8% of the time and the CBS MEC 1 function is picked 46.2% of the time.
An example of a X system would be a X block containing two fields rated at 12 kV that makes use of an LBS MEC 1 and an CBS MEC 1. Extra features can however be added to the aforementioned system.

The following selection of extra optional functionalities are most commonly picked by customers. In Addition, these functionalities also have a significant impact on the production line. The selection was made with the help of the sales department at Company Y.

- IAC bottom venting
- IAC rear venting
- IAC arc absorber
- 0mm 16kA door
- 20mm 16kA door
- 100mm 16kA door
- 0mm 20kA door
- 20mm 20kA door
- 100mm 20kA door

- Cable connection cone: A type (200A) (~20%)
- Cable connection cone: C type (630A) (~64%)
- Cable connection cone: C type Long version (630A) (~16%)
- Horstmann WEGA Voltage Detection System
- Horstmann Compass B short circuit indicator (~7, 7%)
- Mechanical door interlock
- Tool based door interlock
- Top Unit
- 250mm plinth / frame
- Cable clamps
- Auxiliary contacts up to 3 sets (~5%) (microswitches)
- Remote trip
- Remote open / close (~25%) (spoel of motor)
- Remote busbar / earth
- Synchronized Remote Closing (SRC) aka Fast-In
- Under Voltage Release
- Trip indicator
- WIC1 type self-powered protection relay (~47%)
- Other types of protection relay

Appendix D: Production line overview with cycle times

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Appendix E: Literature study on sources of variability

Table 11: Summary of literature search.

Sources of variability	Factors	Researcher
Equipment		
	Information system	(Theodore, 2004)
	Machine defects	(Womack & Jones, 1996) (Millard, 2002)
Raw materials		
	Quality	
	Transport	(Slack, 2016)
	Early/late deliveries	(Slack, 2016)
Production mix		
	Effects of these different order on each other	
	High process variation	(Morgan, 2002)
	Extra features	(Ikonen, 2010)
	Seasonal demand	(Poppendieck & Coldewa, 2003)
	Large batches	(Morgan, 2002)
Personell		
	Errors	
	Unnecessary motion	(McManus, 2004)
	Process efficiency	(UGS PLM,2004)

Table 9 gives an overview of all the relevant sources that were identified with the help of our literature review. This list forms the basis for our Ishikawa diagram that can be viewed in Figure 22
Below we will detail the sources of variability that are affecting the performance of the production line. Identifying and removing sources of variability or “waste” is a very popular research topic. For this reason a literature review that investigates all these sources was conducted. The results of the review were then cut down to a handful of sources with the help of the manufacturing engineers. These sources can be found below in Figure 22. The main 4 sources identified are: Equipment, Raw material, production mix and Personnel. These sources are explained below.

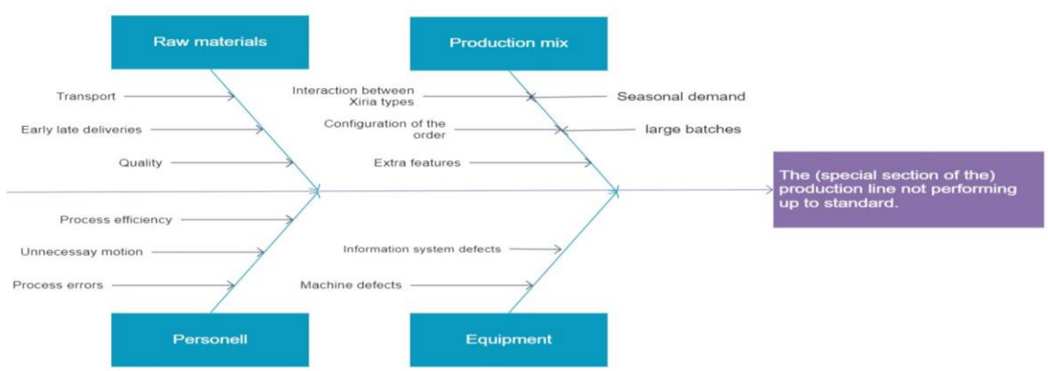

Figure 22: Ishikawa diagram of sources of variability

Appendix F: Determining of distributions

First, we will explain the method that was used to fit an appropriate distribution to the data samples that were retrieved. For all the production tasks that were mentioned in section 2.3, data on the difference between pre- and post-calculation in the year 2020 (January-April) was gathered for all the orders processed during these months. The relative difference between pre- and post-calculation were taken for all orders processed during these months in hours.

From the data mentioned above histograms were created, bins were chosen such that every bin contains at least 5 observations to make sure we can use the chi-square test to assess the goodness of fit. Distributions were then fitted on the histograms assessing their goodness of fit by calculating its chi-square test score. The distribution with the best score was then selected with the appropriate parameter whenever possible. However due to limitations of the simulation software used, certain distributions were not considered since the software does not support the use of these distributions.

Furthermore, it is important to note that the documenting of the post-calculation is a flawed process. Since for certain production tasks no documenting is done at all, namely for the Frame-preassembly 1 and 2, Subs various components, Bosch-line, various components. Whilst for other tasks it can be argued that the workers at the stations have an incentive to overstate the post-calculation. Processing time for tasks for which no documenting is done at all are considered deterministic, this assumption can be made due to the fact that these tasks are all very well standardized In addition to the fact that according to the bottleneck analysis these tasks are not a concern.

An example of a graph with an distribution fitted to it can be found in Figure 23. For all the production tasks mentioned in Table 2, these graphs have been constructed. An important point to mention is the fact that all the distributions that were fitted to the graphs where not statistically significant at a confidence level of 5%. There are multiple reasons for this, one of the biggest being the fact that there are not enough data points.

