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Lead time reduction by production planning and control at Company X

MASTER THESIS

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Preface

This thesis is the final part of my education at the University of Twente, where after five years I concluded my Bachelor and Master in Industrial Engineering and Management. During these years, I had great time with good friends and nice experiences.

I want to thank Company X and their employees for all their contribution to this thesis. In particular, I thank Y and Z for the opportunity they have given to me and their feedback.

Second, I want to thank Leo van der Wegen and Matthieu van der Heijden for their feedback and support as supervisors from the university. Especially during the early phases of this thesis, their guidance was worth a lot.

Last, I want to thank my parents that gave me their unconditional support.

Robert Noordhuis, October 2018

Summary

At Company X, printed circuit board assemblies (PCBAs) are mostly made in two sequential processes. The first process, SMD, is automated and places components on a bare board by a machine. For this process, a lead time of two weeks is used in planning. The second process, HMT, is a merely manual process and also includes the quality tests. For this process, a lead time of three weeks is used in planning. The total lead time is thus five weeks, which is quite high compared to competitors who offer two to three-week lead times. Another disadvantage in the current situation is a high Work-In-Process (WIP), leading to increased costs. Mainly for these reasons, the wish exists to lower the production lead time 50% of the current lead time, meaning lowering the total lead time used in planning to 2.5 weeks.

We started our research by analysing the various components of the lead time, with special interest to the waiting times and actual lead times. We conclude that the waiting times are the biggest part of the lead time, generally more than 80% of the total lead time of five weeks. Especially the waiting until the first operation is performed is too high. After release, it takes on average more than five working days before the first operation is performed. Two remarks are needed here. Picking in the general warehouse is not counted in this measure and that normally takes two days. Second, in the SMD process, operations until the final processing station are not registered. Even with these remarks, the waiting time till the first operation is too high.

With the use of a visual stream map and a problem bundle, we researched the causes of these waiting times. We notice that currently planning and the control of load is only done on a weekly basis, at the tactical planning level. At the operational level, load control is not used. Also, the current system is a push production system, meaning that orders are put in the system and expected to come out before the due date, without further control. For these reasons, we solve the problem of too high waiting times by proposing a new method for Production Planning and Control (PPC) on the operational level. We first research the literature for suggested method and did a qualitative analysis of the suggested method, before making a simulation model to do a quantitative analysis of the best PPC methods.

During the literature research, we mainly looked into methods to reduce the lead time by limiting the WIP. As proven by Little's law, the WIP is directly related to the waiting times. Limiting the WIP can be done by using a Production Planning and Control method on the operational level. During our research, we found three methods that according to the literature could work well at Company X. The first method is Workload Control (WLC), in which each station has a limit for the amount of work that is on the shop floor for that specific station. If the limit is reached and another order is available for processing, it may not be released to the shop floor. The effect of this method is that WIP is limited, reducing waiting times in the system. New orders are released on a daily basis and when a station starving, i.e. it has no orders left to process. The second method is Kanban. In this method, each station has a fixed number of cards and an order needs the card of the station it is moving to. In the case a card is not available, it may not progress to the next station and also does not release the card it is currently holding. Thus, when a station is full, it creates a chain reaction backwards, eventually to the point where new orders cannot be released due to a shortage of cards. The last method is Paired Overlapping Cells with Authorization (POLCA), which creates loops of two stations, which together get a single card. In order to allow processing, generally two cards are needed, one for the loop of the

previous and current station, and one for the loop of the current and next station. Besides the PPC methods, we also researched some priority rules, for determining the order in which we release the orders and in which order the repair department should handle the orders brought in.

Although these methods are recommended by the literature, it is unknown which method works best for the situation at Company X. We made a simulation model so that we can test the various methods and test their performance under the conditions of Company X. In this model we used order data of the second half year of 2018 and simulated the SMD and HMT departments based on their real-life properties.

The best working method for Company X according to our simulation study is WLC. This method provides the best results with lowest lead times and is relatively insensitive to minor changes and variations. For the order interval, we suggest a 4-week period. A shorter interval leads to increased total lead time and a higher interval leads to higher individual processing times due to increased order size, which the system is less capable of handling efficiently. For the transition between SMD and HMT, we suggest to release the HMT order to picking, as soon as picking at the SMD department starts. This ensures the best alignment between the SMD part for the HMT process and the other HMT components coming from the warehouse. Regarding the dispatch rules, no significant difference was found between multiple options. Therefore, we advise for the rules that are easy to implement and understand. This means First Come, First Served with priority for continued SMD to HMT orders for order release and Earliest Due Date for the repair department.

With these methods, it possible to reduce the lead for SMD to 4 working days, HMT to 14 working days and combined orders of these two to working 15 days. We also conducted a sensitivity analysis on this combination of methods. We found that the system is quite sensitive to incorrect estimations of processing times, if the mean is different between the estimated and real processing times. Variation between estimated and real processing times does not matter a lot, as long as the mean of both is equal.

To implement these methods, a 4-5 month period is needed. In the beginning, acceptance needs to established under employees, such that they see the benefits of the methods. Afterwards, a new IT system needs to be developed in which the actual load of each station can be seen. The data for this system is available, although it is spread over multiple platforms, namely Baan and PFS. After implementation, the most important phase of evaluation and control starts. The methods need to be monitored continuously and adjusted where needed. Also the implementation process needs to evaluated, especially if the possibility for implementation at other departments exists.

Further, we recommend to start tracking of processing times consistently, in order to increase the reliability of the data. At the moment this barely done, while WLC is quite sensitive for incorrect processing times. Finally, we recommend looking into the SMD Touch Up station. It no longer functions according to its original intent, as it is executed after the machine has finished instead of the same time, and it is meanwhile the biggest bottleneck in the SMD process. It could be a possibility to get rid of the separate station and merge it with the main HMT production station, which almost all products already pass anyway.

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Glossary

AOI	Automatic Optical Inspection
Baan	ERP software
BGA	Ball Grid Array
BOM	Bill of Materials
CODP	Customer Order Decoupling Point
CTB	Clear To Build
EDD	Earliest Due Date
ERP	Enterprise Resource Planning
ETO	Engineer-to-order
FASFS	First Arrival into System, First Served
FCFS	First Come, First Served
HMT	Hand Mounted Technology, also a department within Company X
JIT	Just In Time
LCFS	Last Come, First served
LUMS COR	Lancaster University Management School corrected order release
MRP	Material Requirements Planning
MRP-II	Manufacturing Resource Planning
MTO	Make-to-order
NPI	New Product Introductions
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly, a PCB mounted with components
PFS	Process Feedback System
PPC	Production Planning and Control
QRM	Quick Response Manufacturing
Rapid Response	Additional Front-End for Baan software, updated daily
RBC	Repeat Business Customizers
SMD	Surface Mounted Devices, also a department within Company X
SPT	Shortest Processing Time
TOC	Theory of Constraints
VSM	Visual Stream Map
VMC	Versatile Manufacturing Companies
WIP	Work-In-Process

Chapter 1 Problem Identification

In this chapter, the problem leading to this thesis project at Company X is introduced and research questions are identified. We start with a short introduction of the company in Section 1.1 and the problem as stated by them in Section 1.2, before giving some context of the problem in Section 1.3. The research questions are defined in Section 1.4, the scope in Section 1.5 and the deliverables in Section 1.6. The planning for the thesis is given in Section 1.7.

1.1 Company introduction

The products of Company X are used in various markets, main markets being aerospace, medical devices and the semiconductor industry. Company X offers two services, design engineering and production. Development of new products is generally not done; end products are designed by the customers. Design engineering for specific parts, given the specifications of the customer can be done by Company X. This can also be done as a separate service. The production process is an assembly process, which starts with an empty PCB and separate components. After assembly, the PCB might be the product delivered to the customer or be used as a component for a cabinet or similar, which is also assembled at Company X. This thesis focusses on the production process of the PCBs.

1.2 Motivation for research

In the current situation, a lead time of five weeks is planned in production for all PCBs. This is independent from the product, batch size or the number of orders in that period. In order to maintain a competitive position on the market, the logistics manager wants to have the lead time shortened and made dependent on the product. The latter meaning that different products can have different lead times, while in the current situation all products have the same lead time. Some of the competitors offer standard lead times of two to three weeks and options for emergency orders in about one week, clearly smaller than the normal five weeks of Company X. Other managers also have an interest in a shorter lead time, for reasons such as a decrease of Work-In-Process (WIP).

1.3 Problem context

Before taking a look at the lead time, we start with a global overview of the actual process of which the lead time should be shortened. Details of the processes have been left out at this moment; they are handled later on in 2.2 . The production process within the scope of this thesis consists of two parts, namely Surface Mounted Devices (SMD) and Hand Mounted Technology (HMT).

The first part of the process, SMD, is merely automated, where components are placed on a PCB by a machine. The production process is linear and almost all products follow the same routing. Company X has three production lines with machines of which two are almost identical, and one is different. This process has a lead time of two weeks and is separated from the second process. Both processes have different order numbers and the SMD order has to be finished, before the HMT order can start.

In the second part, HMT, routing becomes more complicated. A general direction of flow can be distinguished, although the workstations visited are different for every product. For almost all orders, inspections are carried out by testing the circuits, which a large number of orders fail. These failed PCBs are investigated by the Troubleshoot department, before being repaired by the repair department. The standard lead time for HMT is three weeks, making the combined lead time for SMD and HMT five weeks. For a small number of orders, both parts are combined into a single order.

1.4 Research problem and research questions

Based on the motivation for the research in 1.2 , a clear problem can be determined, namely a lead time that is too high. The problem is supplemented with a SMART goal, to get a clear objective. The goal has been set to propose a method that halves the current production lead time, which is 5 weeks. To make the goal specific, we take the lead time that is used on average in planning per order, which is also measurable. This lead time should of course be realistic and achievable in almost all cases, say 95% of the cases should be within the planned time. This goal has been set in collaboration with the company supervisors and has been agreed upon. Based on multiple interviews with managers, production supervisors and other personnel, this lead time is deemed be to achievable with the current machinery. The timeframe for solving the problem is 20 weeks, the length of the master assignment. Implementation of the proposed method is not included in this timeframe. With this information, we constructed the research problem as follows:

What measures should Company X B.V. take in order to get the combined lead time of SMD and HMT halved to two and a halve weeks?

Based on this research problem and the steps of a general managerial problem-solving method (Heerkens & Van Winden, 2012), a number of sub-questions have been established. These are answered throughout the thesis, in order to give an answer to the defined research problem.

1. *What are the causes of the current lead time being too high?*
   In Chapter 2 the process is analysed and we take a closer look at the lead time and its components. The goal is to find the components that cause the lead time to be too high and can be shortened. Interesting parts of the process include the decoupling of processes, planning and production control, and the forming of batches. In order to find the causes, a number of analyses is done. A Value Stream Map is made to achieve an overview of the process and how much time is spent where. Information is gathered from interviews with production personnel, managers and other employees, and data analyses. These data analyses, with data from the ERP package and production systems, look for correlations between lead time and order properties, as well as the correctness of the planned lead time. The following sub-questions are used:
   a. *What does the production process at Company X look like?*
   b. *What correlations exist regarding the lead time?*
   c. *What are the causes of the current long lead time?*
   d. *Which causes should be taken care of to get the largest decrease in lead time?*
2. *What methods are suggested in the literature to reduce the lead time, taking the process, causes, and company into account?*
   Chapter 3 delivers a literature review, focusing on solutions for the causes as identified in Chapter 2. The review sets out a framework and proposes a number of methods to reduce the lead time, for example by putting a limit on the amount of work-in-progress. We construct a couple of alternatives that might be suitable to implement at Company X. We look at pure methods from the literature, but also at combinations of different types of methods. Before constructing the alternatives, demands, wishes, preconditions and assumptions are taken into account as well.
   a. *What methods are suggested by the literature to reduce the lead time by limiting the work-in-progress?*

   b. *What are the preconditions and assumptions from the methods?*
   c. *What are the preferences from the company?*
   d. *Based on the preconditions and assumptions of the methods, which methods can be used to reduce the lead time?*

3. *How do the constructed alternatives perform regarding the lead time and other relevant KPIs in a simulation?*
   Chapter 4 focusses on a quantitative analysis of the various alternatives. This is done in a couple of phases, starting with designing a suitable simulation model, followed by data gathering and model building. Before experimenting, it is important to validate the model and make sure it is suitable for the goal and gives a representation of the actual situation as needed for this goal. After the experiment, the results are analysed.
   a. *How should the performance of the alternatives be measured and assessed?*
   b. *What should be the scope of the simulation model?*
   c. *What data is required?*
   d. *What are the results of the simulation?*

4. *What should be done in order to implement the solutions?*
   In Chapter 5, we take the results from the previous chapter and take a look at the implementation process. We research what needs to be done to make an implementation of the proposed method successful and we propose a global timeline.

After taking care of these sub-questions, we draw the conclusion to the research problem in Chapter 7, as well as giving recommendations and discussing the research.

1.5 Scope

To keep the project manageable, we confine ourselves to the SMD and HMT departments of Company X. Prior processes as designing and purchasing, as well as later processes such as Box Build and physically shipping the orders are outside the scope of this assignment. As mentioned in the previous part, yield has room for improvement, albeit not related to the field of this thesis. Improving the yield is thus outside the scope, although the yield of course has to be taken into account. Some products have a production step outside the facility, due to customer requirements; these are also outside the scope. Internal transport times are negligible and are left out.

1.6 Deliverables

This report yields a number of deliverables:

- A qualitative and quantitative analysis of the current lead time, leading to a method to reduce the lead time.
- An advice for Company X, which includes a proposed method for implementation and a global roadmap of the implementation process.
- A proposal for a method to determine the lead time for an order that can be used in planning.

Chapter 2 Current situation analysis

In this chapter we conduct an analysis on the current situation at Company X. Before going into the analyses, we start with qualitative interviews in Section 2.1 and a process description in Section 2.2, which will answer Research Question 1a. Multiple analyses are done, such as quantitative analyses in Section 2.3 and a value stream map in Section 2.4, which are used to answer Research Question 1b. With the use of a problem bundle in Section 2.5, the causes found in previous sections are organized and a number of issues are selected, to answer Research Question 1c and 1d. These issues are the ones that when solved, should yield a good trade-off between effort and impact on the lead time.

2.1 Qualitative interviews

Qualitative information is gathered by using semi structured interviews with numerous people in different layers of the company. This goes from the management team, through supervisors, till production. Also indirect parties are interviewed, such as IT and the warehouse. Information is checked between different interviews, where possible on multiple layers in the company. In a couple of cases, contradictory information is retrieved. For example, while gathering information for the Value Stream Map, the operational planner told that a product that failed the Flying Probe test and went through debug and troubleshoot, would skip the Flying Probe test for a second cycle and continue in the production process. The supervisors however said that the product would take the second cycle on the Flying Probe. We verified the process by the production employees, who said that the product would generally not take the second and that the planner was right. There are some exceptions for failures and repairs of complicated components, such as Ball Grid Arrays (BGAs).

Most information about the process is gathered by talking to production employees and supervisors. Most of this information is also handled with the operational and tactical planners, to get different views and opinions. Also the members of the management team of operations are interviewed, to retrieve their opinions and views. In the interviews with the supervisors, planners and management, there is a greater focus on possible improvements and what they would like to see differently. During interviews with the production personnel, improvements are also handled, although they focus more on their workstation and job instead of the process as a whole. During the interviews, notes are made, although they are not worked out formally and for that reason have not been included in this report. The information from the interviews is used as major source for the problem bundle in Section 2.5, but also used as a base for the upcoming sections.

2.2 Process description

In order to get a better understanding of the production process, we make a detailed description of the process. Roughly speaking, the process takes place in two departments, Surface Mounted Devices (SMD) and Hand Mounted Technology (HMT). The first process is automated and components are placed on a PCB. The second process handles the components and production steps that cannot be handled by the machines, as well as some inspections. In the second process, routes are different for most products, while in the first, most products follow the same route. The product mix is characterized as low volumes with a high variety, with a couple of dozens of orders a week and an average order size of 70 pieces. The high variety is the cause of the different routes in the second process, as different products need different processing steps. All products are made to customer specification and Company X does not have its own products. Engineering of the products can be done by Company X on request, or by the customer. According to the theory, as explained in Appendix D.1 , Company X is an Engineer-To-Order (ETO) company. It is important to mention that the engineering process is outside the scope of this thesis. The process within the scope by that can also be seen as a Make-To-Order (MTO) process.

2.2.1 SMD

For the first process, SMD, two weeks are reserved in the planning and the process starts with two days reserved for picking components. The PCB is placed in an oven and the components, most of which are on a roll, are placed into a feeder. Multiple feeders with components are placed on a bank, which can be inserted into the machine. After the machine has been set up with the feeders and the PCBs have come out of the oven, the PCBs enter the machine one-by-one. The PCBs first receive a layer of flux, which is needed for the soldering, before the machine places the components. At the end of the machine, the PCB enters an oven, where the soldering is finished. At Company X, there are three lines with SMD machines, which are not identical. Where two of them are quite similar, biggest difference being the maximum number of components that can be placed, the third line has more differences. This line has machines from a different manufacturer, meaning that programs required to use the machine are different, as well as some functionality. Only a limited set of products can be handled by this machine. After the machining, the PCBs go through an Automatic Optical Inspection (AOI). These machines inspect the PCBs on misplaced components and bad soldering with a camera and send deviations with a predefined model to the touch-up workstation. Originally, the AOI machines were a separate step, while new AOI machines are now placed in-line with the SMD machine. The new AOI machines are not suitable for all products yet, meaning that some products will still follow the old path with a separate AOI workstation. In the touch-up step, PCBs should be checked sample-wise, although in practice all PCBs are checked, and PCBs with given deviations are repaired if possible. If a repair is not possible by this department, the PCB is sent to the repair department, which happens rarely. In practice, almost all PCBs are checked by touch-up at the moment. After the touch-up, the first process, SMD, is completed. Some PCBs may skip the AOI step on customer request, to save the money spent on programming the machine, although most PCBs follow the same steps. A flow chart of this process can be found in Figure 2-1.

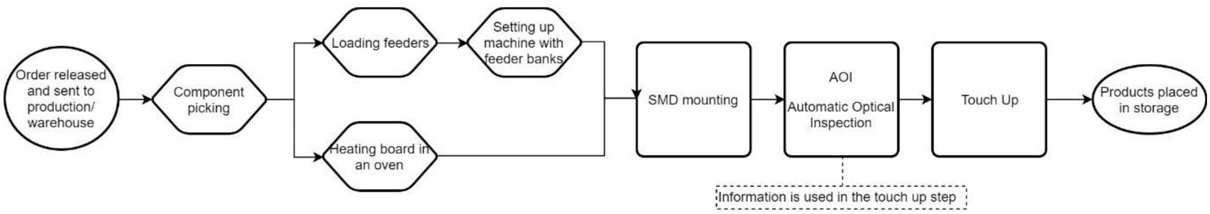

Figure 2-1 Flowchart SMD

2.2.2 HMT

In the second process, HMT, products follow different routes; the general route is explained first, before stating some of the possible deviations. For this process, a fixed period of three weeks is used in the planning. Before the process itself, there are two days reserved to give clear to build (CTB) and to release the order, before the picking of components starts. After the order is released, two days are used for the picking of components, before the hand mounting of these components takes place. These components cannot be placed by the SMD, hence need manual placement. They can be soldered manually or by a selective wave soldering machine. After the soldering, the PCBs are visually inspected, before going to the Flying Probe. These machines place pins on the PCB and put a current on it, in order to check the inner circuit workings. Company X has four of these machines, two pieces of two different types. The programs needed for testing are machine type dependent, hence flexibility is limited. This inspection is the first, including the SMD process, that does not rely on optical inspection and for that reason notices a lot of mistakes that have not been noticed with earlier inspections. It regularly occurs that a PCB fails the test, although the PCB is correct. This can happen for various reasons, as slightly displaced, though functioning, components or environmental factors. In these cases, the program used for testing, needs to be debugged. If the problem is in the PCB, it is send to the Troubleshoot workstation, where they try to find the error. After the error has been found, the PCB is repaired by different people and checked again by the troubleshooters. If the Flying Probe test has passed or the repair is finished, the PCB might undergo some more inspections, such as a Functional Test or Boundary Scan, before being sent to Final Inspection. Here, a final visual inspection is done, as well as some administrative work if necessary. The PCB is afterwards packed, before being sent to shipping for delivery to the customer. The customer might also be internal; in such a case shipping is obviously replaced with sending to another department, e.g. Boxbuild, or warehouse. A general flowchart of this process is given in Figure 2-2.

As mentioned before, not all products follow the same route in HMT, although a general flow can be seen. Some PCBs do not need hand mounting and go straight to the Flying Probe, while others need to go hand mounting twice as they need components on both the top and bottom side, which cannot be soldered simultaneously. While most products go through a flying probe test, the other tests happen at a less regular basis and are different per customer. Other products pass the final inspection station multiple times, all on customer demand and requirements.

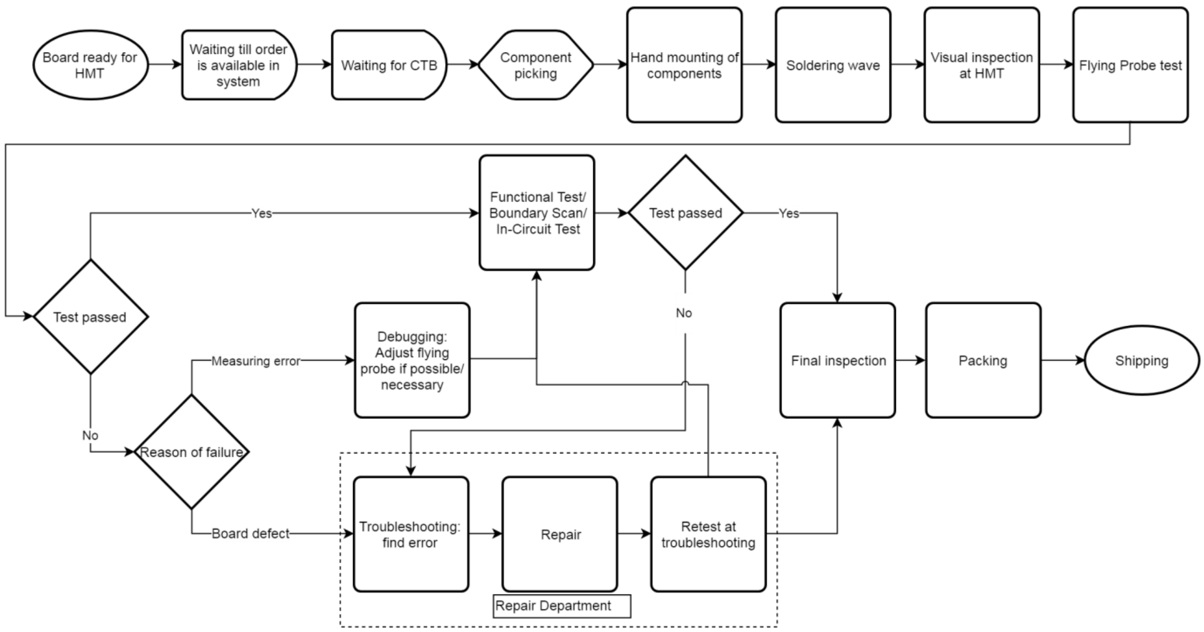

Figure 2-2 General Flowchart HMT

2.3 Quantitative analyses

In this section, we analyse the data available and look for correlations. We first take a look at various IT systems and available data, before taking a look at the current lead time, processing times, waiting times and the yield. The goal is to describe quantitatively and find possibilities for improvement.

2.3.1 IT and data preparation

Within Company X, numerous IT systems are used. In this section, we go through the relevant systems and the data they collect and show. First system is Baan, the ERP package. Purchasing, finance, warehousing and planning are done in this system. Second system is Rapid Response, which is used as a Front-End of the data available in Baan, although it is updated only once a day. This system is used for more detailed capacity planning and checking the clear to build. Due to this fact, orders are only released when they are CTB in Rapid Response, which is a day delayed. Third system is PFS, or Process Feedback System. This system is mainly used in production and is used to keep track of orders and their status. Fourth system is Agile, which is used for documentation and work instructions. Besides these systems, Excel is used for anything that can't be done in the previously mentioned systems. During the research, we had access to all systems except Agile. Additionally, we had access to some of the databases on which the systems work and data dumps from these systems.

In Baan all general data is stored, such as the Bill of Materials (BOM), the routing, and order start and due dates. There is also an option for order tracking, in which the status of various routing steps is tracked. This includes for example when an order has finished a production step according to PFS. The connection from PFS to Baan, however, has a short delay of 30-60 minutes. In PFS data is stored in two important ways. First are the scans of products. Each single product has a unique barcode, that is scanned when it has finished a specific production step. This means that for most production steps, it is known when a product and consequently an order, has finished that step. Unfortunately, this system is not implemented in all SMD steps, where it only starts at Touch Up. Before Touch Up, there is no PFS and hence no order tracking data in Baan. In May 2018, there is a change coming up to start with scanning earlier in the process. A second type of data from PFS are so-called sessions, which can be started by employees while working on a specific order. Unfortunately, employees do not use this function consequently, hence the data is contaminated. At the moment an order is released or completed, this information is sent to PFS, which stores the dates in a database.

