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Reducing the throughput time of product A

By improving planning and control

Bachelor Thesis

Industrial Engineering and Management

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Preface

This report is the result of a bachelor thesis that I have executed for my bachelor Industrial Engineering and Management at the University of Twente. I conducted my thesis at Company A, in Hengelo. The main goal of this thesis to reduce the total throughput time for product A product, processed by Company A.

First, I would like to thank my colleagues at Company A. So many people have helped me during the execution of my thesis. From shop-floor workers to people in the business office, everyone was helpful. Naming all of them would result in a very long list of names. Moreover, I do not want to risk the chance of missing a name. Though, I want to specifically thank two people. The first person is Dennis Bakhuis, the director of Company A, for giving me the opportunity to do the thesis at Company A. Moreover, his personal guidance and opinions helped me a lot to acquire a proper understanding of the problem situation and wishes of Company A. Even though he was very busy, he always found a gap in his agenda to help me out. The second person I want to thank is Marcel Mekkering, the former product A project supervisor, for his help during my thesis. He knew so much about product A such that I could ask him anything. In addition, he really thought along with me and always took a lot of time to discuss things with me.

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Lastly, I want to thank my girlfriend Carlijn, my parents Gerard and Rita, my brother Quinten, and his girlfriend Britt for their unconditional support during my bachelor study. In addition, I want to thank my (study) friends for their support. Naming all of them would, again, result in a long list of names, where I do not want to risk missing some names.

Jesper Rensen

Heeten, July 2019

Management summary

Introduction

Company A is a supplier of high-precision parts and mechatronic integrated modules for the aerospace industry, aeronautical space programs, military programs, and maritime projects. One of their projects is processing products A for customer X. Product A is a titanium aircraft engine component to which the main shaft of the aircraft engine is mounted. The product A project has been in an introductory phase for COMPANY A but, currently, it is time to improve the efficiency of the production. That is why this thesis is needed. The action problem, presented by Company A was: *How can the throughput time of product A be minimized from nine weeks to a maximum of four weeks?*

It was believed that considerable time gains could be acquired by improving the current planning approach that is in place. Therefore, the research question of this thesis became: *How should a production planning approach be applied at Company A such that the relevant characteristics and restrictions of the production are satisfied to reduce throughput time?*

The problem approach

In order to answer this question, the following things were done during the execution of this thesis:

- Identifying the main characteristics of the production process: the production route, the current planning, the process times of departments, the capacity, the demand, the transport-day(s), costs, and potential bottlenecks.
- Doing a literature study to identify planning and control approaches. By doing a literature study, the main characteristics of planning and control were investigated, together with outlining multiple planning and control approaches.
- Selecting three planning and control approaches for COMPANY A. By assessing literature, it was determined that MRP, ConWIP, and bottleneck control were the best options for COMPANY A. The steps and functioning of the three approaches were also outlined.
- Doing a simulation study in order to test the effects of the three different planning and control approaches. In addition, other interventions like transport-days, delivery variability, and adding extra machines were tested.
- Combining the best results of all simulation experiments in one simulation model in order to determine what is needed to reduce the throughput time to a maximum of four weeks.

Main results based on the simulation model

Within the simulation model, multiple things have been experimented. First, the three planning and control approaches were compared to the base model. It turned out that bottleneck control on the grinding machine was outperforming bottleneck control on the turning and milling machine and outsourcing. MRP, ConWIP, and bottleneck control outperformed the base model, mainly because of a reduction in waiting time. MRP and bottleneck control outperformed ConWIP, whereas between MRP and bottleneck control no significant difference in performance was observed.

Second, delivery variability was tested within the simulation model. Decreasing or eliminating delivery variability significantly reduces total throughput time by approximately 2 to 3 days (little variability) and perhaps 3 to 6 days (a lot of variability). Furthermore, negotiating a fixed number is more effective than negotiating a fixed interval.

Third, a different transport-day to the outsourcing company can significantly reduce throughput time. Regarding the assumed transport day in the base model, the throughput time can be reduced by approximately 3 days (in the base model) or 5 days (in an MRP-model) by just choosing a different

transport-day. Driving twice to the outsourcing company can significantly reduce throughput time by approximately 8 days (in the base model) and 8 to 9 days (in an MRP-model).

Fourth, adding an extra turning and milling machine would not reduce total throughput time and only increase costs, whereas adding an extra grinding machine would reduce total throughput time while also reducing costs.

Lastly, a different day for the delivery of new products A and acquiring of finished products A by customer X can improve total throughput time by approximately 4 days (based on the MRP-model). Furthermore, driving twice to customer X can significantly reduce the throughput time by approximately 7 days (based on the MRP-model).