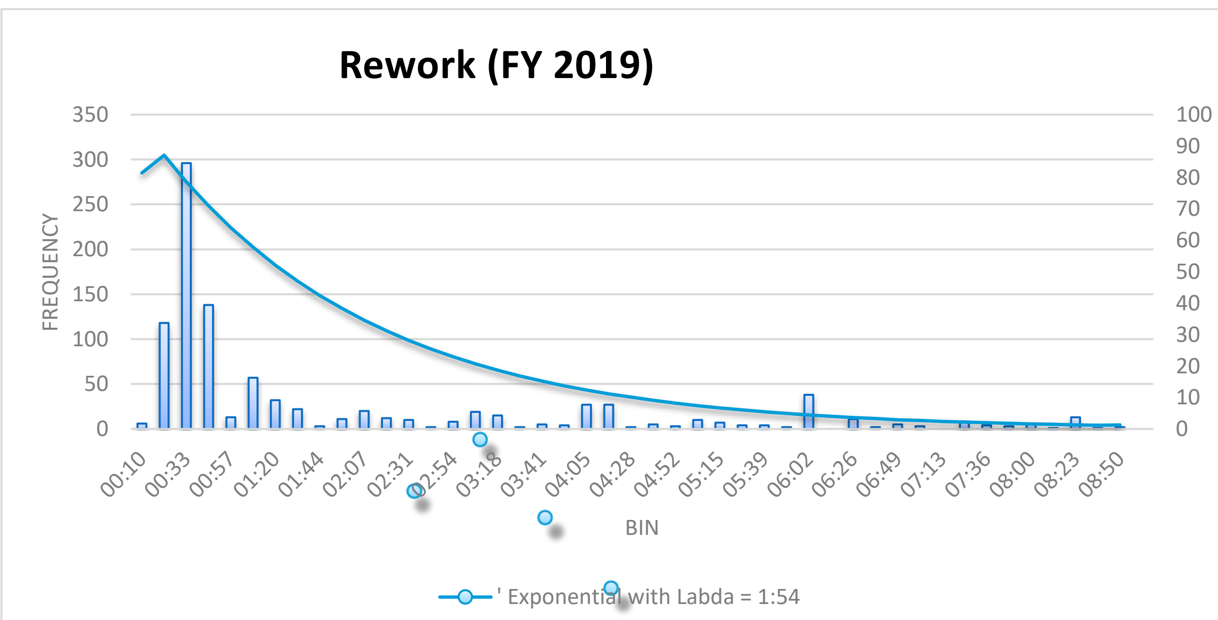

Figure 23: Distribution fitting of the Rework Hours.

Appendix G: Orderbook data

In this Appendix more information is given on the nature of the different input data that is used for our simulation experiments. The information is given along a framework that is a consequence of section 2.2.

Table 10 gives an overview of the average production order mix over the year 2019. The average values will serve as a reference point with which we can further validate certain claims that are made in this research. Table 11 gives an overview of the characteristics of month 1, during this month an average output of 50 fields is attained. Month 1 is unique in the fact that the average number of fields per frame is relatively low, and the ratio of specials and Top-units is relatively high. This month can be considered to be a busy month relatively to the other months considered and the average of 2019.

Table 12 gives an overview of the characteristics of month 2, during this month an average output of 50 fields is attained. During month the average amount of fields per frame Is relatively high, whilst the ratio of specials and extendable's is relatively low compared to the average of 2019. Month 3 is very similar to month 2 in terms of all metrics, whilst differing in the way that the orders are scheduled throughout the month. Month 4 is unique in the fact that it is the only month that operates at an output level of 64 fields.

Table 12: Average product mix over the year 2019

Summary of 2019	indicator	Value
Average Output level	Number of fields produced per day	53
Average size of frame	Average number of fields per frame	2.69
Amount of X Ext.	Ratio of Extendable systems	44.10%

Table 13: Month 1 VC 50 fields per day

Variable	indicator	Value
Average size of frame	Average number of fields per frame	2.178649
Amount of Specials	Ratio of Special systems	54.03%
Amount of Nonstandard	Ratio of non-industrialized systems	10.46%
Amount of X E.	Ratio of Extendable systems	55.99%
Amount of systems	Total amount of systems	459
Amount of Top Units	Ratio of Top Unit systems	15.25%
Secondary hours	Total amount of hours not assigned.	686.96

Table 14: Month 2 VC 50 fields per day

Variable	indicator	Value
Average size of frame	Average number of fields per frame	3.08642
Amount of Specials	Ratio of Special systems	42.59%
Amount of Non standard	Ratio of non-industrialized systems	17.90%
Amount of X E.	Ratio of Extendable systems	21.91%
Amount of systems	Total amount of systems	324
Amount of Top Units	Ratio of Top Unit systems	0.00%
Secondary hours	Total amount of hours not assigned.	588.11

Table 15: Month 3 VC 50 fields per day

Variable	indicator	Value
Average size of frame	Average number of fields per frame	3.136646
Amount of Specials	Ratio of Special systems	46.89%
Amount of Nonstandard	Ratio of non-industrialized systems	17.08%
Amount of X E.	Ratio of Extendable systems	22.67%
Amount of systems	Total amount of systems	322
Amount of Top Units	Ratio of Top Unit systems	0.31%
Secondary hours	Total amount of hours not assigned.	1000

Table 16: Month 4 VC 64 fields per day

Variable	indicator	Value
Average size of frame	Average number of fields per frame	2.311031
Amount of Specials	Ratio of Special systems	53.35%
Amount of Nonstandard	Ratio of non-industrialized systems	12.12%
Amount of X E.	Ratio of Extendable systems	51.54%
Amount of systems	Total amount of systems	553
Amount of Top Units	Ratio of Top Unit systems	12.48%
Secondary hours	Total amount of hours not assigned.	686.96

Appendix H: Possible improvement scenarios

The following section is a result of an brainstorm session with the manufacturing engineers at Company Y, supplemented with ideas stemming from research done by me. From the list one scenario is selected for further analysis. The other scenarios are however interesting to look at in further research.