Based on this data, we constructed a dataset with dates of each orders. This set includes the release and completion date directly from PFS, which are stored from the order release and completion in Baan, extended with the date of the first registered scan action in PFS. This is used as the start date of an order, the moment the employees actually started with an order. It is important to mention that this is not accurate for SMD, as the first steps of that process are not connected to PFS through barcode scanning or another system. Within each order, we grouped the available scan data per product and calculated the date of their last scan. Together with the filter for only completed orders, this corresponds to the completion dates of individual products. Next, when grouping per order, we took the first completed product as first finish, and the last product as last finish. The time between these is very small, if a batch is completed at once. When a product is reworked separate from the batch, the time will be larger. The times between the various dates, is calculated in working days, taking the company-wide holidays into account.

Yields have been calculated on the scan data as well. If a product fails an inspection, it needs to pass the inspection at a later moment before the next step can be signed off. This is registered as a second or subsequent cycle. Yield is then calculated as a percentage that did not need the concurrent cycle.

Processing times are based on the session data of PFS. This data is incomplete and can only be matched with a part of the orders. Orders without available data are not considered. Of the remaining orders, we match the measured processing times with the quoted processing times from Baan. Next, we clean the data before processing. We first look at the outliers from the actual registered processing times and remove the data that was unnaturally high and for example was registered over the weekend. We also checked the Baan data for outliers, but we eventually decided to not delete any data. Outliers in the data were checked and actually corresponded with the data in the system, hence giving a realistic view of the system.

Within the production of Company X, there are multiple departments, which are not all relevant for this research. The best method to filter on department is with the use of the "SFC" planner code, which is known for each order number. This planner code belongs to a department and sometimes has additional properties. Within the data, this is the most reliable method of filtering the data on departments; for this reason, we use this piece of seemingly less relevant information. We briefly go through the most relevant codes in the list below:

- PLN431: HMT
- PLN801: SMD, products that can only be produced on Machine 1
- PLN802: SMD, products that can only be produced on Line 2. This code is being depreciated as all products can also be made on Machine 1 and are thus a subset of PLN803
- PLN803: SMD, products that can be produced on Machine 1 or 2

A couple of other planner codes are used as well on the SMD and HMT departments, these include:

- PLN111: Protocenter, here prototypes and NPIs are made for the PCBA department (SMD + HMT)
- PLN708: Y HMT, HMT for a single customer. Historically from the time it was a separate line in Hengelo owned by Y
- PLN800: SMD for NPIs, for debugging and software programming
- PLN804: Y SMD, products that can only be produced on SMD Machine 3. Also historically it was a separate line in Hengelo owned by Y

2.3.2 Lead times

The lead used in planning is two weeks for SMD and three weeks for HMT. We did an analysis on the lead time as seen in Baan, where we take the time between the moment of order release and the moment the order is completed according to the system, which has a delay on the products physically being completed. We also take a look at the moment the first product is completed and the time between the first and last completed product.

In Table 2-1, we present an overview of the average lead time and some of its components in the period January 2017 till March 2018. The release dates are based on data of the connection between Baan and PFS, while the start and finish date are based on PFS data. All times are given in working days, weekends and company-wide holidays have been left out. The start and finish dates require processing steps connected to PFS, which in SMD is not always the case. In the "normal" SMD lines (Hengelo lines are a bit different), this can be noticed in the average time between start and first finish, which is less than a day. The registration towards PFS only starts at Touch-Up, which is in most cases the only step from that point onwards. Another point of interest is the time between order release and the first start, which is for most planner codes more than 6 working days, including two days reserved for picking. A distinction is made between first and last finish, which is the first PCB and the last PCB of the order to finish a registered production step. The difference between the lead times of these PCBs gives an indication for the amount of time taken by repair. When looking at the time between release and first finish, we see much lower averages, also below the quoted times. This means that there is too much time between the first products finishing and the full order being completed, when compared to the quoted lead time. The process is capable of outputting products within the quoted lead time, although it does not do this consistently for all products. For HMT, the situation is the same.

	Release to first start		Release to first finish		Release to last finish		Start to first finish		Start to last finish		Avg. batch	Number of
Plannercode	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.	Average	St. Dev.	size	records
PLN111	6.96	4.57	12.86	7.54	20.16	20.34	5.89	5.99	13.19	20.39	17.64	379
PLN431	6.75	5.07	12.45	6.81	19.72	18.65	5.68	5.02	12.95	18.31	79.98	1297
PLN708	6.22	4.89	12.78	9.08	15.27	20.72	6.55	8.30	9.04	20.25	6.38	368
PLN800	4.60	3.61	9.42	10.14	10.46	11.68	4.77	8.07	5.80	9.22	43.89	18
PLN801	8.40	5.97	9.33	5.89	16.63	20.80	0.90	2.43	8.20	20.37	268.42	156
PLN802	6.56	4.59	6.56	4.59	9.88	5.93	0.00	0.00	3.33	3.81	1277.47	19
PLN803	6.98	5.65	7.59	6.00	10.39	12.53	0.57	2.54	3.37	11.19	93.04	1026
PLN804	4.48	4.57	16.04	9.10	18.76	12.09	11.55	8.59	14.27	11.86	19.01	232

Table 2-1 Lead time and standard deviation of the population per department/planner code in working days

Next, we start looking for correlations regarding the lead time and order properties. It turns out there is no significant correlation to the order quantity over all orders, as can be seen in Table 2-2. Strongest correlation is 0,14 to the time between the start and the last finish, although it is not significant. From the other correlations, the one between release to completion and start to completion catches the eye, being 1. This would mean the time between release and first start should be quite consistent. It turns out that the standard deviation on this time is indeed lower, as can be seen in Table 2-1.

We have also researched the correlations across the various departments, which can be found in Appendix A . For the standard HMT, PLN431, we notice clear correlations of start to last finish with statistics as release to last finish, release to completion and start to completion. This indicates that in most cases, lead time, which is equal to release to completion time, has a clear relationship with the time between the first and last action on an order. Meanwhile, there is no clear correlation with the times till the first finish. For SMD, PLN801/2/3, we see a similar correlation, albeit not a strong one. We do, however, notice another strong correlation, between release to first start and release to first finish. This data however is probably skewed, as in most cases only one routing step is scanned, such that the time between first start and first finish is 0. When looking at the Y HMT correlations, PLN708, we notice a lot of strong correlations between the different measures. There are no strong relations with the time between release and first start, as well as quantity, with the other times. For Y SMD, PLN804, we notice similar correlations, although the correlations with quantity catch the eye, al being negative. Although they are not as significant, this means larger batches go through the system faster. This might have to be due to the fact that larger batches consist of less complex products, as the correlation between batch size and number of components is -0.278. This correlation is calculated separately. If we split out the SMD codes to the individual codes, we do not see significant differences from the combined result. It is only worthwhile to mention that all PLN802 orders consisted of only one scanned step in the analysed data.

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	0.0001	1						
Start to first finish	-0.1087	-0.0419	1					
Start to last finish	0.1438	-0.0412	0.6676	1				
Release to first finish	-0.0984	0.4254	0.8863	0.5856	1			
Release to last finish	0.1370	0.3059	0.6215	0.9386	0.7048	1		
Release to completion	-0.0066	0.0661	0.0611	0.0087	0.0864	0.0314	1	
Start to completion	-0.0066	0.0653	0.0611	0.0087	0.0861	0.0312	1.0000	1

Table 2-2 Correlations

Next relation to look into, is with start date. In Figure 2-3 a couple of line graphs are given, showing the average lead time per department in three different ways, as well as the average WIP measured in man hours. The dates in the figure are beginning after the summer holiday and have been cut off after February 2018 to make sure the data is complete and not set off by the holiday. On the left-hand side, we see the SMD graphs showing a clear peak around November 2017, which corresponds with a higher load on the system and as expected from Little's Law, the lead time increased. This quarter was the busiest in the history of Company X. In HMT there is also a peak noticeable around December, albeit less clear. Easier to notice is the downwards trend in average time from release to start and first finish. This is due to the fact that the operational planner started shortening the available lead time for HMT. This has had the effect that orders are started sooner after they have been released, although the time to the first has slightly increased. When we compare the lead time with the WIP, we notice that the increase corresponds with the increase in WIP. After the initial increase of WIP, the lead time decreases, while the WIP stays stable for some time, indicating a stabilization of the production process.

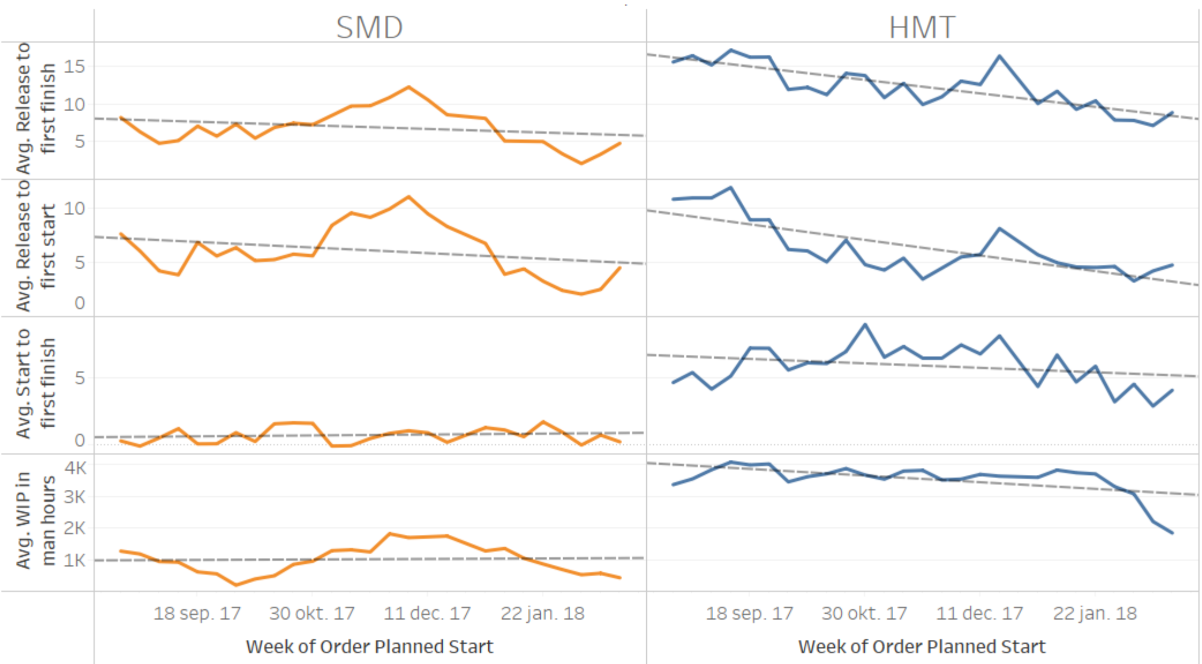

Figure 2-3 Lead times in days with start date on the x-axis

2.3.3 Processing times

Registration of processing times at Company X is difficult. The quoted processing times in Baan are divided by 100 before being used for planning and then a delay is added to make sure due and delivery dates are correct. This is done to make sure all lead times in the ERP software are 2 or 3 weeks and not influenced by the processing times. When transferring the data to Rapid Response, this factor is removed, causing huge shifts in expected lead times. The fact that one system works with working days and the other with calendar days also doesn't make things easier. As the processing times haven't really be used a lot in planning, not a lot of attention is being paid to these and they have not been updated for a long time. Nowadays, they start to get used more frequently for capacity planning. Another reason they have not been updated, is the lack of correct registration of actual processing times. For SMD, no connection towards PFS is available for most steps and data is manually collected. This data is often incomplete. Since April 2018, however, there is a project going to improve the planned processing times of SMD, which is likely be implemented in the coming months. For HMT, a connection to PFS exists for all steps.

The data that is available, actual processing times from PFS and quoted times from Baan, is analysed and the results are summarised in Table 2-3. The first column gives the mean absolute percentage error (MAPE) as |actual-planned|/planned. The second column gives the normal average difference, or the MAPE without taking the absolute value. The table is sorted on the first column and has been filtered on a minimal number of records. We notice that the best performing station already has an average absolute difference of 92%, meaning the estimates are not very accurate. On the average, however, it seems to be quite accurate on the totals with a deviation of -6.2%. In Appendix A we added some additional information for comparing the planned processing times with the actual processing times. Our conclusion is that processing times are barely known in detail and there is currently no priority on gathering this information.

Workstation	Average Abs Diff	Average Diff
Prepacking	92.2%	-6.1%
Selective wave	150.6%	91.9%
Final inspect	158.5%	104.4%
Packing	176.4%	94.0%
Unit montage (HMT)	198.7%	139.7%
Hand mounting	332.1%	256.7%
Depanelisation	433.2%	365.6%
Serienumber conversion	472.9%	390.9%
HMT Touch-up	594.3%	558.1%
SMD Touch-up	771.4%	742.9%

Table 2-3 Comparison of planned and registered processing times

2.3.4 Waiting times

Unfortunately, there is no clear data available from the waiting times at different stations. It is, however, possible to make an estimate of the waiting times by calculating the time between the start of subsequent processes. This method, however, has the drawback that the processing time of the previous production step is included in the waiting time. To compensate, we subtracted the average processing time of the previous operation, if available. The data is based on scan moments from the PFS system. The waiting times are given based on 8 working hours per day and on full days of 24 hours, and weekends and company-wide holidays have been filtered. In Table 2-4 the waiting times for HMT are given. For SMD no clear data is available, due to the lack of registration in PFS. We notice that the two highest waiting time occur at non-default routing steps, namely debug and rework. Further we notice long waiting times for HMT Touch-Up and Final Inspect, which can be explained by the fact that they wait for the complete batch, which is often delayed by the Flying Probe. At the Flying Probe, fails are often given, making debugging necessary which is an additional waiting time for a part of the batch.

Workstations	8 hours/day	24 hours/day
Debugging	12:12:19	40:30:34
Reworking/repair	25:41:13	77:58:29
Flying Probe first side	4:10:35	14:32:43
Flying Probe last side	0:48:28	7:18:23
Depanalisation	0:56:22	11:19:13
Final inspect	7:00:54	26:41:25
Hand mounting	1:41:26	7:08:23
Hand mounting 2nd cycle	4:32:51	18:23:15
Packing	2:27:33	8:18:43
Post solder	2:32:19	13:16:05
Selective wave	2:41:29	20:31:57
Selective wave 2nd cycle	0:46:02	10:33:25
Serienumber conversion	2:49:17	10:49:17
HMT Touch-Up	7:31:21	26:27:20
Unit montage	1:13:01	8:36:06
Serienumber switch	0:05:13	4:50:03
Boundary scan	6:12:13	20:32:55

Table 2-4 Waiting Times HMT in hours:minutes:seconds

2.3.5 Yield

In order to analyse the yield, we look at the number of cycles a single PCB makes at a single station. These results are then grouped by PCB and later by order. This means the numbers in Table 2-5 and Table 2-6 show the number of PCBs going at least once through a specific cycle number, e.g. a third cycle at a single station. The totals at the end of the row are the first pass yield, the second pass yield based on the PCBs that enter the second cycle and the total yield after two cycles. Yield is calculated as the number of PCBs going through the first cycle minus the number going through the second, divided by the number going through the first. Only the first four cycles have been given. We notice that the yield in the general SMD (801, 802, 803) is quite high, while the yield in the general HMT (431) is very low. This does not mean HMT makes more errors, but that during HMT more errors are detected, even though they can be made during SMD. As mentioned previously, non-visual inspections only take place in HMT, hence SMD errors or defect components might only be noticed there. This effect can be witnessed with code 804, which are combined orders for SMD and HMT, where the yield is similar to the HMT yield. We can also see that a decent yield on PCB level, does not result in a good yield on order level. The low score on code is 111 is also not surprising, as these are New Products Introductions (NPIs). These PCBs are new and more prone to small errors and miscalculations. A more surprising yield is with code 708, which is HMT for a specific customer, and has a clearly better yield.

Row Labels	Cycle 1	Cycle 2	Cycle 3	Cycle 4	1st pass	2nd pass	Total after 2nd
PLN111	681	424	166	77	37.74%	60.85%	75.62%
PLN431	1325	780	402	233	41.13%	48.46%	69.66%
PLN708	534	130	42	16	75.66%	67.69%	92.13%
PLN801	288	23	13	5	92.01%	43.48%	95.49%
PLN802	566	11	9	9	98.06%	18.18%	98.41%
PLN803	436	17	4	3	96.10%	76.47%	99.08%
PLN804	228	133	40	9	41.67%	69.92%	82.46%
Grand Total	4111	1547	680	354	62.37%	56.04%	83.46%

Table 2-5 Yields per order

Row Labels	Cycle 1	Cycle 2	Cycle 3	Cycle 4	1st pass	2nd pass	Total after 2nd
PLN111	14567	2908	520	168	80.04%	82.12%	96.43%
PLN431	121175	7356	1591	586	93.93%	78.37%	98.69%
PLN708	3297	630	83	21	80.89%	86.83%	97.48%
PLN801	56321	423	51	11	99.25%	87.94%	99.91%
PLN802	59934	667	135	51	98.89%	79.76%	99.77%
PLN803	52480	381	49	17	99.27%	87.14%	99.91%
PLN804	4931	827	282	12	83.23%	65.90%	94.28%
Grand Total	313161	13278	2726	878	95.76%	79.47%	99.13%

Table 2-6 Yields per PCB

2.4 Value stream map

In order to create a clear view of the current state of the process, we made a Value Stream Map (VSM). The goal is to get an overview of the process, the information flow and the production control. Based on the VSM, we can identify improvement opportunities in the process. The VSM is constructed with Rother & Shook (2003) as a guideline. The information has been gathered by own experiences, interviews and data analysis. The data used is mainly retrieved from the Process Feedback System (PFS) and is based on the length of sessions of employees working an orders and intervals between product registration at different workstations. Cycle times are based on the average number of products passing through a workstation and also take the number of shifts into account. During the process of making the VSM, validation is done in cooperation with operation and tactical planners, the Lean manager and the production supervisors. The production steps used in the VSM, are included in the routing of most products. The timeline is based on the standard routing and a debug or repair cycle is not included in the total time.

Based on the VSM, which can be found in Appendix C , we notice that most of the time is spent waiting. On order level, the waiting is 94.4% of the lead time and on product level even 99.9%. A substantial amount of waiting is after Touch-Up, till HMT starts. If Touch-Up is finished as the last production step, this is not communicated to Baan. The order needs to be closed manually. After the order is closed, it takes another day till the data is visible in Rapid Response, which is only updated once a day at night. The data is from Rapid Response is necessary before the order can released and picking for HMT can start. After picking, there is also a substantial amount of waiting time till the production itself starts.

With regard to the production control, we notice numerous systems that are linked in one or multiple ways with each other and the production process. Some data is updated only once a day, causing delays and a lag in the information flow. We also notice a lack of information from the first production steps, where data and times are not consistently measured. In most steps, a push system occurs, where the first product arriving is also processed first (FIFO). For Touch-Up and Flying Probe, however, a separate new planning is made based on due dates and other priorities. This causes a disruption in the FIFO flow.

2.5 Problem bundle and selection for further analysis

In the current situation, with regard to the lead time, we identified numerous problems and mapped them into a problem bundle. To find these problems, we conducted interviews with various employees, own experiences and analyses. The full bundle can be found in Figure 2-4. Starting with the core problem, a too high lead time, we go towards the various components of the lead time, which are explained in Appendix D.3 . For each component that can be lowered, various causes exist for it being on the current level. We left out the component internal move time, as we assume these to be negligible as mentioned in 1.5 . In the field of wait-to-move time, we did not determine a problem of the time being too high. If a batch is not complete, e.g. due to a PCB in need of repair, the rest of the batch is continuing production as normal.

From the various components, we work towards the root causes. The bundle is quite extensive, although it is not complete. Smaller causes that have a minimal effect on the lead time have been left out, in order to keep the bundle manageable and effective. From the determined root causes, a selection has to be made that can be solved in this project. The goal is to focus on one big cause that has a lot effect on the lead time and can be solved in the period of this project. While solving this problem, some other can be solved in parallel, for example if they are in the same area e.g. planning.

In Table 2-7 we briefly go through the various root causes, stating some additional information about them if necessary and their appropriateness for further investigation.

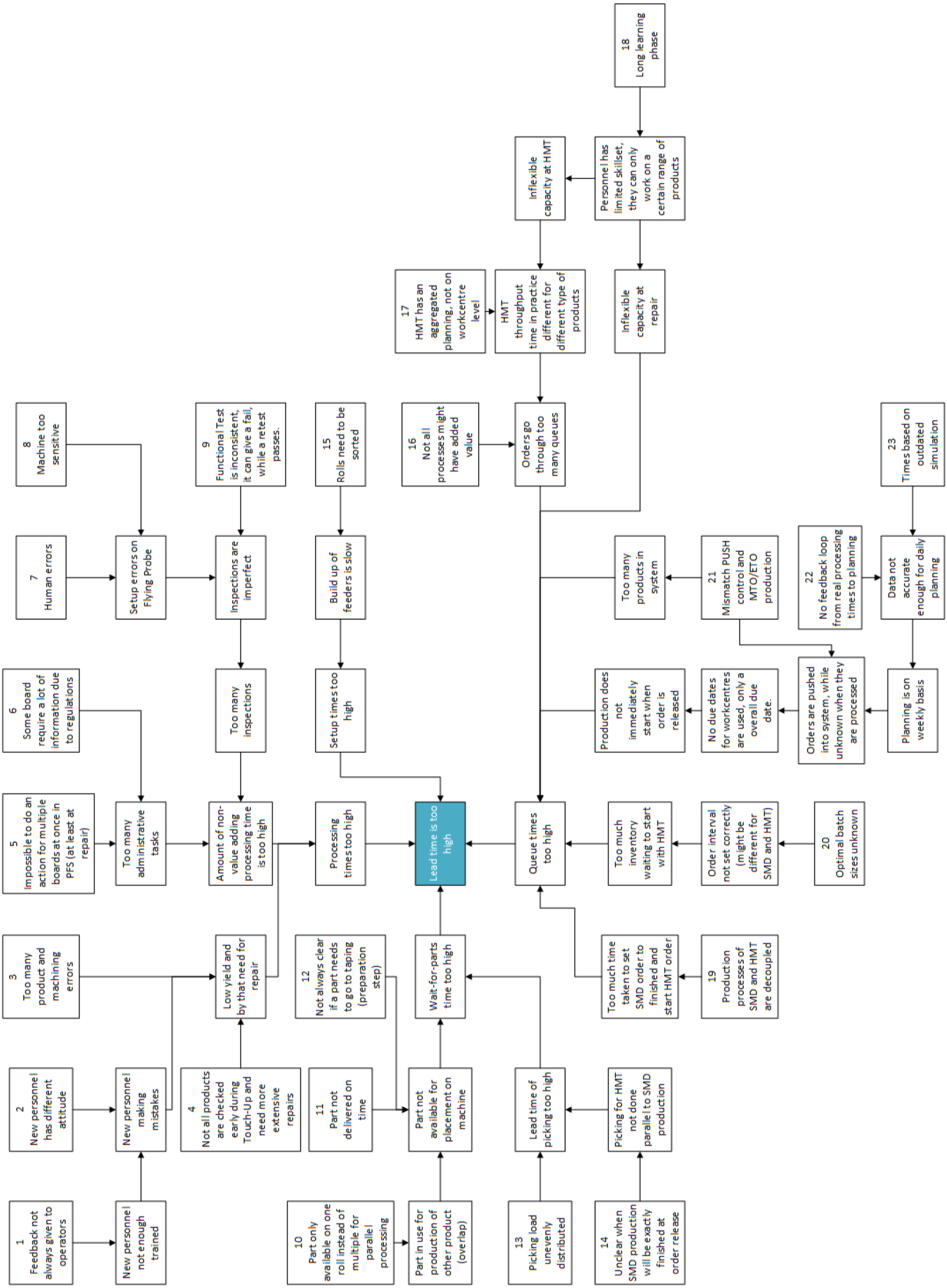

Figure 2-4 Problem bundle

Nr	Explanation	Further investigation
1	The absence of feedback has multiple reasons, sometimes it is for example not possible to see who exactly made the mistakes. In that case only general feedback can be given to all operators.	When the new personnel become more experienced, this problem will become smaller. This is probably a temporary problem.
2	New personnel are not always as connected to Company X as the previous people and show some less effort. This will require some adaptation.	See 1.
3	The machines can make some errors, like slightly displacing a component. Also, components can be placed in the wrong direction, due to it being placed in a wrong way on a roll. These errors have various reasons and are often quite technical.	Outside the scope of this assignment.
4	During Touch-Up, checks are done on a sample, together with the information from the AOI. A repair early on by Touch-Up is generally faster and cheaper than later on in the process.	At the moment, new AOI machines are being introduced, which should make less errors. This should mean that the test at Touch-Up should have less importance.
5	If the same mistake is made in a whole batch, it is necessary to put this into the system for each PCB separately.	These mistakes are not made regularly, hence this problem is not too big.
6		The PCBs in question are generally for military purposes and these regulations cannot be changed.
7		Operators will make mistakes and these cannot easily be reduced. The time lost by operator errors is generally not large.
8	Flying Probe machines place pins on the connections on a PCB, so a small displacement or bend in the PCB will cause problems.	These problems are again quite technical and outside the scope.
9	The machines used for Functional Testing are specific for one or sometimes a few PCBs. These machines are in some cases quite old and inconsistent, it can give a fail for a correct PCB. A pass is still a correct pass though.	As a pass is still a good pass and this is only the case for a limited number of PCBs, this problem is negligible on the whole system.
10	If a part is only available on a single roll, an order needs to wait for previous orders to finish before it can be started.	This problem is recognised and employees are working on a solution. The proposed solution is keeping multiple, sometimes smaller rolls, on stock of products that are

		often used on multiple orders. E.g. 1 roll of 1000 pieces is now bought as 4 of 250 pieces.
11		This problem is recognised and employees are working on a solution. The proposed solution includes a higher safety margin between the latest moment of arrival of parts and the start of the production. This margin is 5 workings days and the proposal is 10 working days.
12		This problem does not regularly occur. In most cases taping can be done in the safety margin as mentioned in 11.
13		This problem is recognised and employees are working on a solution. The proposed solution is a capacity planning for picking.
14	The output process of SMD is unreliable, as the lead time is not the same under all circumstances. It is undesirable to let the picked parts wait a long time due to resource limitations.	With a shorter lead time, the output reliability tends to be higher. Thus, a reduced SMD lead time might help to reduce the overall lead time.
15		This problem is recognised and employees are working on a solution. In the current situation, when a roll is picked, it is placed on a car, together with all other rolls. In the proposed solution, the rolls are placed on a rack in the correct order as given by the system.
16	This point is mainly about going through multiple inspections. For example, after soldering by the selective wave machine, PCBs are checked by the HMT workstation before going the Flying Probe test. It is not completely clear if this is necessary.	As is quite complex and technical, it is left outside the scope.
17	Capacity planning is done on department level on a weekly basis. This causes that workload is not evenly spread over the various processing steps at all times. Some products arrive at a station relatively early or late.	Correlated with 18 and 21, problem should be solvable and have a significant effect on the lead time.