By eventually combining all best results into one model, the things could be outlined that are needed to reduce the throughput time to four weeks. A throughput time excluding the delivery to the customer of less than four weeks can be acquired by using an MRP planning and control approach, buying an extra grinding machine, and driving twice to the outsourcing company. A throughput time including the delivery to the customer of less than four weeks can be acquired by doing the same but also driving two times to customer X. For this, at least 9 full-time employees (FTE's) are needed to eventually do at least 4,82 FTE work, excluding the turning and milling machine. The turning and milling machine needs a 24-hour shift, 6 days per week (of which 8 hours per day are automated). This could be done with 2 to 3 operators.

Recommendations

Based on the problem approach and main results, I recommend COMPANY A to do the following things in order to reduce the throughput time of product A:

- Use MRP or bottleneck control (on the grinding machine) as planning and control approach. MRP would be more interesting if sufficient capacity is present since it is a familiar approach for COMPANY A. In addition, it is simpler to introduce than bottleneck control. Though, I would also recommend to using an extra capacity analysis system to check if the scheduled numbers in the MRP are still suitable. Bottleneck control would be more interesting if capacity is more constrained than assumed in this thesis.
- Try to negotiate a fixed delivery interval with fixed delivery numbers since it reduces variability and thus waiting times. If this is not possible, reducing variability already reduces throughput time significantly. Furthermore, negotiating a fixed number is more effective than negotiating a fixed interval.
- Try to find the right alignment between the transport day to the outsourcing company and the delivery and acquiring day. This is important since it can massively influence the total throughput time. For some combinations, this thesis provides the optimal values which can be used. Determining the transport day changes total throughput time significantly. Transporting to the outsourcing twice can improve the throughput time even more but comes with a cost. Setting the day on which new castings come in and finished products A are acquired by customer X, can also considerably reduce the throughput time. In addition, driving two times to customer X reduces the throughput time even further, but probably also comes with a cost. Driving three times to customer X is not interesting.
- Add an extra grinding machine. This is cheaper than running longer shifts in order to cope with the specified demand. The shift hours can be limited enough in order to save costs such that a second grinding machine is lucrative.
- Review the current calculated process times.
- Re-introduce clocking of the process times.

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Reader's guide

This reader's guide is created to give the reader a better understanding of the structure of this thesis. For this, I will shortly explain the contents of each chapter.

Chapter 1 includes the introduction to this thesis. It contains an introduction to Company A and the problem context. Based on this problem context, a theoretical perspective has been chosen, together with outlining a problem-approach.

Chapter 2 includes the data-gathering. All necessary data was gathered including the production route, the current planning, throughput times, demand, transport-days, and costs. Since current capacity is not sufficient to produce the required amount, a capacity analysis was done and used as input for the eventual simulation model. Based on this analysis, potential bottlenecks were investigated.

Chapter 3 outlines a literature study about planning and control and a simulation study. First, the basic principles of planning and control are outlined. Based on these principles, various planning and control approaches were investigated, of which many used pull-control instead of push-control. Second, the basic principles of a simulation study are explained. Only the simulation things that are needed in this thesis, are explained.

Chapter 4 selects three methods from the outlined planning and control approaches, by assessing the literature on the chosen KPI's of COMPANY A.

Chapter 5 includes the conceptual model for the eventual simulation model, including the model content and scope. Consequently, the chapter explains how the conceptual model was programmed into a simulation model. Moreover, the model is verified and validated within this chapter.

Chapter 6 includes numerous experiments and the results of these experiments. First, the planning approach experiments were conducted within the simulation model. Second, the influence of delivery variability was tested. Third, the influence of driving one or two times and on different days to the outsourcing company was tested. Fourth, the influence of extra machines was tested. Lastly, the influence of driving one or two times and on different days to the customer was tested. Eventually, the best results of these experiments are included in one final model to test what is needed to produce the required amount of products A within four weeks.

Chapter 7 eventually summarizes the conclusions and gives recommendations based on the experiments within the simulation model. Lastly, some shortcomings of this research and the contribution of this research are outlined.

The main points are summarized at the end of each chapter. Furthermore, if this document is read on a device, text in *italics* that refers to a section can be clicked. The document will then jump towards the mentioned section. I hope you (the reader) will enjoy reading my thesis.