Scenario 1: Changing the starting point of the information binder (and thus the information flow) from the Subs. various comp. section to the Bosch-line. This will in turn merge the information flow with the production flow. In order for this to work an alternative information system that enables information to be available at all places of the production line at the same time will be needed. Testing out the benefits of the merger will be interesting, since these results can be used to strengthen a case for an investment into a new information system. A benefit of the merger is the fact that it enables the production of the sub-assemblies to takes place during the production of the fields at the Bosch-line, thus reducing cycle times. Some initial tests looking into the effectiveness of a new information system have already started at Company Y.

Scenario 2: Testing out several of the ideas proposed by the X 500 team that were specifically meant to improve the performance and the capabilities of the special section. The most interesting idea proposed by the X 500 was the following one:

<u>Hypotheses 1</u>: Merging the remote finishing, electrical finishing, plinth and chimney and top box section into one large section that processes all the nonstandard X systems will improve the performance of the line at higher takt levels. This hypothesis can be further divided into two versions namely the version where:

a) A X system is fully processed at one workstation (identical workstations).
b) Certain workstations are specialized in certain activities, by for example having one station solely building Current transformers

Scenario 3: Increasing the number of workstations in the special section, in the bottleneck section of this research it became clear that several sections required more workstations to function up to par at higher takt levels.

Scenario 4: Most of the stakeholders located at the manufacturing engineering department believe that the division between the X Block and the X Extendable is harmful to the performance of the line. This hypothesis could be tested by comparing the performances of a merged flow as opposed to a separated flow at different output levels. Merging the flow of the two types of X's can be done by:

a) Merging the remote finishing and electrical finishing section together as one big section with an x amount of workstations.
b) The coupling of X Ext. system happens in the special section after the system passes through the remote finishing section. However, coupling could also be done at the marriage step located in the Bosch-line. This would create additional workload and variability in the standard section, but it would reduce workload in the special section and it would remove the need for the X Ext. to pass through the primary testing section twice, thus reducing workload and variability at that station. In addition to enabling the merge of the two types of X's.

Scenario 5: Re-dividing the workload over the different sections and thus improving the balance in the line, by shifting some of the workload from one processing step to the other

Appendix I: Scope

Table 17: Components included in the model

Component	Include/ Exclude	Justification
Entities		
Forklift trucks	Exclude	Forklift trucks will not be part of the scope
Information binder	Include	Interesting entity to include, seeing as it dictates the order in which production takes place.
X (E), (Special)	Include	The wide variety of possible X's is one of the inputs for the model.
Activities		
<u>Manual operation</u>		
Processing steps standard section[1]	Include	These production steps are vital for the behavior of the production line.
Processing steps special section[2]	Include	These production steps are vital for the behavior of the production line.
Rework section	Include	One of the experimental factors
Cabinet supermarket	Exclude	Cabinet shortages rarely to never take place.
<u>Machine operation</u>		
Processing steps standard section	Include	These production steps are vital for the behavior of the production line.
Processing steps special section	Include	These production steps are vital for the behavior of the production line.
<u>Transport</u>		
Transport between production steps	Exclude	Travel between the consecutive production steps is not taken into account, as it is a relatively small contribution to the total throughput time. And because it is very hard to model, because there is no clear data on this.
Queues		
<u>Delay</u>		
Delay between production steps	Exclude	Delays between steps will not be included, two consecutive production steps will commence just
Production buffer[3]	Include	Essential for the nature of the system.
Resources		
Workers	Exclude	Will not be included for simplicity sake.

[1] Appendix K
[2] Appendix K
[3] Appendix K

Appendix J: Level of detail

Table 18: Level of detail at which components are included in the model

Component	Detail	Include/ Exclude	Justification
Entities			
X (E)/(special)	Frame	Include	The Frames are the casing of the systems, and their path through the line is essential to the nature of the system.
	Module	Exclude	The inclusion of the modules created at sub assembly station is not vital for the assembly process.
	Boschline finished prod.	Exclude	The inclusion of the Bosch-line finished product is not needed for the modelling of the flow.
	Routing logic	Include	Different X systems have different routes through the process; their route is specified at the product level.
	Processing times	Include	The processing times will be stuck to the different versions of the X
Information binder	Release time onto the line.	Include	The time at which a binder is released is the starting time of production. And is therefore interesting for the throughput time.
	Release protocol	Include	In the current situation orders are released according to their takt time as defined in section 2.1.
Activities			
Processing steps standard section	Capacity	Include	Is an experimental factor.
Processing steps special section	Capacity	Include	Is an experimental factor.
Rework section	Processing time	Include	The processing time distribution of a system entering
Queues			
<u>Delay</u>			
Production buffer	Logic	Include	The way orders are picked from a buffer is essential for the nature of the process.
	Capacity	Include	One of the experimental factors.

Appendix K: Processing step and buffer capacity.

Table 19: Buffer capacity for the different simulated production line models.