18	Personnel is generally educated for a single customer or limited set of customers, as the learning phase is quite long. This causes that a planning on aggregated capacity doesn't match the situation in practice.	Correlated with 17 and 21, problem should be solvable and have a significant effect on the lead time.
19	At this moment, SMD and HMT production processes are completely decoupled for most orders. This means that after SMD, an order is finalized and set in the system as completed. Afterwards, the planner needs to release the new HMT order. This takes two days. Also, the picking for HMT only starts after the release of the HMT order in the current situation, taking another two days. The reason for decoupling is to allow for different batch sizes in the departments.	Due to this problem, products are waiting for four days without added value. Solving this problem yields a significant effect and might be solvable while solving other problems. Solving the problem on its own is difficult, as a stable output process is required for SMD.
20	During SMD, orders have a significant setup time, hence batches are used for multiple deliveries in some cases. The order interval for these has not updated in a long time and it is unknown if these are accurate. During HMT, smaller batches are generally preferred, as processing times per workstation are dependent on the product. A lot of products of the same type may cause a bottleneck at a certain station.	While making a simulation model, batch sizes are an easy input parameter, making the effort for research quite low. The magnitude of improvement is more complicated to estimate, although it is expected to not be enormous.
21	At the moment, the method used for production planning and control, is a PUSH system. Orders are pushed in, based on the due date and a standard lead time of two (SMD) or three (HMT) weeks. This is not dependent on the product or busyness of the system. This causes that more products than necessary are in the system, as they might need less time to process. According to Little's Law, as explained in Appendix D.4 , this causes higher queueing times.	Correlated with 17 and 18, problem should be solvable and have a significant effect on the lead time.
22		This problem is being recognized and worked on for some processes, together with 23. Proposed method is a new simulation, based on the current times. If and how often the simulation will be updated, will determine if a feedback loop comes into place.

23		See 22.

Table 2-7 Problem Bundle Explanation

From the list of problems mentioned above, not all problems are solvable, or solvable within the scope. Also, a number of problems is already being worked on by other employees or are identified as minor problems. If we leave out these root causes, we remain with Causes 14, 17, 18, 19, 20, and 21. Except 14, all these causes are in the queueing component. Cause 14 is also related to this, as the queueing times make the process output unreliable. It thus makes sense to focus on the queueing component. From Causes 17, 18, and 21 we notice problems with the production planning and control methods, on which we decide to focus for the remaining of this thesis. While working on this and making a simulation model, Cause 20 can easily be set a parameter for testing, so we bring this into the research as well. Improving the production planning and control, can yield a better output predictability, which yields improvements to Cause 14 as well. During the research, other identified causes will need to be taken into account, for example the current yield will not be investigated, but used as given fact and a parameter for sensitivity analysis.

For the selected causes, we will improve and measure the improvement by the following method:

14. We do not focus on improving the output reliability, although the effects will be measured by keeping track of the variance of the output process of SMD.
17. We plan to improve by proposing a concept with improved production planning and control and we measure the variance in workload.
18. There will be no focus on improving the employability and skills of the employees, although the simulation will include multiple scenarios regarding the set of products employees can handle and the number of employees.
19. Regarding the decoupling of the processes, two options are available to reduce the waiting time.
    A. The decoupling can be made undone, hence combining SMD and HMT to a single order. In this case, all of the picking is done at once and needs to be stored on the floor. In the case different batch sizes are wanted between SMD and HMT, this method becomes more complicated.
    B. The output process of SMD can be stabilized, such that picking for HMT can be done in parallel and having the components arrive at the time SMD is finished. In this case, also the booking after SMD needs to be improved or neglected. In the latter variant, the new order is released if all parts are finished, but before the order is formally closed in the system.

    Both options can yield similar results in a simulation model. Option A has simultaneous start of picking for SMD and HMT, while in option B you can also delay the start of picking. Option B can have the closing and releasing of an order as disadvantage, although there might be a solution, e.g. starting HMT before SMD has been formally finished or automatically finishing the SMD when all steps are finished in PFS.
20. Order intervals for regularly occurring products can be used as a parameter during the simulation. Beforehand, a mathematical estimation can be made. The performance can be measured by keeping track of total workload and variance of the output process.

21. We plan to improve by proposing a concept with improved production planning and control and we measure the average lead time, which is of course correlated with the average WIP.

2.6 Conclusions Chapter 2

Chapter 2 answers Research Question 1: *What are the causes of the current lead time being too high?*

In this chapter, we found numerous causes of the lead time being too high, of which some are deemed suitable to solve in this thesis, in order to achieve the largest decrease in lead time. With the collected information, we decided to pick a number of causes in Section 2.5, which are related to the production planning and control. In the current situation, planning and load control is done on a weekly basis, while production uses a push system. At two stations, Touch-Up and the Flying Probe, the flow is interrupted by the use of a separate planning. During the analysis, as can be seen in the VSM, we notice that the largest part of the lead time, about 90%, is spent waiting.

In the upcoming chapters, we need to propose a number of alternatives, before we can analyse their performance with the use of a simulation model. Due to the complexity of production planning and control and their influences on the process, we need a simulation model to check our propositions. Other types of models, such as queueing theory, do not allow for this level of complexity. Before constructing the alternatives, we take a look at the literature in Chapter 3 and check their proposals. We need to focus on production planning and control concepts, while also some knowledge regarding the compensation of yield is required, i.e. methods to minimize the effects of disruptions due to a low yield.

Chapter 3 Literature Review

In this chapter, we search for and review Literature, before the knowledge is used in further chapters. We answer Research Question 2: *What methods are suggested in the literature to reduce the lead time, taking the process, causes, and company into account?* From the conclusions of the previous chapters, we know that we need to gain knowledge in the field of production planning and control methods, which we do in Section 3.1. In Sections 3.2 and 3.3 we search for additional information regarding dispatching rules and order release methods, which are necessary in some methods from Section 3.1. Further, in Section 3.4, we go into methods to cope with a certain yield. These sections together answer Research Questions 2a and 2b. Some additional literature with basic knowledge can be found in Appendix B . In Section 3.5 we research the preferences from the company to answer Research Question 2c, before we draw conclusions in Section 3.6 to answer Research Question 2d.

3.1 Production planning and control methods

We discuss multiple Production Planning and Control (PPC) methods that might be suitable for implementation in the system at Company X. Little's Law (also see Appendix D.4) states that lead time is a function of the arrival rate and the number of products in the system. Since we do not want to lower the output rate, which equals the arrival rate in a stable system, we need to reduce the number of products in the system.

We start with the current method used at Company X, MRP with push production. Next, we go through methods as Kanban, POLCA, CONWIP and Workload Control as suggested by Stevenson et al. (2005) in a literature review, focussing on PPC methods for MTO companies. Another great help during the literature review is the book of Lödding (2013) We also handle some extensions of these methods, that might make them more suitable for the situation at Company X.

3.1.1 MRP

Material Requirements Planning (MRP) is a basic planning method, based on fixed periods. Based on a delivery date, a production start date is calculated and together with the BOM, purchase dates for materials are calculated. At production level, a push method is used, meaning that generally no scheduling is done and products are pushed to the next workstation when they have finished a process. MRP has later evolved to Manufacturing Resource Planning (MRP-II) and Enterprise Resource Planning (ERP), gaining additional functions such as forecasting and becoming an integrated ICT system.

3.1.2 Theory of Constraints

Theory of Constraints (TOC) is a method, made by Goldratt, which focusses on bottlenecks and is also known as Drum-Buffer-Rope. The basic idea of the method is that the bottleneck process never stops, and thus needs a buffer to absorb disruptions. The processes before the bottleneck should produce in the rhythm of the bottleneck process, given by the drum. Last, the processes after the bottleneck should not go faster than the bottleneck as well and are slowed down by the rope coming from the bottleneck. This procedure however assumes a clear stationary bottleneck, that can generally be found in flow shops, although being harder to find and use in a job shop (Stevenson et al., 2005).

3.1.3 Kanban

Kanban is a card-based method, used for implementing and regulating the Just-in-time (JIT) concept. Each workstation or group of workstations gets a specific number of cards, which corresponds to the maximum number of jobs allowed in that part of the system. If all cards are in use, new jobs are not accepted and must wait at the previous step or cannot be released yet. If a job is waiting for a card, it also doesn't release its current card, hence limiting the supply of new jobs and queueing times. Besides these "production" Kanban cards, also transfer Kanban cards can be used. In that case, a card is needed to allow transportation and the job stays in transportation until a card is available in the destination workstation. Although JIT is mainly seen as a concept for repetitive manufacturing, some elements can also be used in MTO companies(Hendry & Kingsman, 1989). For example, Gravel & Price (1988) researched the implementation of Kanban in a job shop and concluded that implementation in at test case was satisfactory. This contradicts with (Stevenson et al., 2005), who state that Kanban cannot be used in non-MTS environments. Kanban has seen a number of adaptations and enhancements, such as a dynamic number of cards as suggested by Korugan & Gupta (2001). In their suggestions, an additional queue with cards is available, which are released when demand exceeds a certain level and extra cards are available. Although this system is made for an MTS environment, the idea of a queue with extra cards can be used in a MTO environments as well. For example, an additional card might be released when orders are relatively small.

Originally, cards belong to a specific product. This is not suitable at Company X, due to the large variety of products, hence we need to drop this constraint and make the cards general. Another possible problem, is the large variance in processing times between jobs. As cards belong to an order, the load in the system can vary a lot. To prevent an overload, a quantum can be instituted with each card; a quantum being the maximum amount of load covered by a single card. If an order exceeds this quantum, it will need multiple cards.

3.1.4 POLCA

Paired cell Overlapping Loops of Cards with Authorization (POLCA) is another card-based method for restricting the WIP. It is devised by Suri (2010) as an alternative for Kanban in the context of his concept Quick Response Manufacturing (QRM). Contrary to Kanban, cards are not linked to a single workstation or group of workstations, but to two consecutive workstations. When a product is operated in a workstation, a card must be available that links the current workstation to the next workstation. At the moment an operation can start with this card, the previous card, that linked the previous station to the current one, can be released. As clearly explained by Thürer, Stevenson, & Protzman (2016), there is a second precondition before an operation can start, it needs to be authorized. Authorization is done on the earliest release date from the MRP system for each system, making POLCA a hybrid Push/Pull system. They also mention that the impact of this earliest release date has been researched thoroughly. Within the Netherlands, Pieffers & Riezebos (2006) did some research to POLCA and state that it is mainly usable for MTO companies with relatively small batches when compared to Kanban.

One of the parts of POLCA is the authorization part. For each processing step, an MRP based authorization date should be available. At this moment, Company X works with MRP, although there are no dates set for individual processing steps, only a release and due date exist for the whole process. When combining SMD and HMT, this means there would be an intermediate authorization date for all HMT processes. Thürer, Fernandes, Stevenson, Silva, & Carmo-Silva (2018) state that is not a problem, in fact they argue that POLCA works best without the authorization component and purely as a card-based concept. In this case a dispatch rule can be used, such as Earliest Release Date (ERD). We use this method due to the overwhelming results they show, outperforming normal POLCA with a street length. A precondition of POLCA is the existence of production cells. At Company X, there are no clear cells defined outside the workstations themselves. Compared to the routing in the system, some simplifications can be made, e.g. Functional Tests are dependent on the item and separated in the routing but can be seen as a single production cell. This is not a major barrier, although it will need some research.

3.1.5 CONWIP

Constant Work-In-Process (CONWIP) is a concept developed by Spearman, Woodruff, & Hopp in 1990, where the goal was to develop an alternative to Kanban, having the same benefits, although being applicable to a wider variety of systems. Similarly to Kanban, CONWIP is a card-based system, with the major difference that cards do not belong to a station, but to the whole production line. Once a job is released, there is no further control during the production process and all queues are handled First Come First Serve (FCFS).

3.1.6 Workload control

Workload Control (WLC) is a concept, specifically developed for job shops. The concept acknowledges that queues are inevitable in order to maintain a sufficient utilisation of workstations. (Land, 2004) Controlling these queues is one of the principles of the concept. The main idea of WLC is that the workload in the system is limited and not all jobs are allowed to be released when they become available for release. WLC in not a single clear concept, within the concept multiple options exist. E.g., for the method of job releasing multiple options are available and have been researched. Oosterman et al. (2000) mention three methods for measuring the workload, different in how they take direct and indirect workload into account. Direct workload is the load of jobs for a specific workstation at which they are at the moment of measurement. Indirect workload is the load of jobs for a specific workstation, but from jobs that are in a different location at that moment. The common denominator is the goal to minimize the direct workload. The first method only takes the direct load, the second also the indirect load. The last method finally also takes loads into account that have already passed the station and thus limits the total load on the floor at any given moment. In 2009 Land developed COntrol of BAlance by CArd-BAsed Navigation (COBACABANA) as a new WLC version. Cards are connected to a job and a workstation, making it suitable for complex routings. Cards are attached to a job when it is released and are returned when the corresponding processing step has finished. It thus uses the sum of direct and indirect workload, as the order restricts the load from the moment an it is released till it is processed at the station.

An obvious requirement for WLC, is the knowledge of the load corresponding to an order, which is a problem at Company X. Although estimates exist, there is no recalculation nor keeping track of actual processing times. According to Thürer et al. (2012), WLC already yields improvements when used with infinite capacity, i.e. without norm restrictions. As time advances, Company X should improve their estimations of processing time tracking anyway, hence the effects of this methods will improve. This, however, means that at the time of introduction, the full benefits will not be available. An additional requirement is knowledge of where the products are in the production process, such that the remaining load can be calculated. This data is mostly available in HMT, where the data in SMD is limited. As the routing in SMD is quite linear and short, we don't expect a big problem here. Even more because we do have the data for what seems to be the bottleneck, namely Touch-Up.

3.1.7 PPC in repair shops

According to Guide (2000), PPC for repair shops and remanufacturing is barely researched, although they have unique characteristics making them complicated, as uncertainty in timing and quantity of arrivals, as well as unknown routings and processing times. In the case of Company X, two types of arrivals exist. Repair of products from the production line and RMAs, returns from the customers. These characteristics make planning and production control complicated. Deterministic scheduling is impossible, as processing times are unknown till the product arrives at the repair shop and might even be unknown until the product is being worked on. With regards to PPC, order release methods and priority rules have been researched by Guide & Srivastava (1997). In their case, the best options were a simple order release method, e.g. due data based or FCFS, and a due date-based priority rule. A more complex release method, e.g. complex heuristics, was not giving clearly improved results.

3.2 Dispatching rules

For methods such as Kanban, POLCA and WLC, a pre-shop pool exists in which orders are waiting to be released to the floor. These are orders that are ready to be produced but are not yet allowed to do so by the system. If, for example, a Kanban card becomes available, one of the orders needs to be selected to start. For selecting the order, multiple methods exist, known as dispatching rules. We go through methods as suggested by the aforementioned literature, as well as methods used in comparisons between different PPC methods, e.g. suggested by (Gonzalez-R, Calle, & Andrade-Pineda, 2018; Paul, Sridharan, & Radha Ramanan, 2015; Thürer et al., 2012). These can also be used at station or buffer level. In case no method is specified for the station level, it can be assumed that First Come, First Served is used.

3.2.1 Rules

In the various literature mentioned, we came across multiple dispatching rules. We briefly name and explain them in Table 3-1. This list is obviously non-exhaustive, we have chosen to limit the amount of research to this topic, as complicated rules do not lead to huge benefits compared to simple rules. (Guide & Srivastava, 1997)

Abbreviation	Rule	Explanation
FCFS	First Come, First Served	Job are handled in sequence of their arrival at a station
LCFS	Last Come, First Served	Last arriving job is handled first
FASFS	First Arrival into System, First Served	Jobs are handled in the sequence they arrived in the system, even if other jobs arrived earlier at the station
EDD	Earliest Due Date	The job that should be finished first, is handled first
SPT	Shortest Processing Time	Job with least processing time is handled first. Can be adapted to least processing time remaining
CR	Critical Ratio	Time left till due date, divided by remaining processing time (Gonzalez-R et al., 2018)
PST	Planned Start Time	Earliest planned start date is handled first
MPST	Modified Planned Start Time	Priority given by the max{PST + processing time; current time (of dispatch decision) + processing time}

Table 3-1 Dispatching rules

To understand the difference between FCFS and FASFS, imagine a job shop with three machines, A, B, and C. Job 1 starts on Monday at Machine A and takes three days, before moving to Machine C at Thursday. Meanwhile Job 2 starts at Machine B on Tuesday and after one day, it moves to Machine C on Wednesday. As Machine C is busy till Friday, it will need to choose between Jobs 1 and 2. Under FCFS, Job 2 would be handled first, as it was first to arrive at Machine C. Under FASFS, Job 1 would start, as it arrived in the job shop first.

3.2.2 Comparison

Guide & Srivastava (1997) conclude that a dispatching rule should be oriented on due date, in which they find support by Land, Stevenson, & Thürer (2014), as well as Gonzalez-R et al. (2018) and Paul et al. (2015). All studies show bad performance by FCFS, while LCFS is often not even mentioned. FASFS is tested by Paul et al. (2015), but found to be outperformed by EDD. Thürer et al. (2017) conclude that MPST outperforms SPT and PST, where EDD also outperformed SPT according to Paul et al. (2015). This leaves us with EDD, MPST and CR. In the study of (Gonzalez-R et al., 2018), EDD is also outperformed by CR. We still leave EDD as an option, due to the fact it's easy to implement in practice, as calculations are not needed. Most papers used KPIs as tardiness, throughput and lead time.

3.3 Order release methods

Within the PPC that need further research, WLC is a bit special. In contrast to Kanban and POLCA, where triggers for the release of a new order are cards and authorizations, there is no clear trigger for when to release the next order. Within WLC multiple methods can be used, including periodic review, continuous methods and hybrid methods. Besides methods for the review moments, also various methods can be used to calculate the current load. The Lancaster University Management School corrected order release method, better known as LUMS COR, is one best of the best working methods, which combines periodic and continuous review to a hybrid method (Thürer et al., 2012; Yan, Stevenson, Hendry, & Land, 2016). The method works as follows:

- First there are periodic order releases based on corrected aggregated load. After every fixed time period, jobs are released if they do not let the corrected aggregated load exceed the set norm restrictions for every workstation. The corrected aggregated load, is the remaining load for a specific workstation from all released orders in the system. Once a product has passed the station, the load is subtracted from the corrected aggregated load.

- Second, if a workstation is starving, i.e. there is no direct load remaining, the order with the earliest planned release date and the starving workstation as first station in the route is released. This release can exceed set norm restrictions for workloads.

Various other approaches exist, varying on the method of load calculation, e.g. only direct load available at a station or including indirect load elsewhere in the system, and the moment of reviewing the release of order, e.g. periodic or continuous. Out of the available methods, the hybrid LUMS COR method performs well at throughput time and lateness according to the papers mentioned before, which is the reason why we select this method. Also the fact that is reasonable easy (Thürer et al., 2012) to implement contributes to this decision.

3.4 Yield compensation

In the case that a certain yield is expected, a company can decide to start production with more products than the customer ordered. Products that fail to meet requirements are scrapped or recycled, involving additional cost or some return money for the materials. Under the assumption that products fail independently of each other, a probability can be calculated using binomial distributions, giving the chance that a certain number of products fail to meet the requirements. For each combination of production quantity and failed products, total costs can be calculated, coming together in an expected profit based on the production quantity. This is also known as the reject allowance problem. New & Mapes (1984) suggest a schedule in which a batch is split into multiple smaller batches. Based on the expected yield and realised yield of the previous batches, the size of the later batches can be determined. This system has as disadvantage that it takes multiple production iterations, influencing the lead time.

Another method to compensate yield, is keeping a safety stock of additional products. This means a switch to a hybrid MTS/MTO system, in which products are produced on customer order, but a small inventory is kept as additional supply to compensate failures. These failures can then, if possible, be repaired without due date pressure and added to safety stock afterwards. This method is only feasible for repeat orders, with certain reorders within reasonable time, as items are customer specific and can become obsolete. (New & Mapes, 1984)

3.5 Preferences from the company

From interviews with several people, we notice several preferences. Most important is the wish to use a single system for SMD and HMT. This makes adaptations to the process in the future easier, e.g. moving a station from one process to the other or decoupling the processes. Another preference is that orders should be clear-to-build (CTB) before they are allowed to move towards the production process, it should be impossible for CTB issues to arise on the floor. This preference is more important for the implementation and less related to the PPC methods themselves. A third preference is with SMD, where components are placed on rolls. If two orders use the same components and only a single roll is available, they can’t be produced in parallel, only sequentially. This is a more complicated planning issue and can be solved by adding a rule, to for example, a dispatch rule. At this moment, this is handled on the shop floor, which can continue this way. Another point to keep in mind is the fact that SMD production works 24 hours/day, while the planners only work 8 hours/day. In the case of disruptions in the night, a plan should be available. For example, when components for an order turn out to be incorrect, another order must be available. A final important point mentioned is the wish to minimize the likelihood of errors and miscommunication. This would mean that a method needs to clear and rather easy to understand, while leaving as least room for errors as possible.

3.6 Comparison of the various methods

Based on the beforementioned information, we made a comparison between the different PPC methods, which can be found in Table 3-2.

Method	Shop floor control	Efficient use of capacity	Ease of implementation	Applicability to MTO	Coping with variance between orders
MRP	None	Only if lot of information is available	Very easy	Decent	Good
TOC	Focused on bottleneck	Good efficiency based on bottleneck	Decent if bottleneck is clear	Limited	Limited
Kanban	At station level	Good	Harder and needs constant adjustments if environment changes	Opinions vary	Limited without quantum cards
POLCA	At station level	Good	Hard and needs constant adjustments if environment changes	Good	Limited without quantum cards
WLC	Only at system level	Good	Decent, although needs continuous monitoring of processing times	Good	Good, as it takes expected load
CONWIP	Only at system level	Decent, but heavily dependent on order mix	Easy	Limited	Limited without quantum cards

Table 3-2 Comparison of PPC method

Now the question is, which methods might be suitable to apply at Company X. First, we remove the option MRP, due to the limited shop floor control and the necessity of accurate data. Next, we remove CONWIP, due to mentioned weaknesses as lack of control at station level, and its analysed performance, e.g. Thürer et al. (2012) conclude that WLC outperforms CONWIP in all tested scenarios, with release mechanisms as SLAR, WCPRD and LUMS COR. Gonzalez-R et al. (2018) compared an adapted version of Kanban and WLC, while using the same order release mechanisms and they concluded that Kanban worked best. This is in contradiction with Stevenson et al. (2005), who state that WLC should be better in a job shop environment, although it is unclear if they refer to a classic or adapted Kanban. It is wise to keep both options open. A comparison between WLC and TOC is made by Thürer, Stevenson, Silva, & Qu (2017), who conclude that TOC works best when there is a severe bottleneck in the process. When the bottleneck is moderate, WLC outperforms TOC. In combination with the fact that TOC needs to adapted when the bottlenecks shifts, where WLC does not need to, WLC is likely to outperform TOC at Company X. For this reason, we leave out TOC. This leaves us with Kanban, POLCA and WLC. Of these methods, Kanban might be less suitable for MTO companies, although the opinions are contradictory for this. The method has, however, been researched a lot and multiple adaptations exist, making it a broader applicable tool. Testing these three methods and their applicability to Company X is the focus of the model in the remainder of this thesis.