Production line lay-out	**Original**	**-**	**X 500A**	**--**	**X 500B**	**---**	**Content Buffer**
Buffer name	Takt 50	Takt 64	Takt 50	Takt 64	Takt 50	Takt 64	
Subs Assembly release orders	100	120	100	120	100	120	Info. binder
Frame Info. Binder storage	20	20	20	20	20	20	Info. binder
Frame cabinet storage	20	20	20	20	20	20	Frame
Frame cabinet storage 2	5	12	5	12	5	12	Frame
Boschline Info. binder storage	25	25	25	25	25	25	Info. binder
Boschline Cabinet storage	12	12	12	12	12	12	Frame
Boschline field storage	6	12	6	12	6	12	Fields
Component buffer	6	6	6	6	6	6	X system
Primary testing buffer	10	10	10	10	10	10	X system
Voltage test buffer	5	5	5	5	5	5	X system
Gluing buffer	6	6	6	6	6	6	X system
Leak test buffer	15	15	15	15	15	15	X system
Final Assembly buffer	6	6	6	6	6	6	X system
Secondary buffer Special	20	20	20	20	20	20	X system
Secondary buffer Standard	10	10	10	10	10	10	X system
EOL Assembly buffer	5	5	5	5	5	5	X system
X E buffer	20	20	-	-	-	-	X system
Special Buffer	20	20	-	-	-	-	X system
Coupling ready	15	20	15	20	15	20	X system
Coupling not ready	20	20	20	20	20	20	X system
Afmontage buffer	15	15	15	15	15	15	X system
Chimney and Plinth Buffer	10	10	-	-	10	10	X system
Top Unit Assembly Buffer	50	50	50	50	50	50	Info. binder
Special 500 buffer ready	-	-	20	40	20	40	X system
Special 500 buffer not ready	-	-	20	40	20	40	X system

Table 20: Processing step capacity for the different simulated production line models.

Production line lay-out	**Original**	**-**	**X 500A**	**--**	**X 500B**	**---**
Processing step name	Takt 50	Takt 64	Takt 50	Takt 64	Takt 50	Takt 64
Subs	5	5	5	5	5	5
PreFrame1	1	1	1	1	1	1
PreFrame2	2	2	2	2	2	2
Bottle assembly	1	1	1	1	1	1
Bottle mount	1	1	1	1	1	1
Switch enclosure	1	1	1	1	1	1
Mechanism	1	1	1	1	1	1
Marriage	1	1	1	1	1	1
Conus mounting	2	2	2	2	2	2
Pre components	1	1	1	1	1	1
Components	4	4	4	4	4	4
Visual Inspection	1	1	1	1	1	1
Voltage Test	1	1	1	1	1	1
Gluing	1	1	1	1	1	1
Leakage Test	1	1	1	1	1	1
Final Assembly	1	1	1	1	1	1
Secondary Testing	14	14	14	14	14	14
Secondary Testing Special	6	6	6	6	6	6
Doors	2	2	2	2	2	2
X Extendable	6	6	-	-	-	-
Coupling	2	2	2	2	2	2
“Afmontage”	2	3	2	3	2	3
Special	6	7	-	-	-	-
Chimney and Plinth	2	2	-	-	2	2
Top Box assembly	2	2	2	2	2	2
Special 500	-	-	14	15	12	13
Rework	1	1	1	1	1	1

Appendix L: The simulation model

In Figure 24 a screenshot of the simulation model can be found, in the next section we will start off with giving a quick overview of the model. The simulation model shown in Figure 24 is an exact representation of the conceptual model that was created in chapter 2 and 4, which means all the elements that can be found in the model have already been defined in previous chapters.

On the right side of Figure 24 the controls, the inputs and the outputs can be found. The inputs of the simulation model are a combination of a series of tables and parameters. The orderbook and the processing station table are both directly imported from an excel sheet. The orderbook table contains a data sample of a specific production week that is our base case, whilst the processing station table contains all the data specifying the behavior of the different stations in terms of capacity and processing time. The outputs are a combination of histograms, column-charts, and tables. The column charts that can be found at the top of the outputs try to give insight into the utilization of the different workstations. The histograms try to give insight into the distribution of the amount of WIP that can be found in the line at one particular moment in time. In addition to the distributions of the average throughput in a day and the average cycle time of a system. These graphs provide an adequate overview of the performance of the line. Lastly the controls are located at the bottom left of the picture, these controls are used to initialize, reset and manage the model during runs.