3.7 Conclusions Chapter 3

In this chapter, we answered Research Question 2, *What methods are suggested in the literature to reduce the lead time, taking the process, causes, and company into account?*

The literature suggests numerous methods, although when taking the environment into account, we are left with three methods. These three methods, Kanban, POLCA and WLC, are all putting a limit on the WIP in one way or another. When seen together with Little's Law, a reduced WIP means reduced lead times, done by cutting down the queueing times. These methods are expected to work in the given environment, although it is unknown how well they will work and which one works best. For this reason, multiple scenarios are worked out and tested in the upcoming chapters. Within WLC, decisions need to be made when to release an order and which order to release. For choosing when to release an order, we use LUMS COR, while for choosing the order we have multiple options, namely EDD, MPST and CR. For the repair and debug department another priority or dispatch might be used, such as FCFS. More complicated heuristics, however, do not yield clearly improved results. The exact method to be used will need further research. In order to cope with a certain yield, multiple options exist, such as overproduction and keeping a safety stock.

Chapter 4 Model

In this chapter, a simulation model is built in order to test various scenarios and answer Research Question 3, *How do the constructed alternatives perform regarding the lead time and other relevant KPIs in a simulation?* We first define how we are going to measure and analyse the performance in Section 4.1 to answer Research Question 3a, before setting the scope of the model in Section 4.2 and answering Research Question 3b. In Section 4.3 we gather and prepare the data for the model and answer Research Question 3c. The model itself is handled and validated in Section 4.4. Finally, in Section 4.5 we answer Research Question 3d and go through the results of the model. As a guideline, we use the book of Law (2015).

4.1 Measurements

In order to measure the performance of our model, we need to determine how we measure the performance of our system. As the research is all about lead time, this is our primary measurement. We measure the lead time as the time between order release and the closing of the order. We do keep track of some other measurements, although we do not use them for ranking purposes. We measure lead time as the average of all lead times of all orders across the board. For analysis, we will split out the lead times for example per department. We also analyse the joint lead time of combined SMD and HMT orders, although this is not primarily used as ranking measurement. We do not measure the WIP, due to its direct correlation with the lead time.

4.2 Conceptual model

This section starts with an overview of the simulation model before some details are handled in the subsections. In Subsection 4.2.1 we discuss our method for modelling the orders, Subsection 4.2.2 handles some details of the process that need further explanation and the later subsections handle details of the PPC methods we research.

In compliance with the scope as determined in Section 1.5 , we let our model include all processing steps in the SMD and HMT department, and exclude all other processes and steps belonging to SMD or HMT that take place at an external location. We do take the picking of components for SMD into account, as this is done on the shop floor and can be seen as a processing step. The picking for HMT, on the contrary, is done in the warehouse and is left out of the model. For this warehouse, we set a fixed lead time of two working days, after the signal has been sent that an order is released. This is done in consultation with the external supervisors. Disruptions from the machines are not taken into account, as these occur only rarely. Also, the personnel availability is assumed to be normal, i.e. no long-term illnesses or burnouts are taken into account, while normal holidays are taken into account. We do take the yield and the corresponding debugging and repair into account. We model the products on batch level, as it does not add enough value to model on product level. This can cause some difficulties with repair, in the case rejected PCBs are separated from the batch, e.g. when a safety stock is in use. In this case, the batch will need to be split in two parts and include a value for the number of products in that batch. This is, however, less bothersome than modelling on product level and also saves quite some complexity and running time. Processing times of a batch are calculated based on the size of a batch and product properties and are handled in detail in Section 4.2.1 . The model itself is made in Tecnomatix Plant Simulation 13, due to the availability and knowledge of the program.

In Figure 4-1 we give a general overview of our model in a flowchart. We start with generating the orders and their details. Next, we calculate the CTB issues and their effects on the allowed lead time, details are given in Section 4.2.1. Next, we hand the order to the PPC method of choice and let the method decide when to release the order and control the further movements in the system. When a product is given to a processing station, the queue is again handled by the rules of the PPC method. After processing has finished, it is checked if the product has finished all processing steps or not. If a production steps has finished, it also checked if new orders are available for processing, again according to the PPC method and corresponding priority rule. A second trigger in the model is the moment an order becomes available for processing, e.g. due to the passing of an allowed start date or the availability of a card.

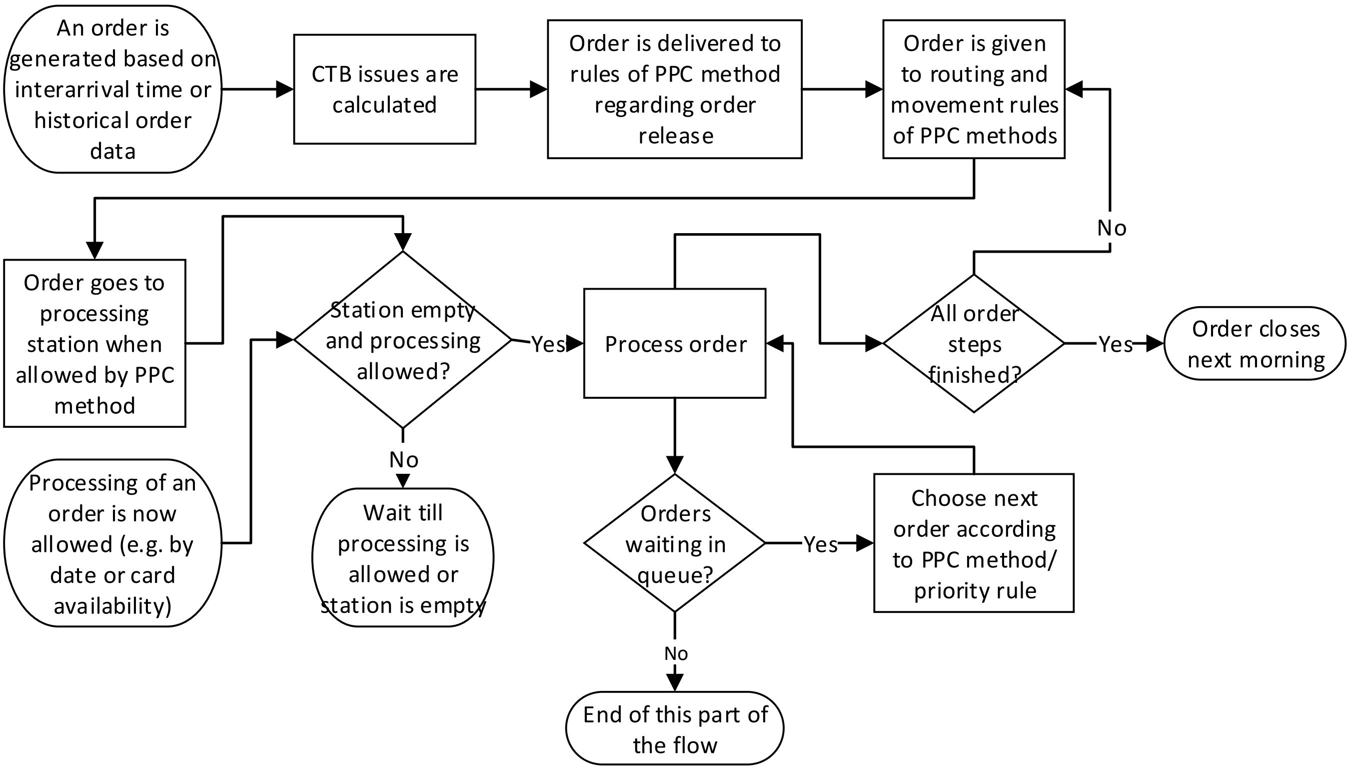

Figure 4-1 General model overview

4.2.1 Modelling orders

In order to test a production planning and control method, we need to have a set of orders on which we run the simulation model. In dialogue with the external supervisors, we determined the wish to test the system under high load. For this reason, we took historical data from Q3 and Q4 from 2017 and future data from Q3 and Q4 2018. These periods are seen as the busiest periods of Company X. This data can be processed in multiple ways, for modelling the first part of the orders, the orders themselves:

- Direct use of available data. In this case the orders are used 1:1 from the available data. The advantage is the direct correlation with reality, while a disadvantage is the limited amount of data. A second disadvantage is with starting a run, as it cannot be expected that the system is empty when it starts. In that case, a filled system must be set up. From the data, we take the expected processing time and the routing.

- Indirect use of available data. In this case, distributions are fitted over the available data and orders are generated based on this data. This can best be done by generating orders on a random interval and predetermine their routes and expected processing times based on the data. Advantage is an unlimited amount of available data, while a disadvantage can be lost correlation between orders, e.g. orders from a specific customer or size of orders not being evenly divided over the quartile.

The first method has as main advantage the correlation with reality, as you practically copy it. The second method, however, is more flexible and allows for changes in the product mix, order quantity and more. For this reason, we choose the second method.

The second important part of modelling the orders is determining the actual processing time. From the historical data, expected processing times are known, but real processing time are mostly not. For all SMD processing steps, estimations have been made with the Tactical planner and external supervisor, based on data gathered with the production supervisors. This gives that for the Picking and Feederbuild, the quoted times are quite accurate, while for the SMD machining process itself and the Touch-Up we need to use a factor of 1.5 and 2.5 respectively compared to the quoted processing time. This is based on manual recording of processing times by the planner in cooperation with the production. For the HMT process, we make an estimation of the efficiency factor, based on hours of work processed and the number of hours available. This estimate is quite rough, only per week and on full process level instead of station or operation level.

We know that the processing time in practice will rarely exactly match the expected processing time, otherwise deterministic scheduling would be possible. To model this, we need a method to determine the difference between the actual and expected processing time in our model. We state a couple of methods:

- Draw an actual processing time from the same distribution as where the expected processing time was drawn from. This is not realistic, as a job with an expected processing time of 8 hours, is extremely unlikely to have an actual processing time of 10 minutes. This is an example that is possible with this method.
- Redraw from the same distribution with restrictions. For example, we restrict that the actual processing time can have a deviation of 20% from the expected time. This method is very computing intensive, as it often needs to redraw multiple times before it finds an allowed time. For this reason, the next method works better.
- Draw a deviation from a separate distribution, e.g. an uniform distribution between +/-20% from the expected processing time. Based on the current processing time, a deviation can be drawn, which might include a limit. This method is less computing intensive.
- Keep the expected processing times. This is an easy method, but it is not a good option in this case as it might add advantages to certain methods, such as WLC which are based on the expected processing times.

Based on this information, we choose the third method, hence draw a deviation from a separate distribution. It is less computing intensive and does add some realism by making the estimates imperfect.

Next, we take a look at the yield. We have historical data from the last 7 years, although a lot of products have been made only once. We can use the data in two ways.

- Use the data per product. This gives a good estimation for products of which a lot of data is available. There are, however, a lot of products without data. There is also a risk of yield changing over time, generally it increases due to experience.
- Use a common factor, i.e. the same data for all products. This method works for all products but leaves out correlations.

We choose to use the second, as it can be used more generally. Finally, we take CTB issues into consideration. Our goal is to halve the lead time to 2.5 weeks, but if CTB issues occurs, we still want to deliver on the original delivery date. As some of our methods are due date based, we need to model this aspect. We will use data from past issues to model their number and how many days delay they cause. We will then shorten the 2.5 weeks by this number of days.

4.2.2 Process details

As we model the orders on batch level instead of product level, we need to take some measures and make some assumptions in order to get a valid model. For example, at the Flying Probe individual products can fail the test, which go to Debugging and if necessary to Troubleshoot and Repair. It is, however, the case that the whole batch waits till it is complete again and it will stay that way by demand of the external supervisor. This allows us to simplify the process and draw a random number for the number of defects, on which we calculate the total time required at debugging, troubleshoot and repair. This matches the actual situation, as the Flying Probe is first finished for all products in a batch and Debugging can't start at the arrival of the first product, due to a queue. Figure 4-2 displays the actual situation at the top and our simplified version at the bottom. In our simplified version, we do not include the scrapping of PCBs, as this is not relevant to our model. If a PCB is scrap, the order is delivered with fewer PCBs than ordered. The batch, however, cannot continue until the decision to scrap is made at the troubleshoot department, as till that moment it is not complete again. After the scrap decision, the batch is made smaller and thus “complete” again.

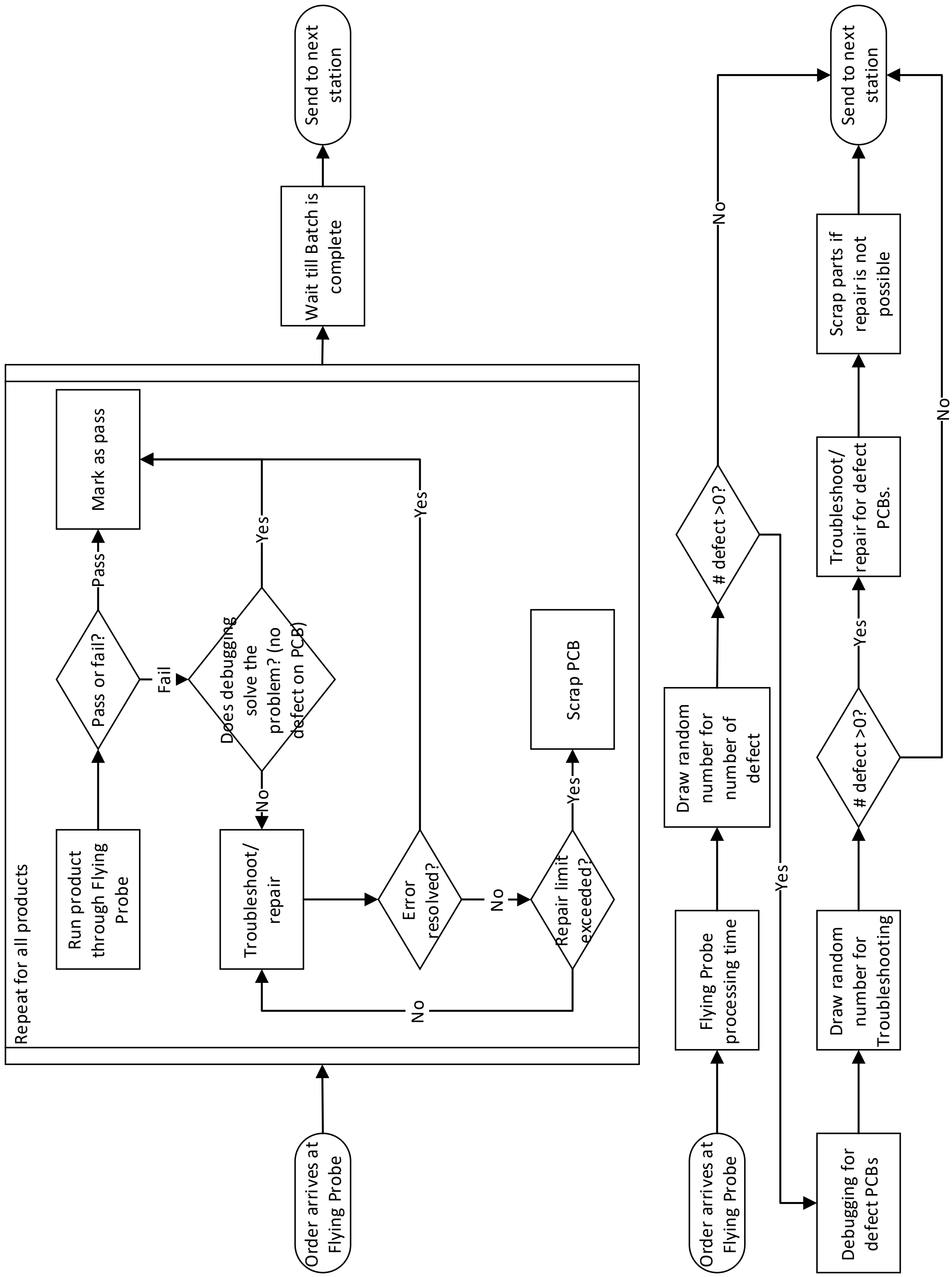

Figure 4-2 Flowchart testing process

Figure 4-3 gives the transition process between SMD and HMT. The first flow gives the current situation, where the second gives a hybrid situation in which the picking for HMT is initiated by the start of Touch-Up in the SMD process. If the Touch-Up is finished the same day, the order is visible in Rapid Response two days later, at which moment the picking for HMT should also be done. This means that the HMT order release is matched with the arrival of raw materials. The third flow gives the situation for a combined SMD and HMT order. In this case, the signal for picking of HMT is sent at the moment picking for SMD has started. When the SMD steps are finished, the raw materials have arrived for HMT. This system can be finetuned by determining the moment the signal is sent to the warehouse. A drawback is the possibility of inconsistent SMD process output, which might lead to orders waiting for materials or the other way around. We will test all three methods.

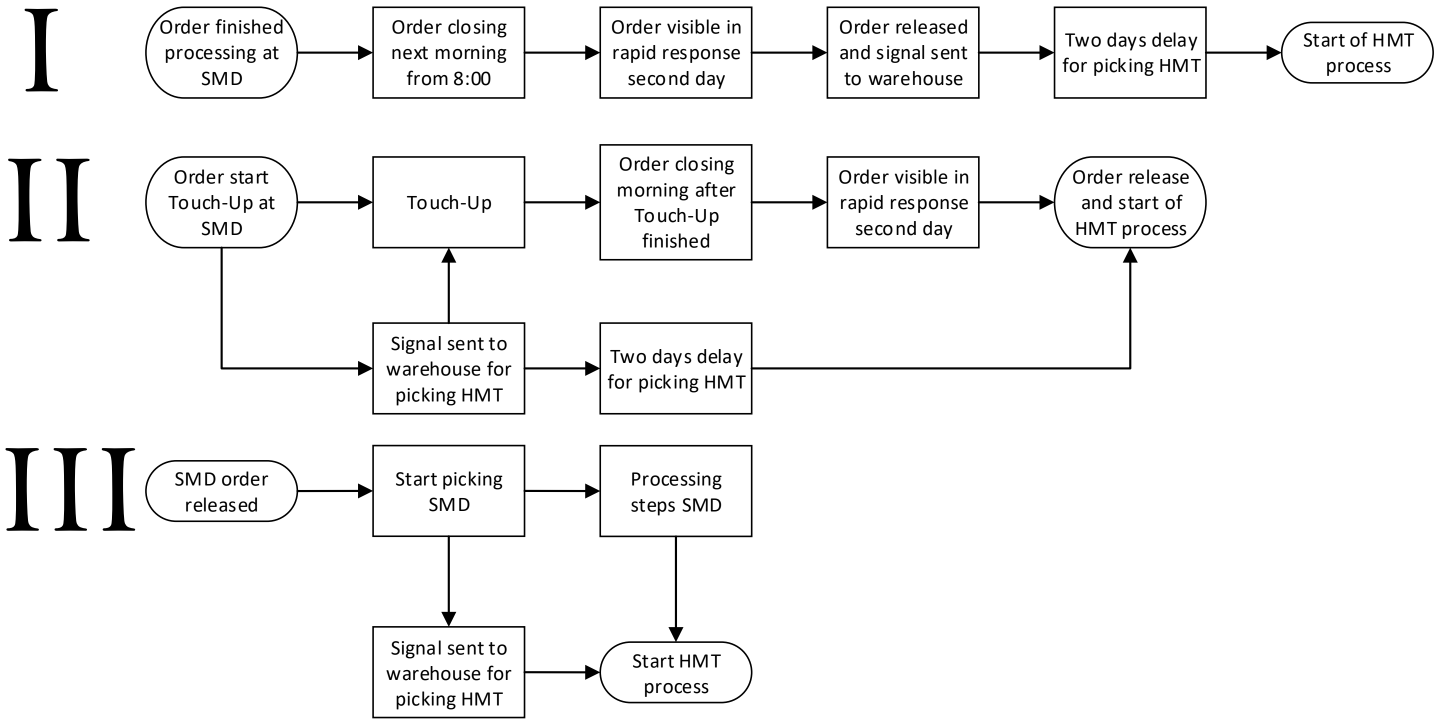

Figure 4-3 Flowchart coupling SMD and HMT. I gives the current situation. II the situation where HMT starts when the SMD order reaches Touch-Up. III the situation where HMT starts when SMD picking starts.

4.2.3 Kanban

In order to implement Kanban, we need to make clear what actions need to be taken at which moment. For this reason, we provide a flowchart in Figure 4-4. In the case we use quantum cards, we need the subprocess as shown in the rectangle. In that case, multiple cards of the same type can be released at once and we need to check for all of them. Without the subprocess, it is possible to release two cards of the same type, have one taken by the first order and stop the process, while a second order that needs a single card can also be released at the same time. In the case we don't use quantum cards, this can be simplified. In that case we only need to check if at least one order is waiting for the card and release the first order if that is true.

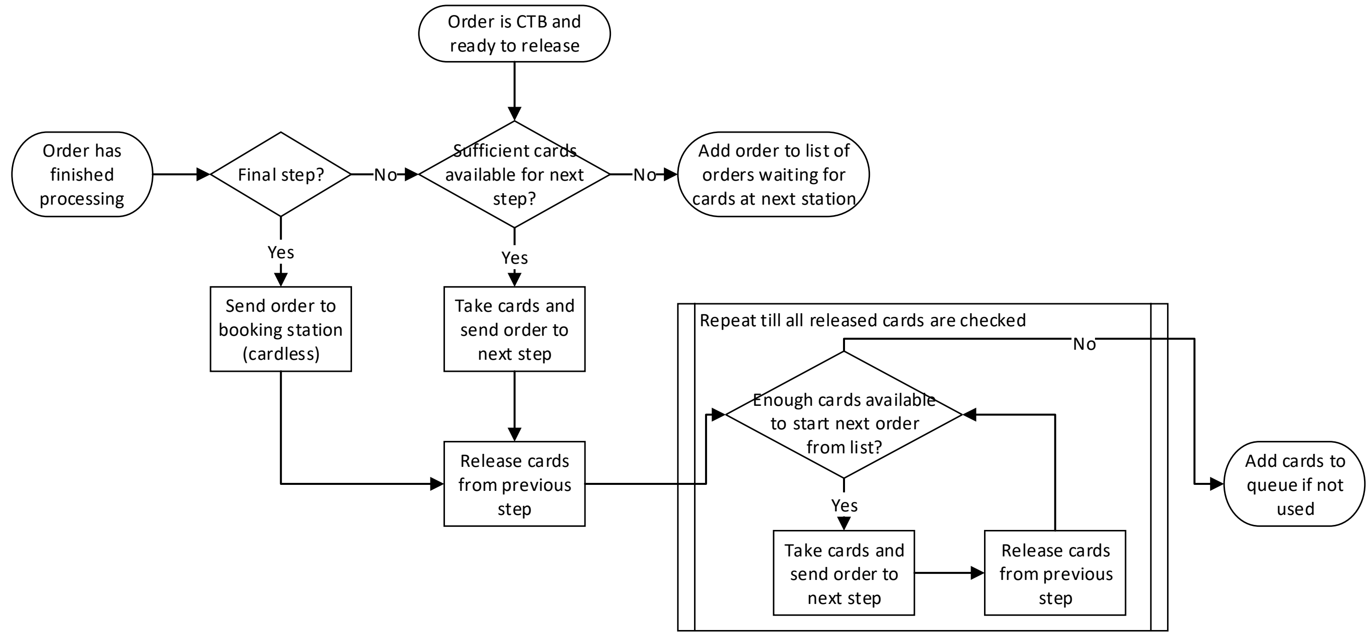

Figure 4-4 Flowchart Kanban

4.2.4 POLCA

For implementing POLCA, we have different decisions to make in the process, as can be seen in Figure 4-5. Compared to Kanban, we no longer need the looping subprocess, due to the difference in the release of the cards. It is good to mention that to process an order, two cards are needed. One in which the processing step is on the second half of the card, and one where it is on the first half of the card. After processing, the first card is released. As mentioned in Chapter 3, we do not use the authorization part of POLCA.