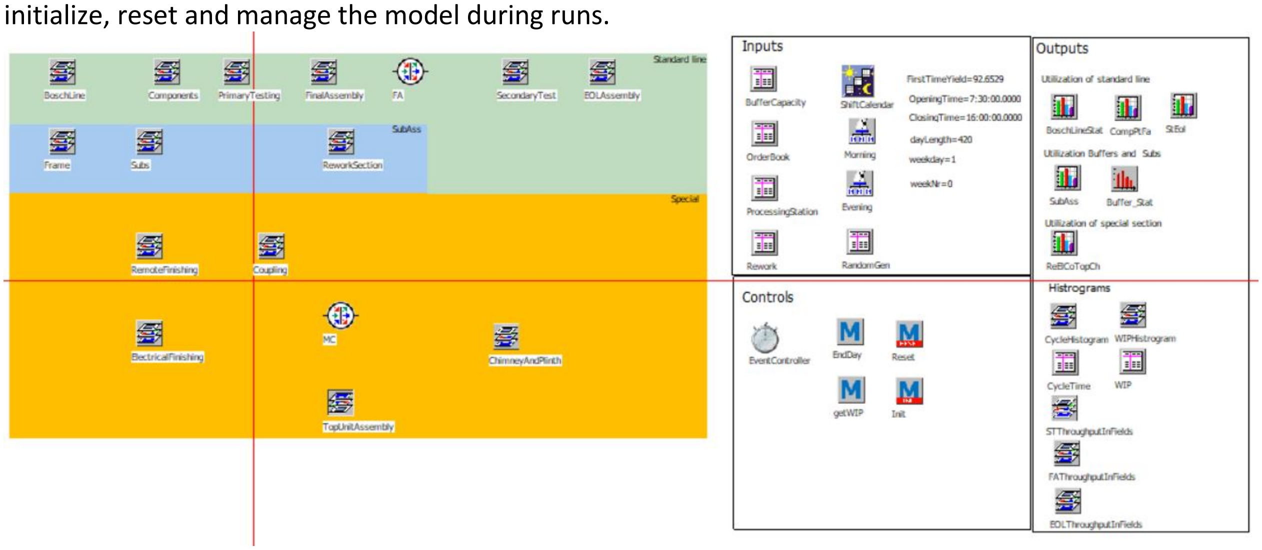

Figure 24: Screenshot of the simulation model

Appendix N: Warm up, Run time and Number of Replications.

The warm-up period will be determined with a visual check as suggested in the literature chapter. To be able to do this the simulation model was ran with the three months of the orderbook used for the validation of the model. The three-month period is extended to a period of 1000 days, and all the possible sources of variability are turned on as suggested in chapter 3.

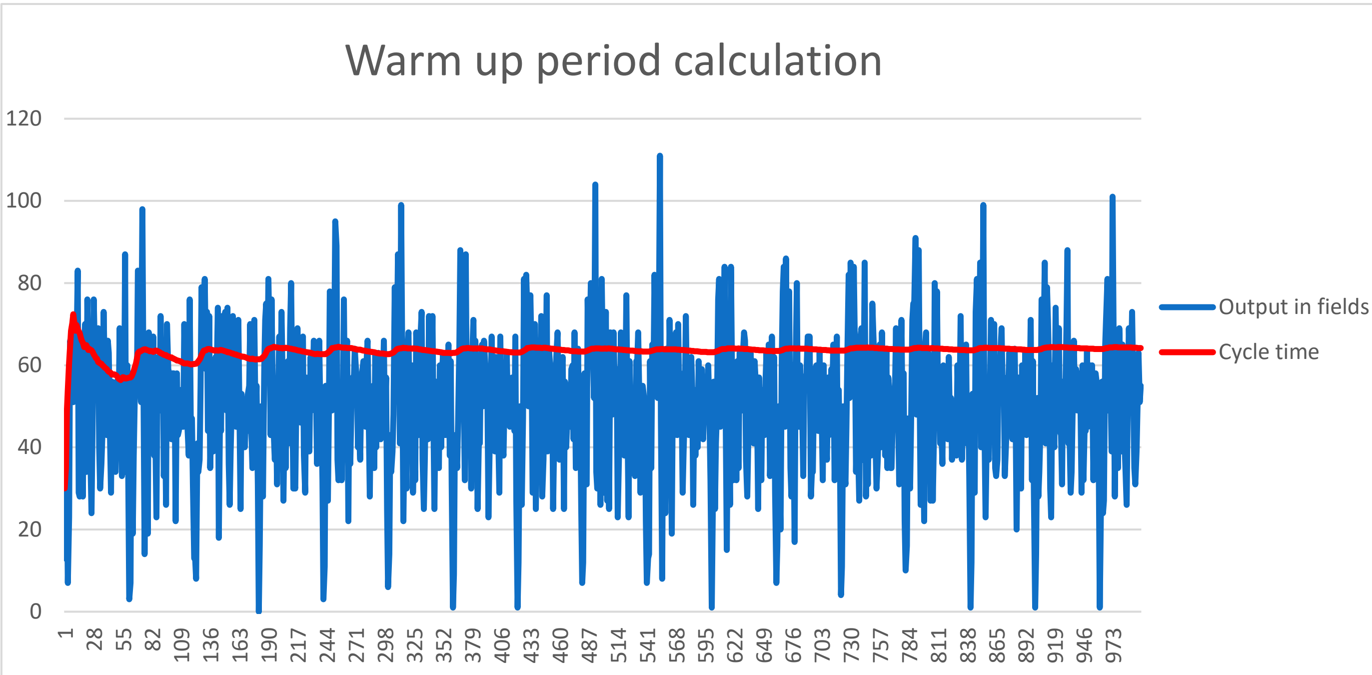

Figure 25: Calculation of the warmup period

From Figure 25 it became clear that the warmup period should be a 100 days. Which means that the appropriate run length should be at least 1000 days, this stems from the fact that the run length should be at least 10 times as large as the warmup according to the literature research.

The number of replications were also calculated with the method suggested in chapter 3 of this research. For a point estimate of our main KPI: Average throughput time to fall within a “small enough” interval we first had to determine what is “small enough”. The small enough interval was determined to be a 5% confidence interval, since most research conducted in the simulation field uses this confidence level. According to the method outlined in chapter 3, this leads to a minimum requirement of 6 replications.

Appendix M: Experimental Results

Figure 26-28 show that the utilization of the testing tasks is very high around 80%, whilst the utilization of the other tasks is around 50%-60%.