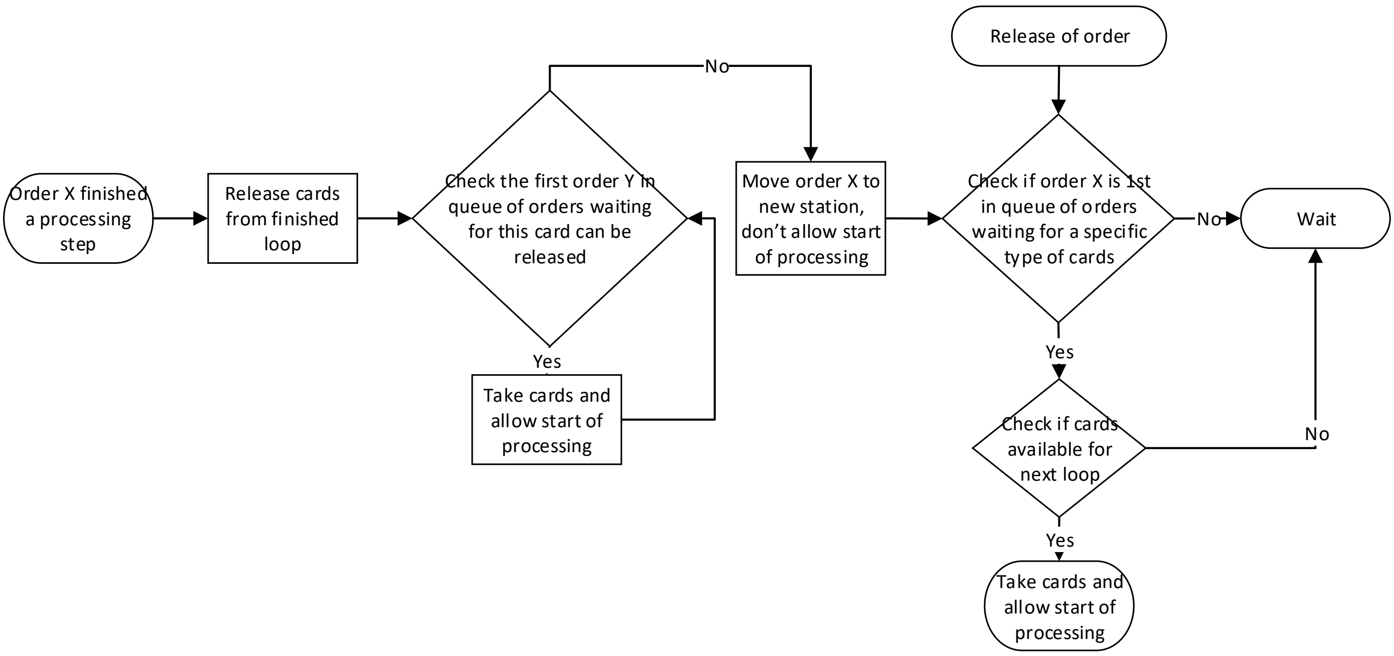

Figure 4-5 Flowchart POLCA

4.2.5 WLC

For WLC with LUMS COR, we need a third trigger for the process, although the flows are now completely separated from each other as can be seen in Figure 4-6.

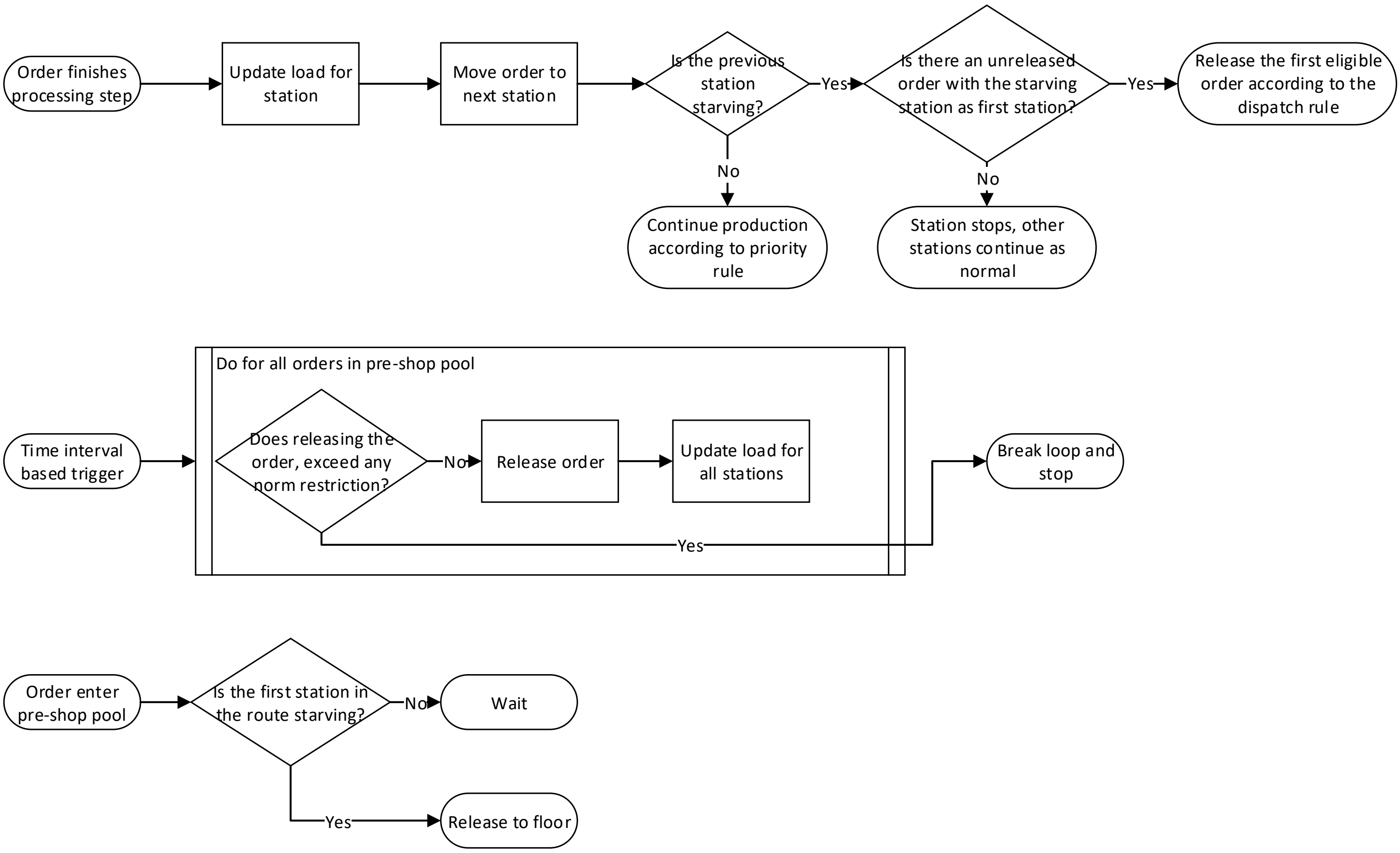

Figure 4-6 Flowchart WLC

4.2.6 Assumptions

In our model, we make multiple assumptions and simplifications. We name the most important ones and explain why they keep the model valid.

- Machines do not break down.
    - Machines are not prone to breakdowns and it generally does not have a big influence on the process.
- Personnel availability is constant, no long-term illness or burnouts are considered.
    - Although these happen in reality, these are hard to model in a meaningful manner. In some situations, temporary workers can be used, although this is not possible in all situations due to the required knowledge.
- Fixed HMT picking lead time from the moment of signal sent to warehouse.
    - The fixed lead time we use, 2 days, corresponds to the maximum time that is given to the warehouse for picking.
- Only production steps inside the facility are considered.
    - There a few cases of production steps outside the facility. As there occur infrequently and are outside the control of Company X, we leave these out.

- Batches are not split, unless required by a method.
  - Splitting of a batch might happen when i.e. a PCB needs repair and the other PCBs of the order continue production. This method is not preferred by the external supervisors and is thus not used.
- If a PCB is scrapped, it does not influence the lead time beyond the scrap decision. The order is delivered with less products.
  - This method corresponds with the situation in practice.
- Serializing not seen as a processing step.
  - This processing step, in which the PCBs are provided with a barcode, takes very limited time and is generally done together with the next processing step, such that no waiting time occurs. We thus decide to leave out this step.
- SMD Machines 1 and 2 are seen as equal and thus as a parallel processing station.
  - Only an insignificant number of orders can only be run on Machine 1. It is not worth the effort to include advanced logic in the model.
- SMD orders close the morning after the final processing step.
  - This corresponds with the situation in practice, where orders are not closed based on their finished processing step, but on daily checks.
  - HMT orders are closed with the last processing step, as they can be shipped immediately.
- At the HMT station, the Y Hengelo group is seen as separate entity from the other groups.
  - This assumption corresponds with the situation in practice, where knowledge of products is the reason. In practice, the Protocenter also has separate employees, although these regularly help the general HMT employees.
- PCA Handmounting is neglected.
  - With some orders, a little bit of handmounting is done during the SMD process. In these cases, the employees along the line take the PCBs and add one or multiple components. They do this at the moment the PCB is halfway the line or at the end of the line. As this is a merely parallel process, we leave it out as a separate process. We also neglect the processing time, as this is also done during the SMD processing time.
- Consecutive processing steps at the same station are handled consecutively without waiting time.
  - If a product has finished for example a Touch-Up step at HMT and the next step is Handmounting, these actions are performed by the same employee. Thus, no waiting time occurs between the steps. The processing times of the two steps are added together.
- Transports between stations happen instantaneously.
  - Distances between stations are small and negligible, so they don't influence the processing time.
- The capacity of the selective wave machine can be increased when demand is high.
  - This corresponds to the situation in practice, where on the weekly schedule capacity shortage is checked. If shortage exists, additional shifts are planned. In our model, this can be done on a daily basis, but only if a significant backlog exists.
- As there is no production in the weekends, these are not simulated. All data and results given in days, are thus equal to working days in practice.

From the previous subsections, we also came across a number of assumptions and simplifications including their explanation. These include:

- A simplified debugging/repair process (Section 4.2.2)
- The transition from the SMD process to the HMT process (Section 4.2.2)
- The Kanban method is made a bit more complicated in order to allow quantum cards (Section 4.2.3)

With these assumptions and simplifications, it is possible to make a valid model, hence we will keep using them. Once the model is made, we do further validation of our model.

4.3 Model building

We will make our simulation in Siemens Plant Simulation, as this is offering the tools we need and it is made available to us.

4.3.1 Data preparation

In dialogue with the external supervisors and the tactical planner, we decided to take order data from the second half of 2017 and the second half of 2018. The 2017 dataset will be used for validation, as the results of this dataset in practice are known. The 2018 dataset will be used for the experiments, as it gives the best indication for the current and future situation. Validation is a bit harder, as not all results are known yet.

4.3.1.1 Order data 2017

We first take a look at the number of SMD orders that have a follow-up HMT order. We matched the various orders with use of the BOM, in which we matched SMD products with corresponding HMT products beforehand. For normal SMD orders, the percentage turns out to be 80.9%. For Y Hengelo orders, it is 12.7%, due to the fact that these orders are often combined for SMD and HMT.

Next, we look at the number released every day. We had a total of 115 records, of which we divided the number of orders released on a specific day in bins of orders. With a total of 115 records, we opt to use 11 bins, which is closest to $\sqrt{115} \approx 10.7$. When analysing the resulting histogram in Figure 4-7, we notice a skewed distribution. We fit a lognormal distribution with mean 2.571 and standard deviation 0.600. A visual check on the distribution graph and the Q-Q plot, which can be found in Figure 4-8, confirms the distribution. A check with chi-squared values, confirms the distribution as well, with a result of 5.68 being lower than the chi value of 18.31 with $\alpha = 0.05$ and $df = 10$.

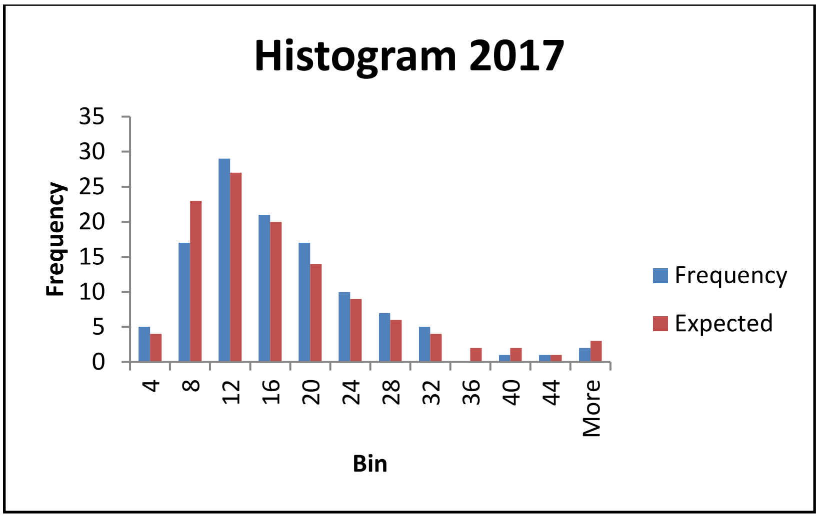

Figure 4-7 Histogram order bins 2017

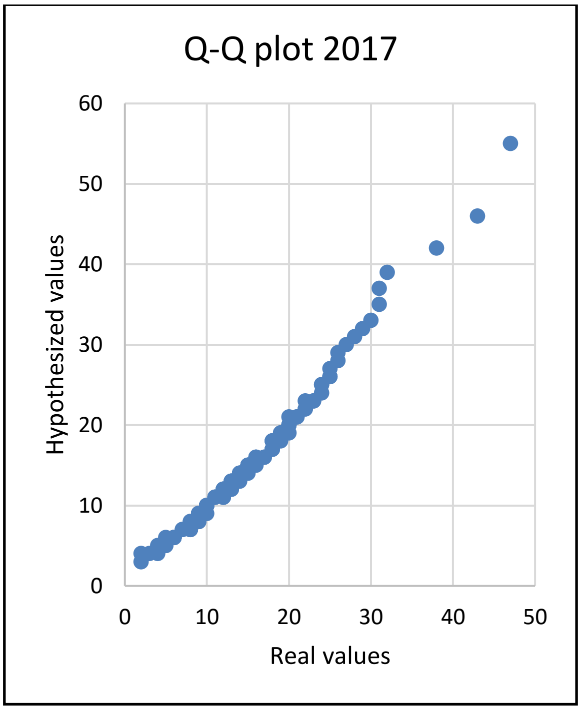

Figure 4-8 Q-Q plot orders 2017

4.3.1.2 Order data 2018

For the 2018 dataset, we execute the same steps as for the 2017 dataset. Of the normal SMD orders, 81.1% continues to HMT and for Y orders it is 10.1%. We have a total of 116 data points for the order release, which means we still use 11 bins for fitting a distribution. We fitted a lognormal distribution with a mean 2.26 and a standard deviation of 11.83. Although the Q-Q plot in Figure 4-10 is not as nice as for the 2017 dataset, the hypothesized distribution still passes the Chi-Squared test with a value of 9.81 below the limit of 18.31.

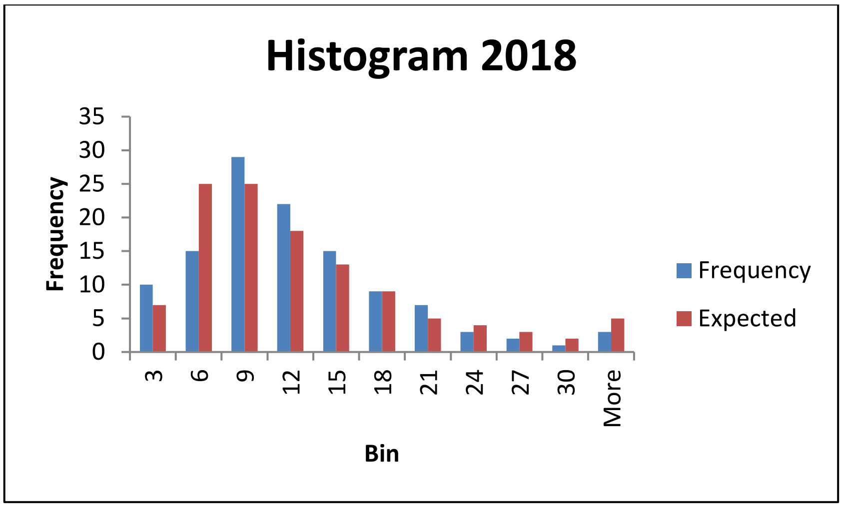

Figure 4-9 Histogram order bins 2017

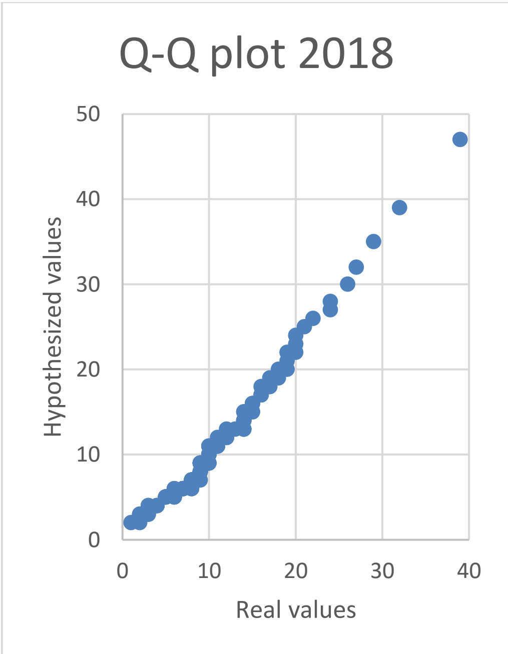

Figure 4-10 Q-Q plot orders 2018

4.3.1.3 Number of employees/stations

Not all stations work the same way. At some stations, the machine is leading for the processing time, e.g. at the selective wave. For some others, the number of people is leading, e.g. at the HMT production and inspection. Based on observations, data and conversations, we decided for each station the correct method. The number of parallel processing stations is chosen based on the number of available/operated machines or the number of FTE available. This gives us the following numbers:

Machine	Number of machines/fte
Picking SMD	1
Feeder build	2
SMD Machine 1+2	2
SMD Machine 3	1
Touch Up	2
Touch Up Y	1
Selective Wave	2
HMT production Y	12
HMT production	17
Flying Probe	3
Boundary Scan	2
Functional Test	1
Inner-Circuit Test	1
HMT inspection	5
Repair	3
Troubleshoot	8
Debugging	2

Table 4-1 Number of parallel machines

4.3.1.4 Efficiency factors HMT

To determine the efficiency of the HMT factors, we calculate the number of planned hours per week and the number of available hours per week. Based on these numbers, we determine an efficiency factor, for how much extra time is needed on average. This data is unfortunately only limited available and cannot be gathered automatically. The data is also only available for the HMT station itself and not for stations such as Selective Wave or the testers. This is not a big problem, since these stations depend on the running time of the machine, which can be estimated quite well. Based on the available data over a period of 8 weeks, we determined an efficiency factor of about 85%, which means we will use a correction factor for the processing times of 1/0.85=1.175.

4.3.1.5 Batch Orders

In the 2017 data, 85% of the orders is a "batch" order, i.e. multiple orders are placed for the product in this batch. In the current situation, the standard order interval is 4 weeks. We will test with the current system, as well as 3 and 5 weeks, to see the effects of having more smaller orders and less bigger orders. For implementation, we alter the number of orders generated, by leaving 15% fixed and altering the remaining 85% with +-25%. This gives generating factors of $[0.15 + 0.85 * (1 - 0.25), 0.15 + 0.85 * (1 + 0.25)] = [0.7875, 1.2125]$. For orders marked as Batch orders, we alter the processing time with +-25%, while the expected setup time is constant. For the 2018 data, the percentage is 81.1% and we use the same method.

4.3.1.6 WLC hours limit

In order for WLC to function, we need to set the limit for workload at each station. According to Lödding (2013) the limit should take direct and indirect load into account. In practice, this means that stations that occur relatively late in the routing, need a higher limit due to the indirect load, i.e. upcoming workload of which the physical order has not yet arrived on the station. The load limit is also dependent on the number of available hours of a station, the product of the number of parallel stations and the number of hours each station is available per day. The formula as proposed by Lödding can be found in Equation 4-1. It states that the WIP limit of station j equals the amount of WIP planned for station j, multiplied by the total workload of all orders from start to station j, divided by the total workload on station j.

$$WIPL_j = WIP_{plan,j} * \frac{\sum_{i=1}^{NO}(WC_{i,j} * TTP_{plan,tot,i,j})}{\sum_{i=1}^{NO}(WC_{i,j} * TTP_{plan,i,j})} \tag{4-1}$$

$$\begin{aligned}
&WIPL_j = WIP\ limit\ station\ \ j\ in\ hours \\
&WIP_{plan,j} = planned\ WIP\ for\ station\ j\ in\ hours \\
&NO = number\ of\ orders \\
&WC_{i,j} = workload\ of\ job\ i\ at\ station\ j\ in\ hours \\
&TTP_{plan,tot,i,j} = \ planned\ throughput\ time\ of\ order\ i\ from \\
&\qquad\qquad\qquad its\ release\ till\ the\ end\ of\ processing\ on\ workstation\ j \\
&TTP_{plan,i,j} = \ planned\ throughput\ time\ of\ order\ i\ on\ station\ j
\end{aligned}$$

In our case, we don't have the throughput times, so we have to make an estimation. Based on information from the current situation and pilot runs of our model, we settle to the formula as can be found in Equation 4-2 for SMD stations and Equation 4-3 for HMT stations. In these pilot runs, we executed a full factorial design in which we tested all factors used in the formula against the base scenario of WLC, in which all settings correspond to the current situation. We decide to use two formulas, as the differences between both processes are quite significant regarding flow and the inclusion of two days of picking. For SMD, we expect an average of 1/3 day per station and for HMT 1 day per previous station. These values are made by a rough estimation as baseline, after which we executed experiments to optimize the results. In our model, we include a check that the limit should at least be equal to the longest processing time, to prevent orders from being blocked from entering the system at any point, even if the system is empty. After an experiment with our model, based on 17 runs for each setting, where we varied the various parameters in a full factorial design, we settled on 1.5 days for HMT and 0.75 days for SMD, a bit higher than our original expectations.

SMD

$$WIPL_j = m * hrs * \frac{1}{3} * (avgpos + 1) \tag{4-2}$$

HMT

$$WIPL_j = m * hrs * (avgpos + 2) \tag{4-3}$$

$$\begin{aligned}
&m = number\ of\ machines \\
&hrs = hours\ available\ per\ day\ per\ machine\ or\ person \\
&avgpos = average\ position\ in\ routing, measured\ in\ step\ number
\end{aligned}$$

4.3.1.7 Number of Kanban cards

In the same fashion as in which we set a workload limit for WLC, we need to set the number of cards for Kanban. In this case, we only need to take the direct load into account. Again, we use the formulas as provided by Lödding as a baseline. In case quantum cards are used, we estimate a factor of 4 instead of 1.5 with a quantum of 8 hours. The formula is based on the idea that enough cards should be available for 1.5 days of WIP at each station in HMT. After setting this baseline, we executed experiments with our model to optimize these numbers, which led to a factor of 0.75 and an extra factor of 3.5 for SMD stations. In case quantum cards are used, we included a check to see if the order with the longest processing time is allowed. For quantum cards, after experiments, we settled with a factor of 5, an additional factor of 2 for SMD stations and a quantum of 4 hours per card.

SMD
$$Cards_j = \left\lceil \frac{0.75 * m_j * hrs_j}{3.5 * avgproc_j} \right\rceil \tag{4-4}$$

HMT
$$Cards_j = \left\lceil \frac{0.75 * m_j * hrs_j}{avgproc_j} \right\rceil \tag{4-5}$$

$$\begin{aligned}
&m = number\ of\ machines\ or\ fte\ at\ station\ j \\
&hrs_j = hours\ available\ per\ day\ per\ machine\ or\ person\ at\ station\ j \\
&avgpos = average\ position\ in\ routing, measured\ in\ step\ number \\
&avgproc_j = average\ processing\ time\ at\ station\ j
\end{aligned}$$

4.3.1.8 Number of POLCA cards

For POLCA, the calculations become a bit more complicated, as two stations need to be considered and we need to decide which loops to give cards and which not. We decide to use cards if at least 25 orders use it during the period of the data, half a year. Below this number, mostly only a single card should be used, which works contradictory. This means we use the loops as displayed in Appendix G To calculate the number of cards for the loop between station i and station j, we use formula 4-6. After experiments with our model, we settled on a station factor of 4 for SMD, a destination weight of 0.5 and a constant of 10. For quantum cards, these become 3, 1.5 and 14 respectively.

$$\begin{aligned} Cards_{i,j} = \Bigg\lceil & FlowPerDay_{i,j} * (Constant + \frac{avgproc_i}{hrs_i * stationfactor_i} \\ & + \frac{DestFactor * avgproc_j}{hrs_j * stationfactor_j} \Bigg\rceil \end{aligned} \tag{4-6}$$

$$\begin{aligned}
&FlowPerDay_{i,j} = number\ of\ orders\ per\ day\ between\ station\ i\ and\ station\ j \\
&hrs_i = hours\ available\ per\ day\ per\ machine\ or\ person\ at\ station\ i \\
&avgproc_j = average\ processing\ time\ at\ station \\
&stationfactor_i = 1\ if\ i\ is\ a\ HMT\ station, a\ variable\ if\ i\ is\ SMD \\
&Constant = factor\ to\ correct\ for\ fixed\ delay\ in\ the\ route\ such\ as\ picking \\
&DestFactor = factor\ to\ give\ station\ j\ a\ different\ weight\ than\ station\ i
\end{aligned}$$

4.3.2 Settings

We use the replication/deletion approach for doing multiple runs of model, as recommended by Law (2015), due to the fact that is easy to use and implement, while giving good statistical performance and being applicable to all types of output parameters. With this approach, we use multiple runs to get reliable results for each experiment, where each run is started with an empty system. Due to the start with the empty system, the first part of the results is unreliable and needs to be deleted. This part is called the warm-up period.

Our model starts empty, but when an order normally arrives, the production environment is not empty. This means that the first part of a simulation is useless, as it does not reflect the real situation. For this reason, we use a warmup period in which we don't store any data. We use the Welch method to determine this period as suggested by Law (2015). We let the simulation make 20 runs for 2000 days under the standard settings for the 2018 dataset and take the average time in the system as KPI, also known as the lead time. This KPI indicates clearly when the system is stable. We first take the average over the various runs, before taking the average over 1800 orders where possible. 1800 is chosen as it equals about a quarter of the number of data points, as suggested by Law (2015). We notice in Figure 4-11 that the average stabilizes after about 3000 datapoints, and with the total number of datapoints a bit above 30,000 for 2000 days, the warmup period is set to 200 days. We set the run length to five times this period, namely 1000 days.

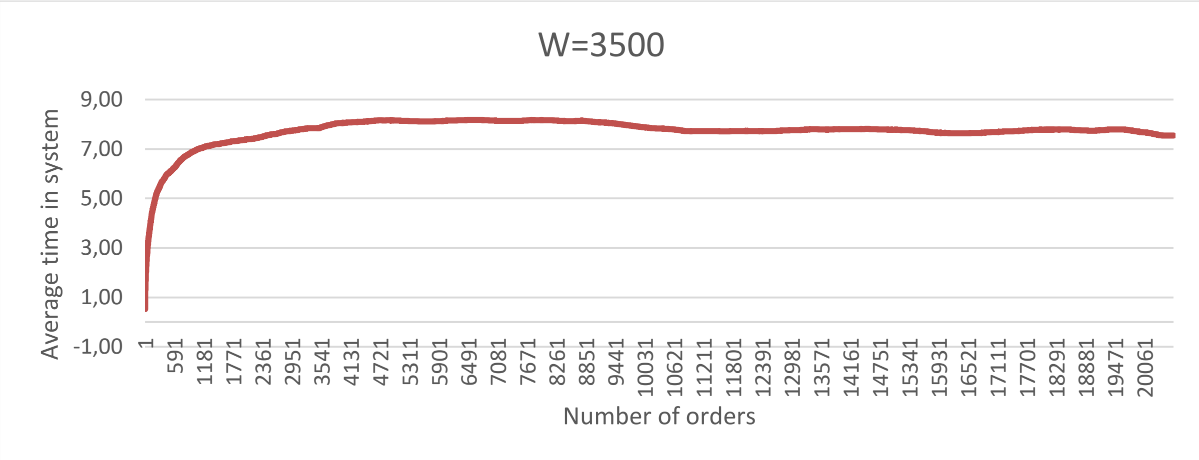

Figure 4-11 Warmup period

With the warmup period and run length set, we determine the number of replications needed for reliable results. We use a method based on the confidence interval, in which we use the t-distribution with a gamma of 0.05 and t set to the number of runs. We start with 20 runs, which we use with the settings, warmup period and run length mentioned above. Each run uses different random numbers. After 17 runs, the error comes below the allowed error, meaning we set the number of replications to 17. In Appendix E the table of the calculations can be found.

4.3.3 Verification & validation

We validated the model in a couple of different methods, suggested by Law (2015) and Robinson (2014).

4.3.3.1 Verification

We start with the verification of the logic. Our logic is stated in Section 4.2 and is implemented according to the logic displayed in the flowcharts. During the implementation, the logic is checked by the use of debugging statements, following the code and visual inspection. The model matches the logic as proposed and behaves as expected. Since the logic in the flowcharts is verified with the external supervisors and employees, we deem the logic of the simulation model valid. During the building of the model, we also did White-Box validation, during which we checked for individual parts, if they match the real world to the extent necessary. A clear example is the fitting of a distribution to the order data. Another important step, is our verification of the assumptions. We verified the assumptions as stated in Section 4.2.6 with either the external supervisors, production supervisors or planners.

4.3.3.2 Validation

Next, we do black-box testing, meaning that we look purely at the inputs and outputs. The reason for this, is to test how accurate our model is. For this purpose, we use the 2017 dataset, as we have the inputs and outputs available from the real system. For the 2018 data, availability of real system data is limited and the data is likely to not accurately represent the complete system.

When we insert the 2017 input data in our model, we should receive the same or at least similar outputs. For this reason, we run our system without additional PPC methods. We compare the results of our models in Table 4-2 and Table 4-3, to the properties of the real system as mentioned in Section 2.3.2 and Section 2.3.4 We notice that our lead times correspond quite well to the times between release and first finish. When comparing the waiting times, we notice that our repair shop, consisting of Troubleshoot (which is passed twice) and Repair, is a bit more efficient than the actual system, with a total waiting time of 1.52 days compared to 3.2 days. This is due to the fact that limited details of the repair shop are available, mostly with RMAs. This is probably also the cause of our lead times matching the first finish lead times instead of the last finish, which is often skewed as it includes multiple repair cycles, while we assume only a single repair cycle per test station is allowed. It is important to note that while we can replicate the simulation data, real data is only available of a single half year. Our model on the other hand, used the data of more than 60 half years. This means, that where the output data of our model is consistent when averaged over all runs, the real data might not be consistent. With these remarks in mind, we accept the output as reasonable and foremost usable.

For the 2018 data, we added the waiting times to same table as the 2017 data. We don't have accurate 2018 data on the waiting times. Regarding the lead times, we do have some data, especially from Q3 2018. This data however is probably not really accurate due to the holiday period, which might explain the differences we notice in the data. When comparing 2017 to 2018, we notice a smoother SMD process, where especially is loaded less. We checked our data on this and it was valid. This is thus due to a change in order properties between 2017 and 2018. It is important to mention that between 2017 and 2018 we increase the number of fte at HMT production to 17. This explains why the average waiting time at this station has gone down. This is done in correspondence to the situation in practice.

Planner code	Average of Time In System from model (days)	Release to first finish real system (days)	Release to first start from real system (days)
PLN111	11.42	12.86	6.96
PLN431	12.01	12.45	6.75
PLN708	3.05	12.78	6.22
PLN800	6.93	9.42	4.60
PLN801	8.42	9.33	8.40
PLN802	7.05	6.56	6.56
PLN803	7.73	7.59	6.98
PLN804	12.04	16.04	4.48

Table 4-2 Average lead time per planner code 2017

Planner code	Average of Time In System from model (days)	Release to first finish real system (days)	Release to first start from real system (days)
PLN111	8.06	15.01	7.23
PLN431	12.37	13.99	6.31
PLN708	5.16	16.18	4.56
PLN800	5.86	9.09	2.49
PLN801	4.17	9.43	6.25
PLN803	2.71	5.88	2.25
PLN804	7.54	22.72	5.43

Table 4-3 Average lead time per planner code 2018

Station	Average waiting time model (days)	Waiting time 2018 model (days)	Average waiting time real system 2017 (days)
Picking SMD	0.20	0.18	unknown
Feeder build	0.02	0.02	unknown
SMD machine 1+2	0.64	0.17	unknown
SMD Machine 3	0.03	0.05	unknown
Touch-up SMD	3.98	0.94	unknown
Touch-up Y	3.53	1.58	unknown
Selective wave	0.90	0.40	.83
HMT production Y	0.01	0.09	0.52
HMT production	1.51	0.51	
Flying probe	0.78	0.51	0.58
Boundary scan	0.34	0.14	0.85
Functional test	0.25	0.26	0.67
Inncer-circuit test	0.29	0.16	0.45
HMT inspection	0.60	0.77	0.875
Repair	0.26	0.12	3.21 for repair + 2x troubleshoot including some processing time
Troubleshoot	0.63	0.36	
Debugging	1.09	0.78	1.50

Table 4-4 Waiting times per station

As the logic in the system is valid and the results correspond to the actual system in a reasonable fashion, we deem the model to be valid and suitable for our purpose.

4.4 Experimental design

We have three different PPC methods, which are the basis for the different scenarios. Within each method, we have four different options for the dispatch rule, including FCFS, which in practice means using no special method. Together with the current PPC method, it forms a baseline. Within the different options, we can also vary the priority rule for debugging, troubleshoot and repair, in the same way as we do for the dispatch rule for releasing orders. Within Kanban and POLCA, we also take the division between normal and quantum cards into account and for all methods we research different batch sizes and transition methods between SMD and HMT.

Besides the PPC method, there are a couple of other things we want to test. These include compensation for the yield and a sensitivity analysis. If the yield is compensated, e.g. by overproduction, the time pressure on the repair shop is reduced. As the processing time is not thoroughly assessed with actual processing times, we execute a sensitivity analysis on the processing times. Another sensitivity analysis will be done regarding the number of employees. These options are only tested with the best options for a new method.

With the settings as set in Section 4.3.2 a single experiment takes about 3 minutes to run. In the case parallel set-up of experiments is possible, we can do 8 experiments simultaneously. This gives us the possibility of around 150 experiments/hour. With the experiments mentioned above, we have 864 experiments, which takes about 5-6 hours, which is suitable for a full factorial design. On the best solution, we will afterwards do an extra analysis for sensitivity and extra options. For each experiment, we use so-called common random numbers. This means that the e.g. all first runs of each experiment use the same random numbers and are easily comparable.

4.5 Results

In this paragraph, we analyse the results from our simulation model. We start with analysing the runs from our experimental design, before doing some auxiliary runs. Afterwards, we do sensitivity analysis on our best experiments, analyse the possibilities for yield compensation and do further analysis on how to use the results.

4.5.1 Original runs

After running our model with a full factorial design, we have a big list of results, which we sort on the average time spent in the system, corresponding with the lead time of an order. The top 55 results consist of only WLC and Kanban with normal cards experiments, before other methods set their best results. The complete top 20 is given in Appendix H and more detailed results in Appendix I The single best run used WLC with a classic SMD-HMT transition, standard 4 week order interval, modified planned start time as dispatch rule for releasing orders and critical ratio as priority rule for repairs.

If we look at the average performance of the various methods in Table 4-5, we notice that on average, only WLC offers a clear improvement over the current system. POLCA, with normal and quantum cards, does not offer improvements over the current system, it simply does not have any influence. The Kanban system offers more interesting results, where the average is similar, but the standard deviation of the average per run has increased, indicating that it works better on certain cases and worse on others. This corresponds with the fact that Kanban with normal cards occurs in the top 20 results a couple of times. For us, these results show that WLC is the best method for Company X, as it clearly delivers the best results on average and on single experiments, together with robustness shown by a low standard deviation across the various experiments.

PPC Method	CardType	Average time in system	StDev of average time in system per run
Current	Normal cards	7.84	0.37
WLC	Normal cards	7.38	0.38
KANBAN	Normal cards	7.82	0.56
	Quantum cards	7.93	0.69
POLCA	Normal cards	7.85	0.37
	Quantum cards	7.83	0.36
Grand Total		7.77	0.49

Table 4-5 Results per PPC method

The detailed results given in Appendix I are filtered on WLC, thus only the effects of a setting on WLC are made visible, as this is our method of choice. Regarding the order interval, the currently used 4 weeks is the best option. A shorter interval leads to increased total processing time, which clogs up the system. A higher interval causes higher individual processing times per order, which can't be handled as efficiently by the system. As the current interval works best, we keep using the current interval.

Regarding the transition between SMD and HMT, we notice that the classic method used currently, works best for the lead time. This is logical, since we measure the lead time of individual orders and not of combined SMD and HMT orders. For this, we need to use different measures, namely the time from release of the SMD order till completion of the HMT order and the mismatch between completion of the SMD order and start of the HMT order. Both of these do not apply to all orders, but only exist on HMT orders that had prior SMD orders. We need more runs to gather these results.

Next, we look at the dispatch rule for the release of orders. The current system of FCFS works best on average, although differences are small. Also, in the individual results, we only need to look in the top 7 to find all different methods. Our expectation is that the general release rule is not very important, although we do extra runs, to see if it has an influence on the transition between SMD and HMT. With this information in mind, we add an auxiliary dispatch rule to our tests. In this version, we use the standard FCFS system, but prioritise an order if it is a continuation from an earlier order.

Using a priority rule for the repair department, on the other hand, does have an effect on the lead time. In this case, adding a rule other than FCFS has the biggest influence, while between only a marginal difference exists on the average. Critical Ratio and Earliest Due Date, also bring down the standard deviation the lead time. For this reason, we will take these two methods to our next run.

With an addition of measures for lead times of combined orders, we now perform extra runs. All these runs use WLC and standard 4-week order intervals. All methods for the transition between SMD and HMT are used, just as all dispatch rules for the release of orders. The latter now features one additional rule, in which orders which are a continuation have priority. Last, we use 2 methods for the repair rules. This gives us a total 30 extra runs.

4.5.2 Additional runs

The complete and detailed results of the additional runs can be found in Table 4-6 and Appendix J The full results are sorted on the average lead time, while the experiment with the shortest lead time for combinations of SMD and HMT orders is made green. As we can see in Table 4-6, a classic transition offers the best individual lead time, while a start of the HMT order at the moment the SMD orders starts picking has the lowest combined lead time. The increased lead time can be explained by the fact that HMT now sometimes need to wait on the SMD parts to be finished, thus increasing the lead time. If HMT does not start their picking before the SMD order is completely finished, this can, of course,

SMD HMT transition	Dispatch rule order release	Dispatch rule repair	Average time in system (days)	StDev of average time in system across runs (days)	On time delivery (%)	Average over due (days)	mismatch between	time in system SMD/HM
Classic	FCFS	CR	6.83	5.85	0.82	5.34	2.64	12.99
Classic	FCFS + continuation	CR	6.84	5.86	0.82	5.16	2.61	12.92
Classic	FCFS + continuation	EDD	6.87	5.89	0.82	5.65	2.65	13.09
Classic	FCFS	EDD	6.87	5.94	0.83	5.36	2.68	13.13
Classic	MPST	EDD	6.88	5.89	0.83	5.03	2.67	13.09
Classic	CR	CR	6.89	5.79	0.82	4.86	2.73	13.22
Classic	CR	EDD	6.89	5.83	0.82	5.15	2.79	13.35
Classic	EDD	CR	6.91	5.96	0.81	5.58	2.83	13.24
Classic	EDD	EDD	6.91	5.97	0.82	5.86	2.68	13.18
Classic	MPST	CR	6.92	5.94	0.81	5.17	2.78	13.17
Touch Up start	EDD	CR	6.96	5.97	0.82	5.24	1.90	11.28
Picking SMD Start	FCFS + continuation	EDD	6.96	5.98	0.82	5.49	2.00	10.78
Picking SMD Start	FCFS	CR	6.97	6.05	0.81	5.53	2.04	10.76
Picking SMD Start	EDD	CR	7.00	6.02	0.81	5.23	2.05	10.77
Picking SMD Start	MPST	CR	7.01	6.01	0.81	5.12	2.09	10.83
Touch Up start	MPST	CR	7.03	6.05	0.81	5.30	2.01	11.48
Touch Up start	FCFS	CR	7.04	6.05	0.81	6.11	1.90	11.45
Touch Up start	FCFS	EDD	7.04	6.06	0.82	5.92	1.88	11.41
Touch Up start	CR	EDD	7.04	5.92	0.82	5.21	1.93	11.55
Picking SMD Start	CR	CR	7.04	5.95	0.80	4.97	2.02	10.90
Picking SMD Start	MPST	EDD	7.04	6.05	0.82	5.25	2.12	10.96
Touch Up start	FCFS + continuation	CR	7.04	6.04	0.81	5.70	1.86	11.35
Touch Up start	MPST	EDD	7.05	6.02	0.82	5.48	1.97	11.49
Picking SMD Start	FCFS + continuation	CR	7.05	6.07	0.80	5.35	2.01	10.85
Touch Up start	FCFS + continuation	EDD	7.06	6.11	0.81	5.99	1.90	11.44
Touch Up start	CR	CR	7.07	5.98	0.81	5.12	1.88	11.48
Picking SMD Start	EDD	EDD	7.07	6.12	0.81	5.97	2.09	10.98
Picking SMD Start	FCFS	EDD	7.11	6.14	0.81	6.14	2.11	11.05
Picking SMD Start	CR	EDD	7.13	6.02	0.80	5.44	2.08	11.12
Touch Up start	EDD	EDD	7.13	6.12	0.81	5.94	1.94	11.67

Table 4-6 Full results of additional runs

not happen. With these results, it is logical to use the Picking SMD Start option, as this benefits the overall results. Looking at both tables regarding dispatch rules, we see minimal differences between the various results. If we compare the two best experiments, based on the SMD-HMT lead time, with a paired T-test, we get a 95% confidence interval of {-1.04,1.02}. Since 0 is inside the interval, the difference is not significant. The paired T-test can be used, due to the common random numbers that we used. When we do the same test for comparing the best experiment with a Touch Up Start transition with experiment 25, we get an interval of {-1.14,0.13}, which is still insignificant. Although statistical insignificant, we still suggest to use Picking SMD Start transition method. As the dispatch rule does not have a huge impact, we suggest to take one that is easy to implement and explain. This is why we choose for Earliest Due Date as repair dispatch rule, and then the first option we come across uses FCFS with priority for continued orders. The main benefit of Earliest Due Date is that the priority does not change over time and the priority number is thus a constant, this is contrary to Critical Ratio for the repair shop. This means our complete proposed method consist of WLC, 4-week order interval, a Picking SMD Start transition, FCFS with priority for continuation order release and due date-based priority at the repair department.

4.5.3 Further analysis for planned lead times

Now that we found our best method, we analyse these specific results in more detail. We start with exploring the lead time per department, or planner code. For this purpose, we analyse the results of the last run of our chosen experiment. We start with the results per department in Table 4-7, where we show the average lead time in days, the percentage on time delivery and the 90th percentile of the lead times per planner code. We see that the normal SMD codes, PLN801 and PLN803, offer quite good results. Further analysis on PLN801 shows that some of the orders are combined orders instead of pure SMD orders. If we leave these out, the average decreases to 2.23, the 90th percentile to 4.10 and the on-time delivery increases to 0.99. Based on this information, we would advise to set the SMD lead time to 4 days, as most order can be processed within this timeframe. For HMT, mainly PLN431, it does not look very good. The 90th percentile is higher than the current lead time of 15 days. However, when we calculate the average and 90th percentile of the current system for PLN431, we get 13.99 and 23.99 respectively. This means that we still save 6 days on the current situation regarding the 90th percentile.

Planner code	Average lead time (days)	90th percentile	on time delivery (%)
PLN111	6.10	11.95	0.73
PLN431	10.63	18.27	0.72
PLN708	5.21	11.01	0.95
PLN800	5.35	11.18	0.81
PLN801	3.62	6.73	0.92
PLN803	2.39	4.04	0.98
PLN804	7.74	15.92	0.85

Table 4-7 Results per department

The reason for this can be found in the waiting times, which are given in Table 4-8. We see that waiting times arise at the Selective Wave machine and the Debugging station. For the first two stations, we will manually lower the WLC limit and see the effects. The waiting time at Debugging is hard to resolve, but for the Selective we had the assumption that it could not be a big bottleneck. In the case the capacity at the selective wave is expected to be insufficient, extra shifts are planned. We also do this in our simulation, but the setting is clearly not aggressive enough under these conditions. For this reason, we make this setting more aggressive, as we could also do this in practice. Further, we notice high waiting times at the Flying Probe, meaning the hour limit is probably too high. This can be explained by the fact that our average position calculation has been done based on the original routing, in which the Flying Probe is often two steps, one for each side of the PCB. In the simulation, these steps have been merged to a single step, as they are executed sequentially without additional waiting time. For this reason, we manually lower the hour limit for the Flying Probe. Finally, given that the current situation is better optimized than the original situation, we repeat some of the testing we did in Section 4.3.1.6 and adjust the common factor for HMT to 1.2 instead of 1.5.

Machine	Average waiting time (days)
Picking SMD	0.16
Feeder Build	0.02
SMD Machine 1+2	0.09
SMD Machine 3	0.06
Touch Up SMD	0.68
Touch Up Y	1.87
Selective Wave	1.09
HMT Production Y	0.04
HMT Production	0.22
Flying Probe	0.63
Boundary Scan	0.09
Functional Test	0.28
Inner-Circuit Test	0.17
HMT Inspection	0.11
Repair	0.14
Troubleshoot	0.30
Debugging	0.78

Table 4-8 Waiting times per station

With these changes done, we get the results per planner code as displayed in Table 4-9. With these adjustments, HMT can consistently deliver within 14 days, 1 day less than the currently used 15 days for planning. These 15 days, however, are not always reached in practice, as we found out in Chapter 2. The SMD lead time also decreased a bit, although the 90th percentile increased for PLN801. This is due to the fact that part of the orders are combined orders of SMD and HMT. If we filter on the pure SMD orders, we can still finish more than 90% of the orders within 4 days lead time. For the proto orders, PLN111 and PLN800, a lead time of respectively 7 and 8 days can be reached consistently. For the Y SMD departments, PLN804, a lead time of 10 days is necessary, with the remark that most orders are combined for SMD and HMT. The Y HMT department can have a consistent lead time of 9 days. For combined SMD and HMT orders, the average lead time is 7.42 days and the 90th percentile is at 14.52 days.

Planner code	Average lead time (days)	90th percentile	on time delivery (%)
PLN111	3.83	7.00	0.93
PLN431	8.39	14.13	0.87
PLN708	3.92	9.28	0.99
PLN800	3.63	8.20	0.93
PLN801	2.65	8.03	0.93
PLN803	1.73	3.05	0.98
PLN804	5.25	10.29	0.97

Table 4-9 Updated results

Now that we have our general lead times, we want to know if all orders should have the same lead time or that the planned lead time for orders should depend on for example the number of operations. For this, we calculated the average lead time and 90th percentile for all orders, as well as specifically for the HMT process, in Table 4-10. We notice a clear increase in the times, together with the number of routing steps in the order. Most importantly, we see that above 10 steps, the 90th percentile comes above the 90th of the average HMT order. It might be worthwhile to implement variable planned lead times, depending on the routing, if Company X wishes to improve its due date performance.

Further, it is interesting to know how long it takes for orders to be released. Although the time spent in the pre-release pool is not measured in our lead time, it is included in the lead time encountered by the customers. We find that in our chosen scenario, the average time spent in the pool is 1.06 day, with the 90% of the orders spending less than 3 days in the pool. About half of the orders does not need to wait at all.

Number of steps	Average	90th percentile	PLN431 average	PLN431 90th percentile
1	2.66	6.07	1.64	2.12
2	2.18	4.03	2.5	3.04
3	2.99	4.59	3.42	6.17
4	3.71	6.04	4.25	6.02
5	3.92	7.46	6.3	9.13
6	4.81	10.09	6.21	11.23
7	4.60	9.21	5.99	12
8	5.15	8.99	6.96	10.99
9	5.83	11.04	6.71	11.02
10	9.45	14.97	11.35	16.06
11	7.89	15.14	10.24	17.16
12	8.93	17.04	10.53	23.01
13	7.82	14.20	10.29	16.04
14	8.93	13.25	10.92	13.76
15	8.17	17.00	11.34	18.02

Table 4-10 Lead times split per number of routing steps

4.5.4 Sensitivity analysis

We performed a sensitivity analysis on a number of factors. First is the processing time, of which we tested the influence of bad estimation for the processing times. We tested the deviation around the estimated processing time, which we modelled with a uniform distribution. The standard factor of 0.2 means that the real processing time lies in in an interval of [0.8,1.2]*expected processing time. This factor does not have a big influence on average lead time. Actually, our base scenario performs best, which might indicate some overfitting. Since the differences are negligible, we ignore this. Next, we use a deviation of the average processing time. In this case, all processing times are multiplied with the factor. This has clearly a bigger impact and is not working well for the system. The model is very sensitive for this. In fact, it is more sensitive for an increase in processing time, than for an equal increase in the number of orders. Although the load should change in equal amount, the size of individual makes the system less flexible. Finally, we took a look at the number of people working at the HMT production step. The current number of 17 seems good. Using less people causes a clear increase in average lead time, while more people do not cause a clear decrease. Regarding sensitivity, we conclude that the system is relatively insensitive if the number of employees is sufficient, once they drop below a certain number, the sensitivity increases.

Absolute change processing time	Average lead time (days)
0.95	6.40
1.00	6.96
1.05	7.99
1.10	9.17
Processing time deviation	**Average lead time (days)**
0.0	7.05
0.1	7.00
0.2	6.96
0.3	7.03
0.4	7.05
Number of orders factor	**Average lead time (days)**
0.90	6.36
0.95	6.64
1.00	6.96
1.05	7.56
1.10	8.24
Number of HMT fte	**Average lead time (days)**
16	7.38
17	6.96
18	6.80
19	6.77

Table 4-11 Results sensitivity analysis

4.5.5 Yield compensation

In the current system, a high number of orders fails at least one test. After a PCB has failed a test, the test software has to be debugged, to check for false-positives. If it is real failure, a PCB needs to be investigated and repaired. During this whole time, the whole batch cannot continue with the production process, increasing the lead time. As we want to lower the lead time, we want to minimize the time we are waiting for this process. We research two methods. The first method is keeping a safety stock of regularly produced items. If a PCB fails a test, it is sent to the repair department, while a PCB is picked from the stock and added to the batch at the final stage. After the repair, the product is placed in the stock. An advantage of this system is that does not throw away items unnecessarily. Disadvantages are that is only suitable for products that are made on a regular basis and that there is a risk that products become obsolete while being in stock. Second method is overproduction, in which we start production with more items than ordered. We than expect a certain number of items to fail and scrap these. The advantage of this method is that is applicable for all orders. The disadvantage would be high costs, since more products are scrapped or more products are delivered than ordered.