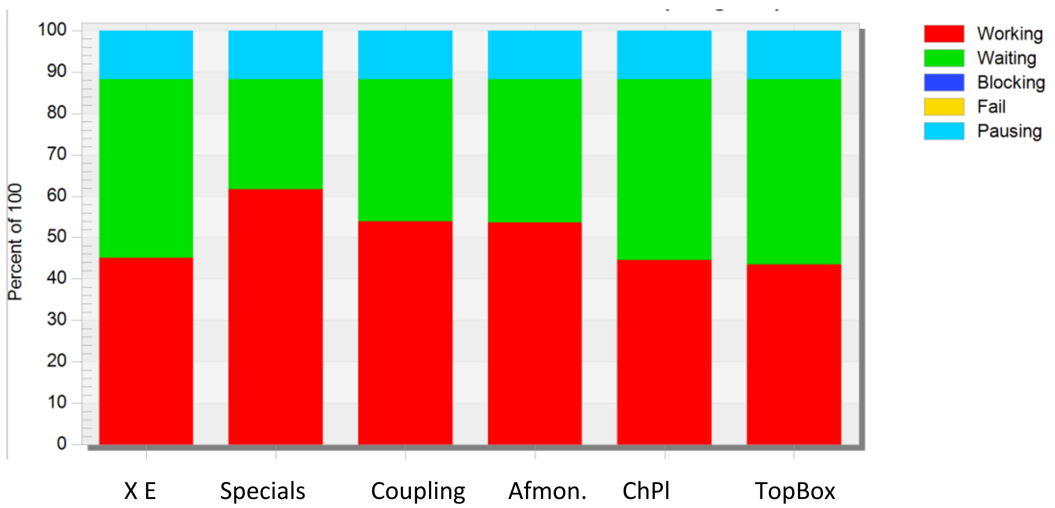

Figure 26: Utilization Special section scenario 1

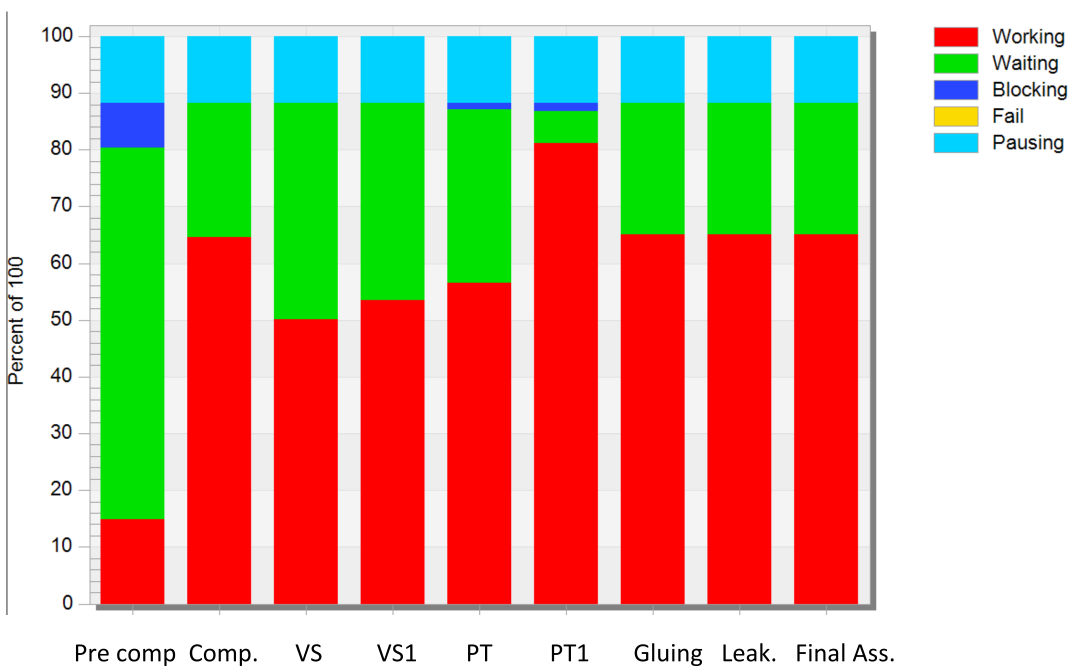

Figure 27: Utilization Standard section scenario 1 part: 1

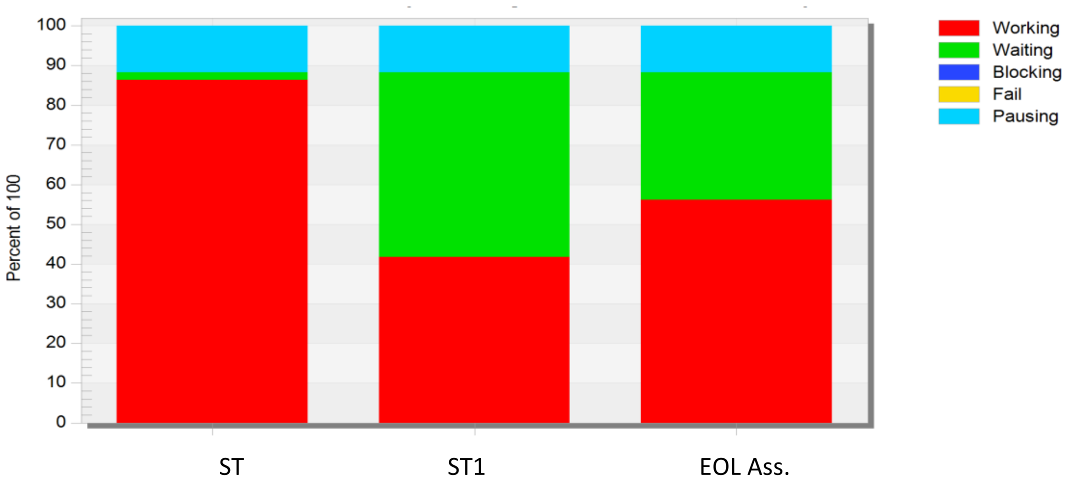

Figure 26: Utilization Special section scenario 1
Figure 28: Utilization Standard section scenario 1 part: 2