Since this thesis is focused on lead time and logistic performance, we will test the performance of these parts. The financial side is not included. For keeping a safety stock, we set a lower bound of at least 5 orders per half year for a product. Otherwise the frequency of orders is too low and the risk increases. For all these products, we keep 5% of the average batch size as safety stock. When testing overproduction, we produce for each order 5% extra products, round up.

Both methods have been tested under our chosen WLC scenario with a total of 17 runs for each experiment. When the safety stock method is used, the average lead time decreases by 0.3 days and on-time delivery increase by 2 percentage points. When opting for 5% overproduction, the average lead time decreases by 0.5 days and the on-time delivery increases by 3 percentage point. Both methods give quite a clear decrease, although the overproduction variant might be very costly, depending on the costs of recycling and possibilities of reuse. With some customers, you might for example be able to negotiate a variable quantity. Instead of a fixed price, they pay for the number of products delivered, where extra delivered products do not necessarily need to have the same price. The safety stock method seems more reasonable and although it was tested with only a limited set of 65 products, this corresponded to 457 out of 1020 orders containing a test step.

4.6 Conclusions

In this chapter, we answer Research Question 3, *How do the constructed alternatives perform regarding the lead time and other relevant KPIs in a simulation?*

We developed, verified and validated a simulation model, which we used to assess the different method we found in Chapter 3. Based on the results, the best PPC method for SMD and HMT at Company X is WLC. This method performs best on individual and average results, besides being most constant. For the order interval, we suggest a 4-week period. A shorter interval leads to increased total lead time and a higher interval leads to higher individual processing times, of which the system is less capable of handling efficiently. For the transition between SMD and HMT, we suggest to start with the HMT as soon as picking at the SMD department starts. This makes the best alignment between the SMD part for the HMT process and the other HMT components coming from the warehouse. Regarding the dispatch rules, no significant differences were found between multiple options. In this case, we opted for the rules that are easy to implement and understand. This means First Come, First Served with priority for continued SMD to HMT orders for order release and Earliest Due Date for the repair department. Important to notice is that WLC is quite sensitive to wrong estimations of the lead time, if the mean is different from the actual processing times. Variation between estimated and actual processing times is not so bad, as long as the mean stays the same. With WLC the lead time for normal SMD can be set to 4 days, normal HMT to 14 days, Y SMD to 10 days and Y HMT to 9 days. Combined SMD and HMT orders should use a planned lead time of 15 days.

Now that we know which methods we want to use, we need to know how to implement these methods. In the next chapter, we research the implementation process.

Chapter 5 Implementation

In this chapter, we answer Research Question 4, *What should be done in order to implement the solutions?* In order to analyse the implementation process, we look at a couple of factors, including data requirements, technical requirements and acceptance in the first three sections. In Section 5.4 we handle the controlling of the method and in Section 5.5 we provide a global timeline.

5.1 Data

Starting with data, we need two up-to-date pieces of data for WLC. First, we need up-to-date and accurate processing times. Processing times are generally available, but not always accurate and mistakes occur. As processing times are the basis of WLC, these need to be at a certain level. A second required piece for data, is live information of the current direct and indirect load per station. For most stations, this data is available based on scan moments in PFS. This data is accurate for this purpose, if a scan has been passed, the item has indeed passed the processing step. This data is, however, not available for all stations, although this situation is being worked on in for example the SMD process. Concluding, the necessary data is available and suitable for the purpose of WLC.

5.2 Technical implementation

Technical implementation is a bit more complicated. The data is spread across two systems, namely Baan, the ERP software and PFS, the production system. At this moment, overviews exist in which both pieces data are combined, but the data is gathered from daily file dumps and thus not live. As WLC requires live data, another method needs to be used, especially since live data is needed to prevent starving of stations.

5.3 Acceptance

The most important part of the implementation process, is to convince the employees convinced to use the system. Most importantly the managers, who need to approve the usage of WLC, and the planners, who mainly need to apply WLC. To get the buy-in from the managers, they need to see the advantages of WLC in respect to the current situation. Although the implementation of WLC will require some investments of time and money, these will be limited, while the benefits are clear and provide a stable system. For the planners, main advantage is a tool in which they can easily check if the production needs more orders, or cannot process additional orders at this moment. With the current system, they have no easy method to do this.

5.4 Controlling

After implementation, controlling WLC is very important. Results of the simulation study might not match the real system perfectly, hence after implementation, finetuning is needed. Directly after implementation, a lot of finetuning is needed, although this is also not a one-time process; the performance of the method and production system needs to be monitored consistently and be adjusted where and when needed. This is especially true if changes in the production mix occur. Another very important control, is using the method in the first place. If the method is bypassed on a regular basis, a flaw exists and needs to be resolved. For this reason, bypasses of the system need to be registered and researched. It might be worth to limit the computer systems from releasing an order, unless it is allowed by the method or a bypass is made with automatic registration.

5.5 Timeline

We suggest to take the following steps to implements WLC:

1. *Create acceptance under employees*
   First, we need to make sure the employees want to use the system, hence we need to convince them of the benefits of this method. The timeframe for this would be a couple of weeks to a month.
2. *Create a project group and a detailed implementation plan*
   In this plan, more details should be put, including stakeholders and responsibilities. The timeframe for this is about a month.
3. *Make a functional design of the necessary IT systems*
   As a new system needs to be developed, requirements and functionality need to be formalized. Timeframe is a couple of weeks to a month, since various stakeholders needs to engaged.
4. *Development and testing of system*
   After the design, the system needs to be developed and tested, before implementation. Testing needs to be done thoroughly, preferable in an environment with real data. If the system is tested with live data, also finetuning can begin. This process can easily take two months.
5. *Actual implementation*
   With the system in place, it needs to be used. After the system has been developed, usage can start within a couple of weeks.
6. *Evaluation and control*
   With the system in use, the most important phase starts, where the system needs to be monitored and evaluated. This should not happen a single time, but continuously. After implementation, also an evaluation on the implementation should take place, to check for improvements of future implementation processes, e.g. at different departments.

With the steps mentioned above, the whole implementation process should take about 4-5 months. This is of course a very rough estimate and can be elaborated further during the second phase.

5.6 Conclusion

This chapter answers Research Question 4, *What should be done in order to implement the solutions?* Implementation should take a total of 4-5 months and include the development of an IT system, of which the data is already available. Before implementation, the employees should be convinced of the benefits of WLC. After implementation, it is very important to control and evaluate the system. Also, the quality of data should not be forgotten, especially since WLC is sensitive to inaccurate processing times.

Chapter 6 Conclusions and recommendations

In this chapter, we answer our main Research Question, *What measures should Company X B.V. take in order to get the combined lead time of SMD and HMT halved to two and a halve weeks?* Section 6.1 provides the answer to this question and in Section 6.2 we do further recommendations.

6.1 Conclusions

- *In the current situation, the greatest part of the lead time is waiting time, caused by the lack of production planning and control at the operational level.*
  Currently, load control is done on a weekly basis at the tactical level. At operational level, no load control is applied and orders are pushed through the system.
- *According to the literature, WLC, Kanban and POLCA are suitable methods to implement at Company X in order to control the load and reduce the lead time.*
  These methods have been proven to work in similar environments, given characteristics as variety in routing and processing times. These methods limit the load allowed in the system in various ways, which according to Little's Law lead to a reduction of lead time.
- *The best working method for Company X is WLC according to our simulation study and it is capable of reducing the combined lead time of SMD and HMT to 15 working days.*
  By implementing WLC, a limit is placed on how much load is allowed in the system. This means that not all orders can be released at the same moment they do in the current situation, which prevents overloading the system. This lowers the WIP in the system and by that shortens the waiting times and the lead time.
- *Besides testing the suitable PPC methods, we tested multiple settings such as priority rules and the transition between SMD and HMT. For each setting we found an optimal result with WLC due to our full factorial design.*
  The differences between multiple options with different priority rules were small, thus we recommend to implement options that are easy to understand and use. This means FCFS with priority for orders that continue from SMD to HMT for the release of orders and Earliest Due Date for the repair of orders. We also looked into the order interval, which is currently set at 4 weeks. A lower interval of three weeks increases the total workload and creates an overloaded system. A higher interval of 5 weeks causes longer processing times of individual orders, of which the system is less capable of handling within the same timeframe. We thus conclude that the current interval of 4 weeks is good. Next, we researched the transition between SMD and HMT. We concluded that a system in which the HMT order is released to the warehouse for picking, as soon as the SMD starts picking, works best. In the two days reserved for picking HMT components from the warehouse, the SMD order is often finished and delivered to HMT.

6.2 Recommendations

This section lists recommendations for further research, as well as recommendation for other improvements.

- *Implement WLC with the additional settings mentioned in the conclusions*
  As we concluded that this method works best and shows significant improvements, we recommend to implement the method.

- *Start keeping track of actual processing times and implement feedback loops for the estimated processing times.*
  Feedback loops regarding processing times are mostly absent, the actual processing times are not registered. Since WLC is quite sensitive to incorrect processing times, especially if the mean is incorrect, it is important to start keeping track of actual processing times and implement feedback loops, to use the data gathered and continuously monitor the processing times. An option to register the processing times is available in PFS, but is not used consistently, making the data extremely noisy and useless.
- *Research the possibility of removing Touch-Up as a separate station and merging it with HMT*
  The Touch Up process at SMD is not functioning according to its original intents. Originally, its goal was to give feedback to the SMD machine, while it was still running, such that adjustments could be made. In the current situation, Touch Up often starts after the machine has finished and thus only inspecting the PCBs in hindsight. It might be worthwhile to get rid of Touch Up as separate station and merge it with the HMT production station. This removed the bottleneck with the greatest waiting times from the SMD process, allowing a smoother process. The HMT stations itself is much bigger and thus allows for more risk pooling. Also, waiting for a whole step is skipped for most products, as most products go through HMT production anyway. This will however need further research on technical limitations.
- *Reduce the number of errors made*
  Although it was outside the scope of this assignment, Company X should continuously work on bringing down the number of made mistakes. By making fewer mistakes, less time will be spent in the repair department, lowering the lead time. Also, lowering the number of mistakes generally generates costs reductions on the long term.
- *Research the effects and possibility of item dependent lead times*
  In Section 4.5.3 we found a clear relation between the number of order steps in the routing and the lead time. If Company X wants to increase due date performance, it can be very useful to implement variable lead times for at least the HMT process. This however needs further research.
- *Research the possibilities and need for PPC methods as WLC for other departments*
  Implementation of a WLC at SMD and HMT is a first step. We don't know the exact needs for PPC methods at different departments of Company X, but we recommend to also do at least an explorative research at other departments for the need of a PPC method. In the case that the needs exist, Company X should think about applying WLC also in those departments, to minimize the number of different methods used. Using different methods may lead to confusing, while using the same stimulates learning from each other and the sharing of knowledge.

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Appendix

Appendix A Correlations lead time

General

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	0.0001	1						
Start to first finish	-0.1087	-0.0419	1					
Start to last finish	0.1438	-0.0412	0.6676	1				
Release to first finish	-0.0984	0.4254	0.8863	0.5856	1			
Release to last finish	0.1370	0.3059	0.6215	0.9386	0.7048	1		
Release to completion	-0.0066	0.0661	0.0611	0.0087	0.0864	0.0314	1	
Start to completion	-0.0066	0.0653	0.0611	0.0087	0.0861	0.0312	1.0000	1

PLN431

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	-0.1065	1						
Start to first finish	-0.2267	-0.0413	1					
Start to last finish	0.1420	-0.0124	-0.0103	1				
Release to first finish	-0.2542	0.4686	0.8631	-0.0145	1			
Release to last finish	0.1241	0.1421	-0.0167	0.9880	0.0579	1		
Release to completion	0.1042	0.2061	0.0922	0.6392	0.1867	0.6647	1	
Start to completion	0.1279	0.0092	0.1027	0.6556	0.0965	0.6505	0.9804	1

PLN801/2/3

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	-0.0555	1						
Start to first finish	-0.1794	-0.2097	1					
Start to last finish	0.0830	-0.0583	0.2386	1				
Release to first finish	-0.1613	0.8034	0.4134	0.0902	1			
Release to last finish	0.0635	0.2488	0.1671	0.9524	0.3328	1		
Release to completion	0.0055	0.2338	0.2552	0.4693	0.3726	0.5267	1	
Start to completion	0.0291	-0.1774	0.3451	0.4984	0.0443	0.4292	0.9153	1

PLN708

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	-0.0068	1						
Start to first finish	0.2251	-0.1229	1					
Start to last finish	0.3502	-0.0220	0.6730	1				
Release to first finish	0.2020	0.4263	0.8453	0.6016	1			
Release to last finish	0.3408	0.2146	0.6284	0.9717	0.6883	1		
Release to completion	0.3128	0.3191	0.7314	0.6776	0.8384	0.7372	1	
Start to completion	0.3312	-0.0845	0.8207	0.7216	0.7025	0.6849	0.9174	1

PLN804

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	-0.0653	1						
Start to first finish	-0.2748	-0.1461	1					
Start to last finish	-0.0434	-0.1415	0.6583	1				
Release to first finish	-0.2911	0.3623	0.8690	0.5492	1			
Release to last finish	-0.0665	0.2375	0.5903	0.9279	0.6748	1		
Release to completion	-0.0656	0.2273	0.5543	0.7841	0.6355	0.8548	1	
Start to completion	-0.0431	-0.1397	0.6184	0.8499	0.5124	0.7812	0.9325	1

PLN111

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	-0.1395	1						
Start to first finish	-0.0311	-0.0006	1					
Start to last finish	0.5077	-0.1241	0.2087	1				
Release to first finish	-0.1076	0.6062	0.7948	0.0923	1			
Release to last finish	0.4779	0.1007	0.2092	0.9747	0.2292	1		
Release to completion	0.3524	0.1825	0.2688	0.6415	0.3269	0.6848	1	
Start to completion	0.3961	-0.1017	0.2722	0.6846	0.1571	0.6641	0.9595	1

PLN800

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	-0.2270	1						
Start to first finish	-0.3528	0.4507	1					
Start to last finish	-0.3605	0.6012	0.9509	1				
Release to first finish	-0.3624	0.7122	0.9474	0.9611	1			
Release to last finish	-0.3558	0.7830	0.8830	0.9676	0.9735	1		
Release to completion	-0.2767	0.8116	0.5659	0.7389	0.7315	0.8284	1	
Start to completion	-0.2724	0.7375	0.5651	0.7348	0.7035	0.8013	0.9930	1

PLN801

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	-0.0693	1						
Start to first finish	-0.1335	-0.2336	1					
Start to last finish	0.1359	-0.0704	0.1615	1				
Release to first finish	-0.1249	0.9153	0.1769	-0.0054	1			
Release to last finish	0.1132	0.2176	0.0910	0.9583	0.2571	1		
Release to completion	0.0309	0.2865	0.1241	0.3433	0.3398	0.4177	1	
Start to completion	0.0604	-0.1116	0.2235	0.3849	-0.0223	0.3442	0.9200	1

PLN802

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	-0.0643	1						
Start to first finish	#DIV/0!	#DIV/0!	1					
Start to last finish	0.5040	-0.0034	#DIV/0!	1				
Release to first finish	-0.0643	1.0000	#DIV/0!	-0.0034	1			
Release to last finish	0.2697	0.7734	#DIV/0!	0.6314	0.7734	1		
Release to completion	0.0213	0.3559	#DIV/0!	0.3410	0.3559	0.4922	1	
Start to completion	0.0502	-0.0465	#DIV/0!	0.3660	-0.0465	0.1960	0.9170	1

PLN803

	Quantity	Release to first start	Start to first finish	Start to last finish	Release to first finish	Release to last finish	Release to completion	Start to completion
Quantity	1							
Release to first start	-0.0854	1						
Start to first finish	-0.2087	-0.2570	1					
Start to last finish	0.1628	-0.0604	0.1147	1				
Release to first finish	-0.2331	0.6816	0.5318	0.0333	1			
Release to last finish	0.1332	0.2378	0.0349	0.9552	0.2342	1		
Release to completion	-0.0487	0.1370	0.2422	0.4954	0.3030	0.5226	1	
Start to completion	-0.0145	-0.2458	0.3345	0.5066	0.0374	0.4200	0.9264	1

Appendix B Charts processing time

In Figure 0-1 scatter plot is added of the planned times in comparison to the measured duration in PFS, where a slight trend towards shorter PFS duration vs estimated hours is visible. A second graph is added for the Selective Wave in Figure 0-2, where the points are already scattered all over the graph. Finally, a graph for SMD Touch Up is added in Figure 0-3, where it is clear quite clear that the estimates are far too low for the processing times in practice. One reason for this, is the fact that inspection should be done sample-wise, but in practice is done on all PCBs. This is known and capacity is larger than it should be according to the estimations.

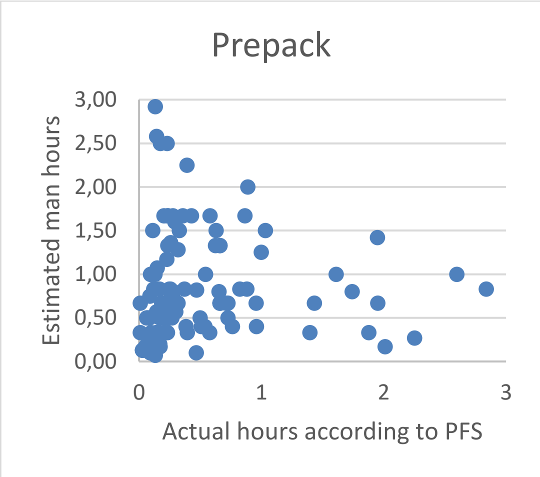


Figure 0-1 Plot of selected points of registered times vs estimated times Prepacking

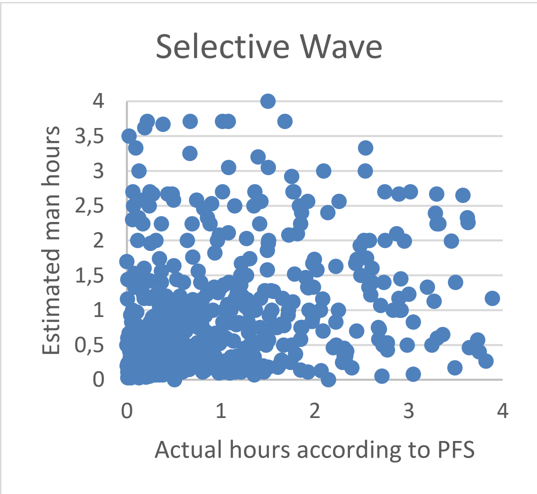


Figure 0-2 Plot of selected points of registered times vs estimated times Selective Wave

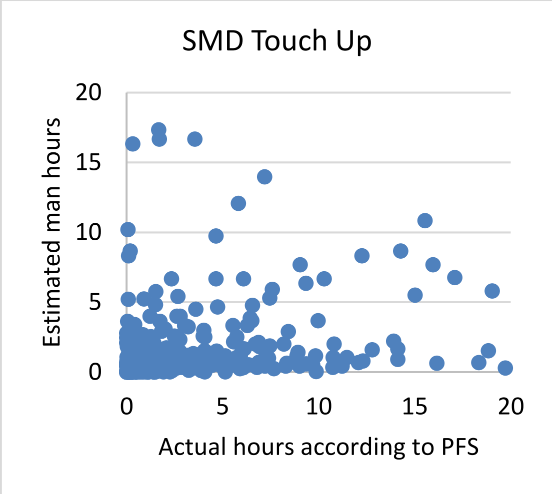
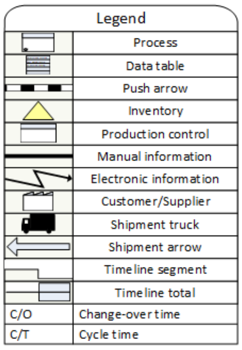
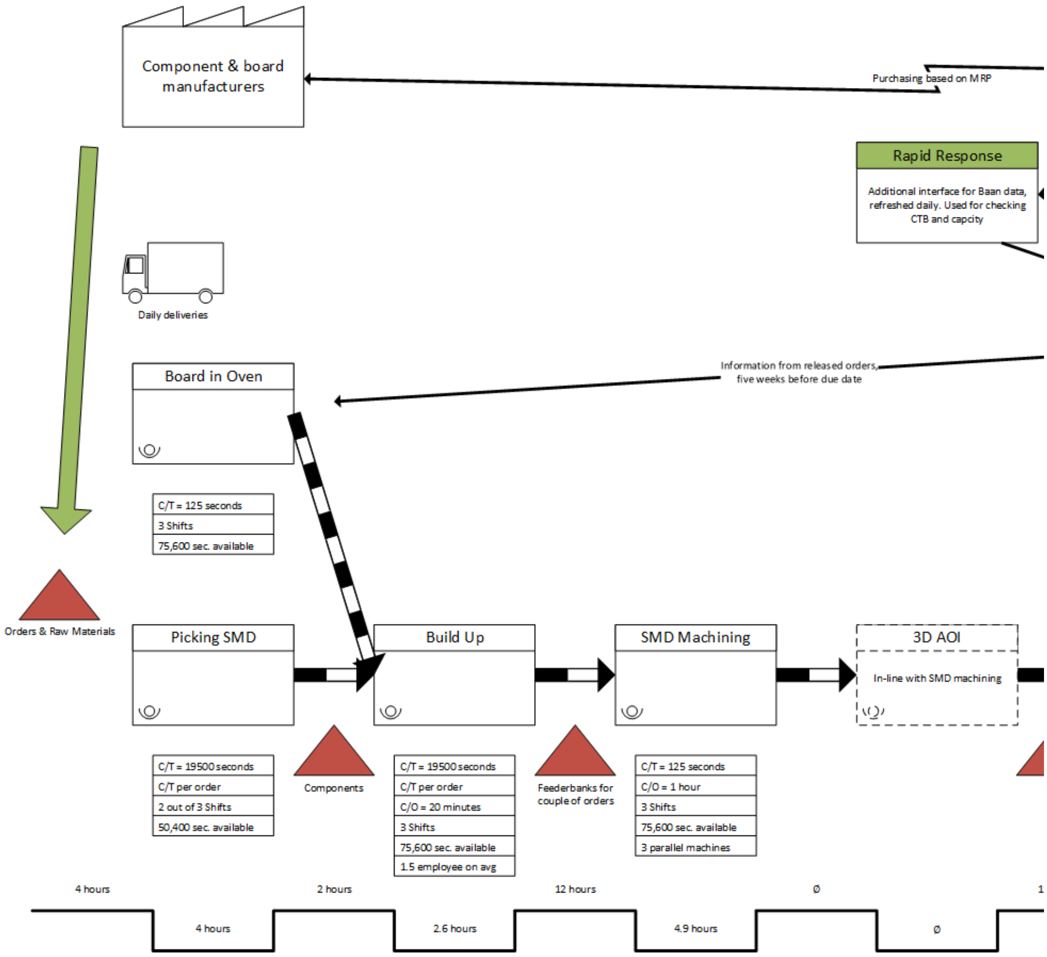
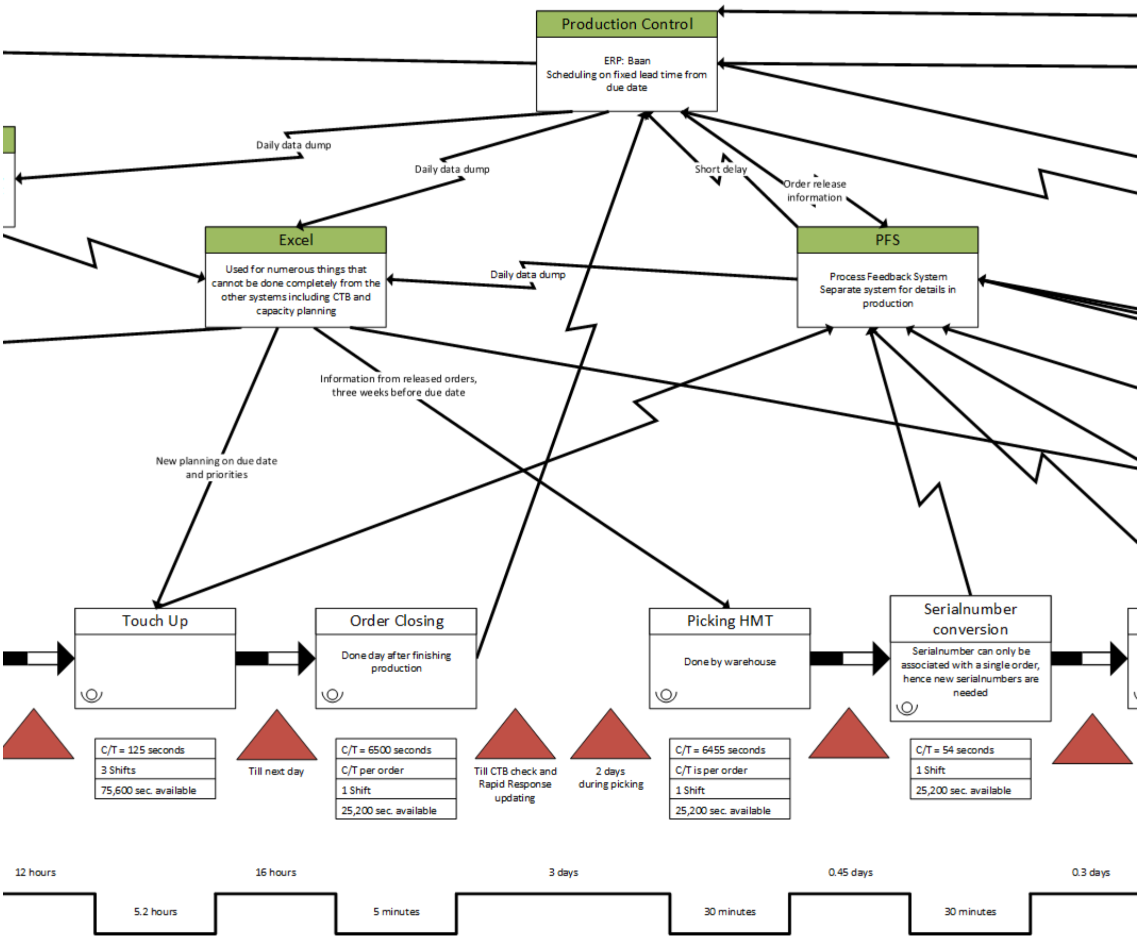


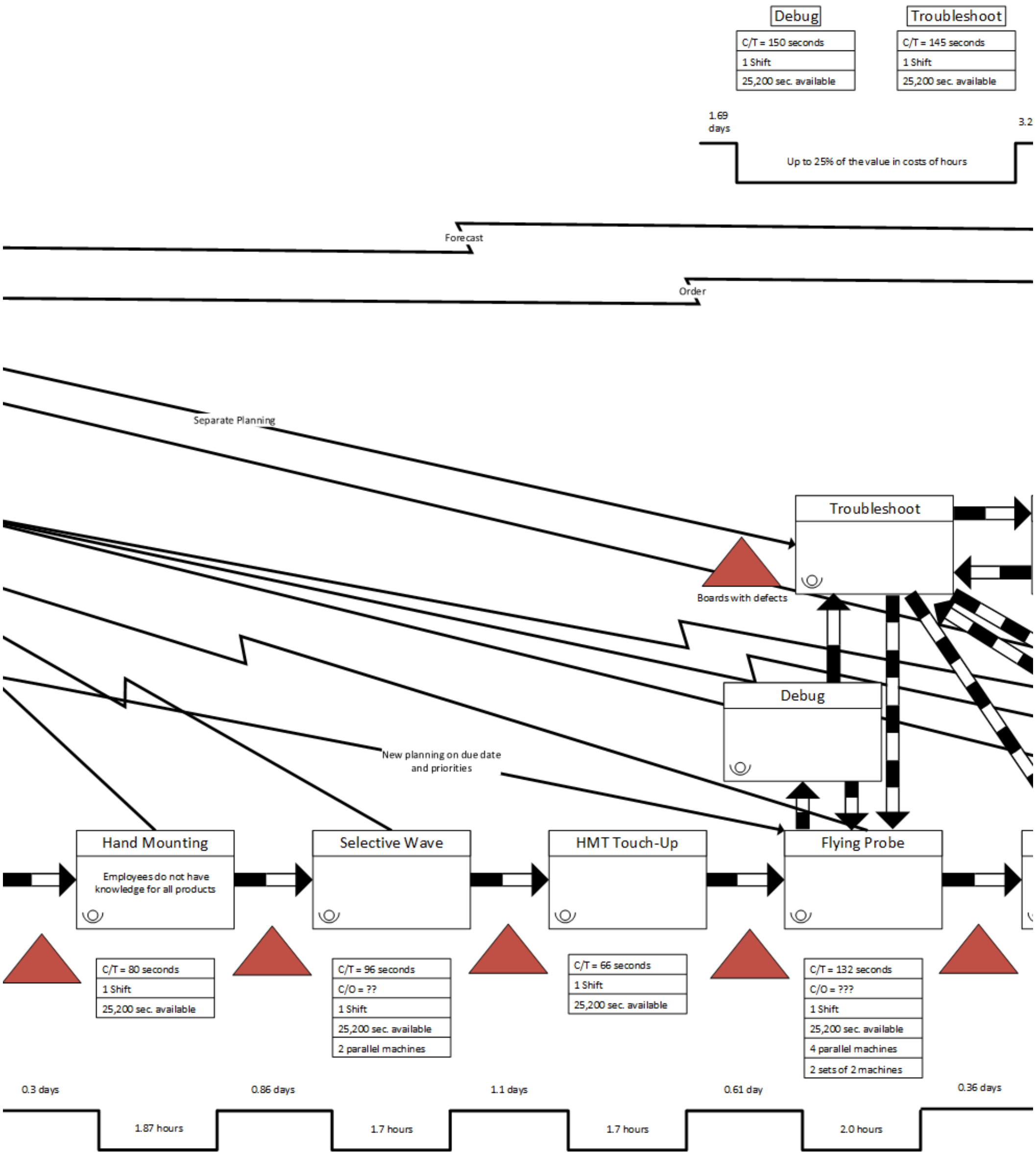
Figure 0-3 Plot of selected points of registered times vs estimated times SMD Touch Up

Appendix C VSM

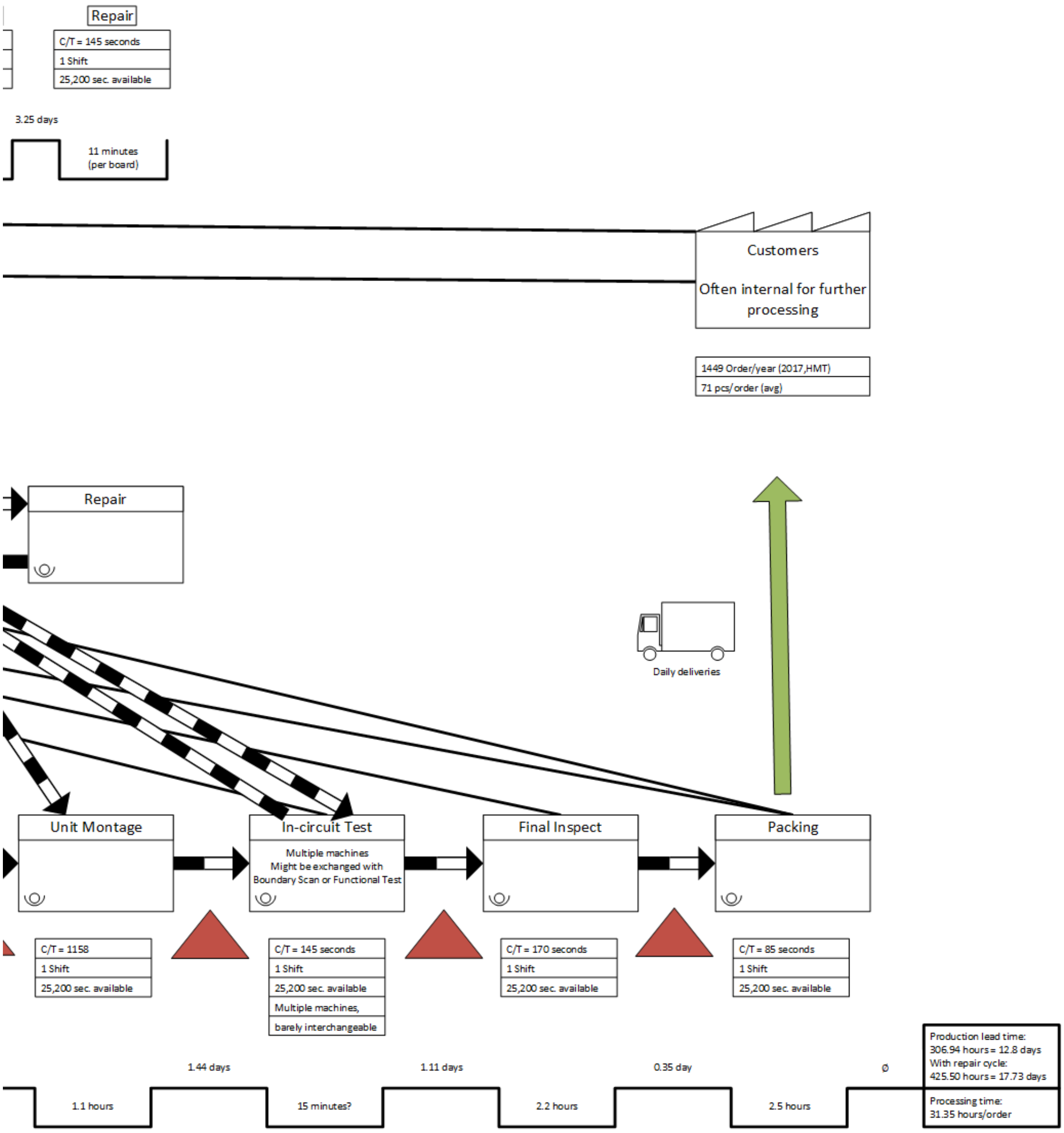





Production Control
ERP: Baan
Scheduling on fixed lead time from due date
Daily data dump
Daily data dump
Short delay
Order release information
Excel
Used for numerous things that cannot be done completely from the other systems including CTB and capacity planning
Daily data dump
PFS
Process Feedback System
Separate system for details in production
Information from released orders, three weeks before due date
New planning on due date and priorities
Touch Up
Order Closing
Done day after finishing production
Picking HMT
Done by warehouse
Serialnumber conversion
Serialnumber can only be associated with a single order, hence new serialnumbers are needed
C/T = 125 seconds
3 Shifts
75,600 sec. available
Till next day
C/T = 6500 seconds
C/T per order
1 Shift
25,200 sec. available
Till CTB check and Rapid Response updating
2 days during picking
C/T = 6455 seconds
C/T is per order
1 Shift
25,200 sec. available
C/T = 54 seconds
1 Shift
25,200 sec. available
12 hours
16 hours
3 days
0.45 days
0.3 days
5.2 hours
5 minutes
30 minutes
30 minutes



Debug
C/T = 150 seconds
1 Shift
25,200 sec. available
Troubleshoot
C/T = 145 seconds
1 Shift
25,200 sec. available
1.69 days
3.2
Up to 25% of the value in costs of hours
Forecast
Order
Separate Planning
Troubleshoot
Boards with defects
Debug
New planning on due date and priorities
Hand Mounting
Employees do not have knowledge for all products
Selective Wave
HMT Touch-Up
Flying Probe
C/T = 80 seconds
1 Shift
25,200 sec. available
C/T = 96 seconds
C/O = ??
1 Shift
25,200 sec. available
2 parallel machines
C/T = 66 seconds
1 Shift
25,200 sec. available
C/T = 132 seconds
C/O = ???
1 Shift
25,200 sec. available
4 parallel machines
2 sets of 2 machines
0.3 days
0.86 days
1.1 days
0.61 day
0.36 days
1.87 hours
1.7 hours
1.7 hours
2.0 hours


Repair
C/T = 145 seconds
1 Shift
25,200 sec. available
3.25 days
11 minutes (per board)
Customers
Often internal for further processing
1449 Order/year (2017,HMT)
71 pcs/order (avg)
Repair
Daily deliveries
Unit Montage
In-circuit Test
Multiple machines
Might be exchanged with Boundary Scan or Functional Test
Final Inspect
Packing
C/T = 1158
1 Shift
25,200 sec. available
C/T = 145 seconds
1 Shift
25,200 sec. available
Multiple machines,
barely interchangeable
C/T = 170 seconds
1 Shift
25,200 sec. available
C/T = 85 seconds
1 Shift
25,200 sec. available
1.44 days
1.11 days
0.35 day
ø
1.1 hours
15 minutes?
2.2 hours
2.5 hours
Production lead time:
306.94 hours = 12.8 days
With repair cycle:
425.50 hours = 17.73 days
Processing time:
31.35 hours/order

Appendix D Additional literature

We look how to describe the process of Company X, which is useful while searching for solutions and literature. We first look at the production environment and the Customer Order Decoupling Point (CODP), before taking a look at shop floor layout. Finally, we review the components of lead time.

Appendix D.1 Manufacturing environment

According to among others Olhager (2003), and Amaro, Hendry, & Kingsman (1999), there are 4 general methods for running a manufacturing environment, based on where customer demand is separated from the production process. The point in the supply chain where the separation takes place is called the Customer Order Decoupling Point (CODP). In a single company, or even production process, multiple CODPs can be used alongside each other, e.g. for different customers or product types. In short, the different CODPs are be described as follows according to APICS (2017).

1. *Engineer-to-order (ETO)*: Products whose customer specifications require unique engineering design, significant customization, or new purchased materials. Each customer order results in a unique set of part numbers, bills of material, and routings.
2. *Make-to-order (MTO):* A production environment where a good or service can be made after receipt of a customer's order. The final product is usually a combination of standard items and items custom-designed to meet the special needs of the customer.
3. *Assemble-to-order (ATO):* A production environment where good or service can be assembled after receipt of a customer's order. The key components (bulk, semi-finished, intermediate, subassembly, fabricated, purchased, packing, and so on) used in the assembly or finishing process are planned and usually stocked in anticipation of a customer order. Receipt of an order initiates assembly of the customized product. This strategy is useful where a large number of end products (based on the selection of options and accessories) can be assembled from common components.
4. *Make-to-stock (MTS):* A production environment where products can be and usually are finished before receipt of a customer order. Customer orders are typically filled from existing stocks, and production orders are used to replenish those stocks.

Appendix D.2 Shop floor layout

Generally two types of routing configurations are used in literature to describe a factory, namely job shop and flow shop (Enns, 1995). In a job shop, routings are completely random and each machine has the same probability to be required for the next operation. In a flow shop all products follow the same route. It is trivial that these are two extremes and while flow shops exist in reality, pure job shops don't appear regularly. In most job shops a dominant flow exists. The categorisation between the extremes can be done in multiple ways.

Oosterman, Land, & Gaalman (2000) added two categories, general flow shop and restricted job shop. In a general flow shop, the workstations visited in the route are random, although they are visited in a predetermined sequence. In the restricted job shop all workstations are visited, although the sequence is random. Stevenson et al. (2005) also define the general job shop, where a dominant direction of flow exists, although routings are allowed to include the opposite direction. Besides the manufacturing units, repair shops exist. Characteristics include a stochastic demand and unknown routings and processing times at the time of arrival (Keizers, Adan, & Van Der Wal, 2001).

At Company X, we notice that two different layouts are used for SMD and HMT. SMD is closest to a pure flow shop, as products follow the same routes, with some minor exceptions. In HMT, the layout is best described as a general job shop. A major flow direction can be seen, although routings are very different for each product and multiple visits, including steps backwards, to a station are allowed. Besides these department, the repair part can be seen as a classic repair shop, with random arrivals, routings and processing times. There is, however, a theoretical limit on the time the repair shop may spend a certain product, based on the costs.

Appendix D.3 Lead time components

Lead time can be described as the sum of a number of components, in which the lead time can then also be broken down (Hopp, Spearman, & Woodruff, 1990). These components, accompanied by a short description are:

- *Processing time:* time needed by the work centres to perform operations on the product.
- *Setup time:* time needed to change the settings of the machines to make it able to process the product. Hopp et al. (1990) use the internal setup time, being the time that the machine cannot perform operations.
- *Move time:* time needed for internal transportation between work centres.
- *Queue time:* time spent waiting in line for the next operation. This includes waiting for resources, such as operators or transportation vehicles.
- *Wait-for-parts time:* time spent waiting for parts necessary for production.
- *Wait-to-move time:* time spent waiting for the batch to be complete, before going to the next work centre.

Appendix D.4 Queueing theory and Little's Law

Analysis of some of the lead time components as mentioned in Appendix D.3 , can be done by using queueing theory. As expected from the name, the queueing time can be analysed. This is especially easy if the processing and interarrival times at a single station can be assumed to exponentially distributed. In that case, the queue time at a single station can be calculated using Little's law (Zijm, 2012):

$$EL = \lambda EW \tag{D-1}$$

This formula shows that the cycle time (EW), or time in the system (=lead time), is dependent on the expected number of jobs in the system (EL) and the arrival rate (λ). Queueing theory is based on states and transitions between these states. The states are given by the number of items in the system. Transitions happen when an item enters or leaves the system and are always towards an adjacent state. The probabilities to go to a new, higher or lower, state are dependent on the processing rate (μ) and the arrival rate (λ). In order to obtain a stable system, the service rate should be higher than the arrival rate, otherwise the system will trend towards a state with infinite items in the system. With this knowledge, we know that if we want to reduce lead time by reducing the queueing time, the number of products in the system needs to be reduced.

Appendix E Numbers of runs calculations

AvgTimeInSystem	AVG	Var	T	Error	Test	RunNr
7.762						1
6.553	7.157	0.731	12.706	1.518	NIET GENOEG	2
7.127	7.147	0.366	4.303	0.257	NIET GENOEG	3
7.377	7.205	0.257	3.182	0.129	NIET GENOEG	4
8.622	7.488	0.595	2.776	0.143	NIET GENOEG	5
7.918	7.560	0.506	2.571	0.108	NIET GENOEG	6
7.957	7.617	0.445	2.447	0.087	NIET GENOEG	7
9.075	7.799	0.647	2.365	0.092	NIET GENOEG	8
8.184	7.842	0.583	2.306	0.079	NIET GENOEG	9
9.157	7.973	0.691	2.262	0.079	NIET GENOEG	10
8.645	8.034	0.663	2.228	0.071	NIET GENOEG	11
8.048	8.035	0.603	2.201	0.064	NIET GENOEG	12
8.741	8.090	0.591	2.179	0.060	NIET GENOEG	13
8.201	8.098	0.546	2.160	0.055	NIET GENOEG	14
8.784	8.143	0.538	2.145	0.052	NIET GENOEG	15
7.618	8.111	0.520	2.131	0.049	NIET GENOEG	16
7.512	8.075	0.508	2.120	0.047	GENOEG	17
7.651	8.052	0.488	2.110	0.044	GENOEG	18
7.025	7.998	0.517	2.101	0.045	GENOEG	19
7.259	7.961	0.517	2.093	0.043	GENOEG	20

Appendix F WLC hours limit and number of Kanban cards

Machine	WLC limit	Normal Kanban cards	Quantum Kanban cards	Quantum hour limit
Picking SMD	18	3	15	4
Feeder build	54	4	30	4
SMD Machine 1+2	72	3	30	4
SMD Machine 3	36	2	15	4
Touch-up SMD	45	3	15	4
Touch-up Y	60	4	10	4
Selective wave	142.8	4	20	4
HMT production Y	949.08	17	110	4
HMT production	1458	34	180	4
Flying probe	809.28	14	80	4
Boundary scan	475.2	5	41	4
Functional test	228.48	3	20	4
Inner circuit test	204.72	4	20	4
HMT inspection	636	8	50	4

Appendix G Number of POLCA cards

Current	Destination	Normal cards	Quantum cards	Quantum hour limit
Picking SMD	Feeder build	44	82	12
Feeder build	SMD Machine 1+2	36	116	12
Feeder build	SMD Machine 3	9	30	12
SMD Machine 1+2	Touch-up SMD	36	153	12
SMD Machine 3	Touch-up Y	9	33	12
Picking	HMT production	50	30	12
Picking	HMT production Y	34	21	12
HMT production	Selective wave	55	221	12
HMT production	Selective wave	9	46	12
Selective wave	HMT production	50	183	12
Selective wave	HMT production Y	13	47	12
HMT production	Flying probe	29	113	12
HMT production	Functional test	9	34	12
HMT production	Inner circuit test	6	22	12
Flying probe	HMT production	32	70	12
Flying probe	HMT production Y	2	8	12
Flying probe	Boundary scan	5	10	12
Flying probe	HMT inspection	8	18	12
Boundary scan	HMT production	5	15	12
Functional test	HMT production	3	8	12
Functional test	HMT inspection	8	23	12
Inner circuit test	HMT production	3	5	12
Inner circuit test	HMT inspection	5	8	12
HMT production	HMT inspection	42	167	12
HMT production Y	HMT inspection	44	223	12
HMT inspection	HMT production	47	231	12
HMT inspection	HMT production Y	24	115	12
HMT inspection	Inner circuit test	2	10	12

Appendix H Top 20 results

PPC Method	Card type	Batches	SMD HMT transition	Dispatch rule order release	Dispatch rule repair	Average time in system (days)	StDev of average time in system across runs (days)	On time delivery (%)	Average over due (days)	Average time from generation to completion (days)	Average mismatch SMD order and picking HMT (days)
WLC		Standard	Classic	MPST	CR	6.86	5.87	0.83	4.58	7.36	2.63
WLC		Standard	Classic	EDD	EDD	6.89	5.91	0.83	5.44	7.53	2.60
WLC		Standard	Classic	FCFS	MPST	6.89	5.97	0.83	5.75	7.59	2.62
WLC		Standard	Classic	EDD	CR	6.91	5.92	0.82	4.95	7.45	2.56
WLC		Standard	Classic	MPST	EDD	6.91	6.05	0.83	5.17	7.52	2.69
WLC		Standard	Classic	FCFS	EDD	6.93	5.98	0.83	5.17	7.49	2.55
WLC		Standard	Classic	CR	MPST	6.93	5.87	0.82	5.22	7.65	2.65
WLC		Standard	Classic	EDD	MPST	6.94	5.98	0.83	5.41	7.55	2.58
WLC		Standard	Classic	FCFS	FCFS	6.95	6.29	0.82	6.14	7.57	2.57
KANBAN	Normal	Standard	Classic	FCFS	EDD	6.96	6.11	0.84	4.74	7.31	2.00
WLC		Standard	Classic	FCFS	CR	6.97	5.97	0.82	5.43	7.63	2.56
WLC		Standard	Classic	EDD	FCFS	6.97	6.33	0.82	5.99	7.56	2.65
KANBAN	Normal	Standard	Classic	EDD	MPST	6.99	5.99	0.84	4.58	7.45	2.00
WLC		Standard	TouchUpStart	FCFS	CR	7.00	6.00	0.82	5.16	7.61	1.84
WLC		Standard	Classic	CR	CR	7.01	5.91	0.81	4.88	7.68	2.66
KANBAN	Normal	Standard	Classic	FCFS	CR	7.01	6.13	0.83	4.58	7.36	2.00
WLC		Standard	PickingSMDStart	EDD	EDD	7.02	6.07	0.82	5.82	7.77	2.07
WLC		Standard	Classic	CR	EDD	7.03	5.94	0.81	5.24	7.76	2.71
WLC		Standard	PickingSMDStart	EDD	MPST	7.03	6.06	0.82	5.33	7.64	1.98
WLC		Standard	Classic	MPST	MPST	7.03	6.07	0.82	5.28	7.70	2.68

Appendix I Detailed results per setting filtered on WLC

Batches	Average time in system	StDev of average time in system per run	Average of StDev of time in system per run
3 week interval	7.81	0.35	7.88
Standard/4 week	7.06	0.09	6.14
5 week interval	7.26	0.09	6.69
Average	7.38	0.38	6.9

Table 0-1 Results per batch order interval

SMD HMT Transition	Average time in system	StDev of average time in system per run	Average of StDev of time in system per run
Classic	7.24	0.34	6.76
Picking SMD Start	7.44	0.37	6.95
Touch Up Start	7.45	0.39	6.99
Average	7.38	0.38	6.9

Table 0-2 Results per SMD HMT transition method

Release rule	Average time in system	StDev of average time in system per run	Average of StDev of time in system per run
None/FCFS	7.33	0.31	6.86
Critical Ratio	7.38	0.42	6.97
Earliest Due Date	7.45	0.39	6.89
Modified Planned Start Time	7.36	0.37	6.88
Average	7.38	0.38	6.9

Table 0-3 Results per order release dispatch rule

Repair rule	Average time in system	StDev of average time in system per run	Average of StDev of time in system per run
None/FCFS	7.54	0.51	7.22
Critical Ratio	7.33	0.31	6.68
Earliest Due Date	7.34	0.33	6.56
Modified Planned Start Time	7.31	0.26	7.14
Average	7.38	0.38	6.9

Table 0-4 Results per repair dispatch rule

Appendix J Detailed results additional runs

SMD HMT transition	Average time in system	Average of StDev of time in system per run	Average of SMD HMT lead time
Classic	6.88	5.89	13.14
Touch Up Start	7.05	6.03	11.46
Picking SMD Start	7.04	6.04	10.90

Table 0-5 Results per SMD HMT transition method

Release rule	Average time in system	Average of StDev of time in system per run	Average of SMD HMT lead time
None/FCFS	6.98	6.02	11.80
Earliest Due Date	7.00	6.03	11.85
Critical Ratio	7.01	5.92	11.94
Modified Planned Start Time	6.99	5.99	11.84
Continuation/FCFS	6.97	5.99	11.74

Table 0-6 Results per order release dispatch rule

Repair rule	Average time in system	Average of StDev of time in system per run	Average of SMD HMT lead time
Earliest Due Date	7.00	6.01	11.89
Critical Ratio	6.97	5.97	11.78

Table 0-7 Results per repair dispatch rule