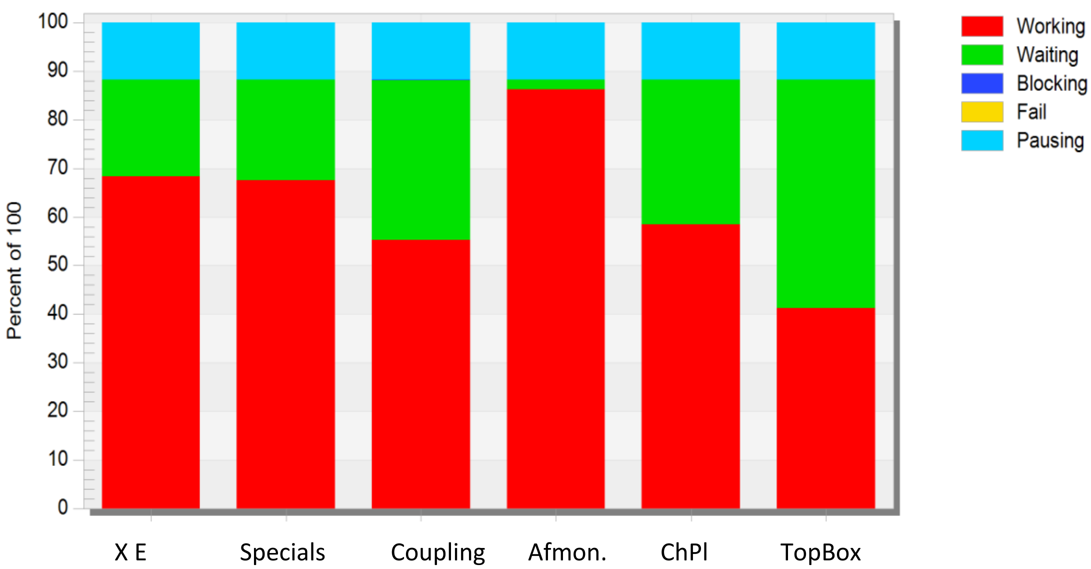

Figure 28: Utilization Special section scenario 4

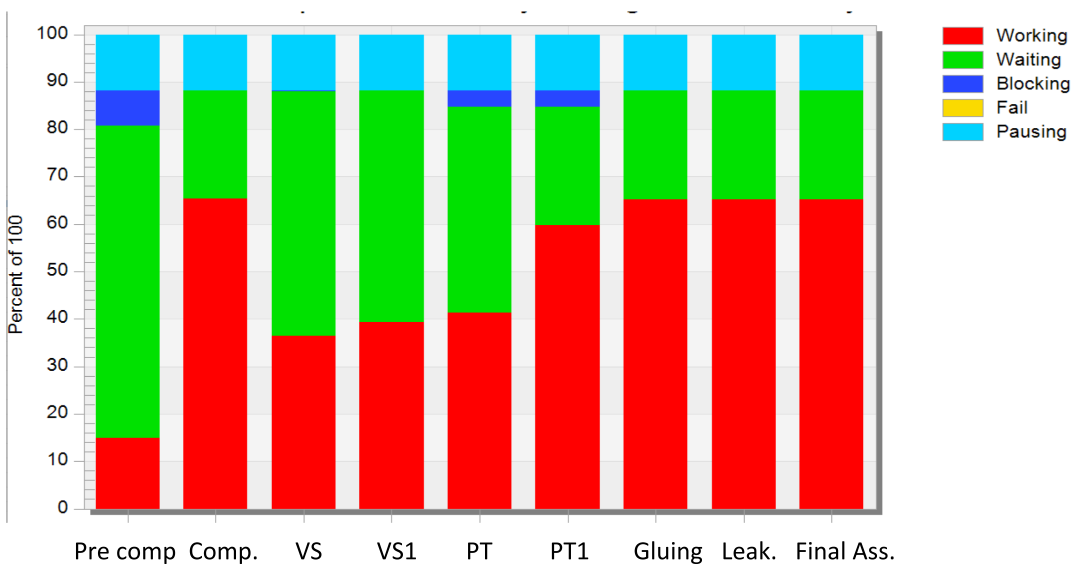

Figure 29: Utilization Standard section scenario 4

Figure 28-29 shows that upon enabling the sources of variability the bottlenecks shifts from the Standard section to the Special section.

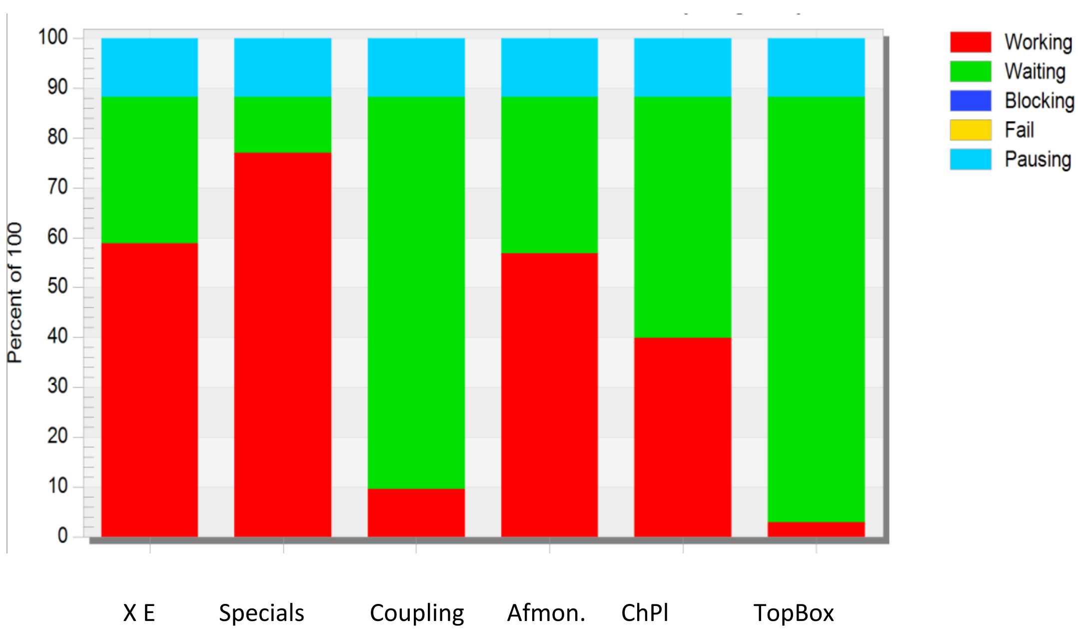

Figure 30: Utilization Special section scenario 6

Figure 27 and 30 shows us the effects of different production order mixes on the utilization of the special section. Figure 31 shows us the improvement in OTP over the different months that the X 500B production line is able to achieve.

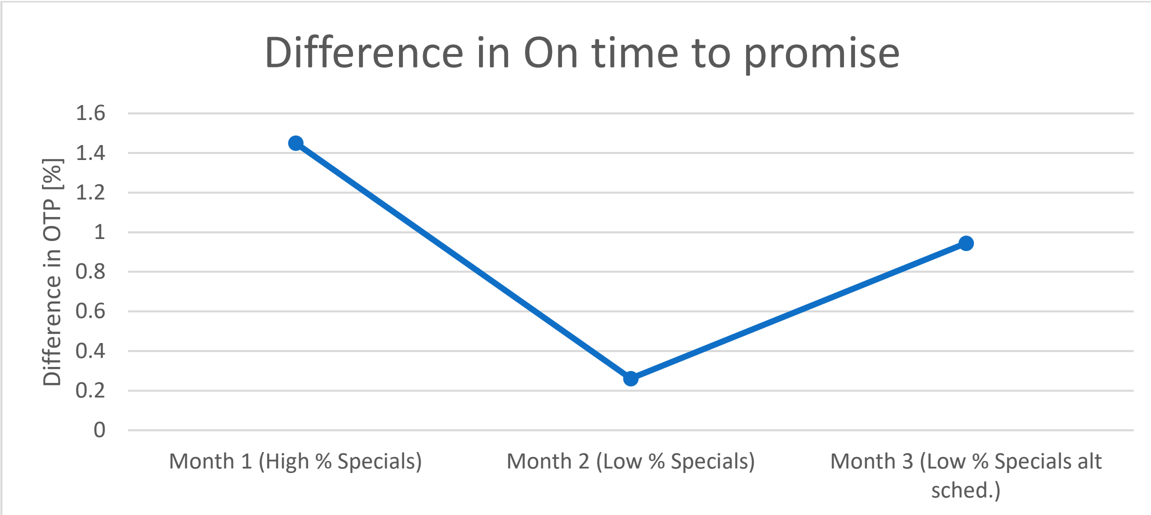

Figure 31: Difference in OTP between X 500 B production line and Original production line

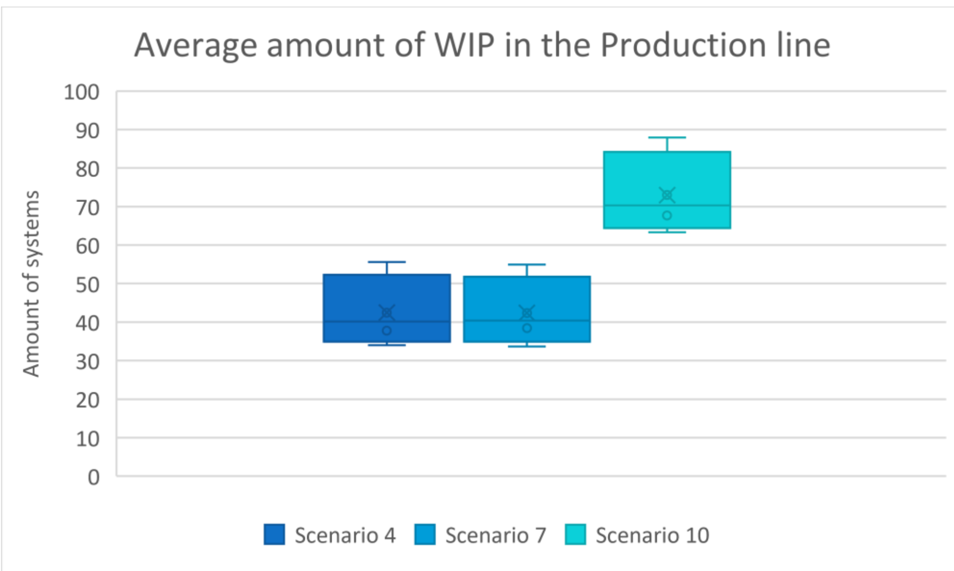

Figure 32: Average amount of WIP