Jesper Rensen

Heeten, July 2019

Definitions

- **Delivery and acquiring day:** the day on which new product A castings come in from customer X, and finished products A are delivered to customer X. This is one truck that comes and leaves on a certain day.
- **Deviation:** a production error within the product such that it does not conform the quality standards anymore. For example, tears or dents in the material. After a deviation, the customer needs to assess if the product can still be used or if it will become scrap.
- **Machine 1:** the brand-name of the turning and milling machine, that turns and mills product As. In spoken language, the Machine 1 is more often used than the turning and milling machine.
- **Kanbans:** an object that triggers the movement, production, and supply of units between workstations. Usually, a card is used, containing the relevant workstation, job type, lot size, and card number.
- **Transport day to THE OUTSOURCING COMPANY:** the day on which a truck leaves to bring products A to the outsourcing company THE OUTSOURCING COMPANY and brings back products A that have been processed.
- **Waiver:** see deviation.

Chapter 1: Introduction

This chapter will outline the project plan for this thesis. First, an introduction to COMPANY A and the problem context will be given. Next, the scope of this thesis within this problem context together with the theoretical perspective will be determined in order to set the focus for this research. Based on this, sub-questions will be constructed and outlined together with making a problem approach for answering these questions.

1.1 About Company A and product A

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These few examples indicate that the scope of Company A is focused on precision metal manufacturing for specific components and customers, focusing on performance and quality. In literature, this is identified as a make-to-order company, where manufacturing starts after a customer's order is received (Slack, Brandon-Jones, & Johnston, 2013, p. 296). Every product can be seen as a separate project with its own special needs.

This bachelor thesis is mainly about product A which is produced for customer X. The name of the customer is not mentioned because of confidentiality issues. Product A is a titanium aircraft engine component to which the main shaft of the engine is mounted. The casting of the product is not done by COMPANY A. COMPANY A receives the casted products from customer X and processes them to eventually deliver them back to customer X. A drawing of a product A is displayed in figure 1.

CEN
SOR
ED

Figure 1: Product A.

The core processes of COMPANY A regarding product A are turning, milling, and grinding the product. However, in order to do, check, and finalize these processes, a lot of other necessary production steps are needed. Think about expedition work, measuring, cleaning, deburring, marking, documentation, inspections, sandblasting, and assemblies of sub-parts. Eventually, the production of one product A consists of 27 steps. Identifying the contents, characteristics, and throughput times of all these steps will be part of this thesis (see *chapter 2).*

1.2 Problem context

Like almost every production environment, the production of product A also has its own problems. COMPANY A started making ideas to produce product A in February 2016. However, it took a long time before the project was officially approved by customer X. The project was officially started around October 2016. As with many new projects, the start of this project was difficult. Today, April 2019, the project is in its ramp-up phase. The last technical problems are being solved and it is time to improve the efficiency of the production. Therefore this thesis is needed. One of the main problems of COMPANY A is to reduce the throughput time. Throughput time is the "average elapsed time taken for inputs to move through the process and become outputs" (Slack, Brandon-Jones, & Johnston, 2013, p. 100). The initially acquired action problem was: **How can the throughput time of product A be minimized from 9 weeks to a maximum of 4 weeks?** Main reasons for reducing the throughput time are:

1. Decreasing WIP. The customer remains the owner of product As. If COMPANY A decreases the throughput time of product A, the customer has less business capital tied-up in inventory. Furthermore, the high WIP takes in a lot of space in the production hall of COMPANY A. Therefore, COMPANY A risks damaging the products when they are in their WIP.

**Text in italics that refers to a section within the document can be clicked.*

2. Reducing planning uncertainty. By producing faster, the planning uncertainty for the customer will reduce. In addition, it increases the flexibility of the customer since they can order parts in a short time-horizon.
3. Invoicing. By producing faster, COMPANY A can send their invoices to the customer earlier than before, which will speed up the cash flows.
4. Competitive position. COMPANY A is not the only producer of products A. By increasing the throughput time, the competitive position of COMPANY A will improve since throughput time is a competitive factor.

To solve this problem, the managerial problem-solving method (MPSM) of Heerkens and van Winden (2012) is used. The first step of this method is the problem identification step. This identification starts with basically acquiring all problems within a company. This was done by interviewing the director, the project supervisor, the production planner and multiple shop floor workers that work with product A on a daily basis. The list was completed by looking into certain company documents and by simply looking around. This resulted in a long list with problems, that eventually was shortened to display only all relevant problems. This long list can be found in *appendix A.1.*

Since problems have been identified, the second phase of the problem identification is to make a problem-cluster. The problem cluster is made to provide a structure of all problems. All problems have been linked to their causes to investigate the root causes of problems. The problem of paper waste has been left out. This problem is considered minor and can probably be solved easily. The links will be explained briefly.

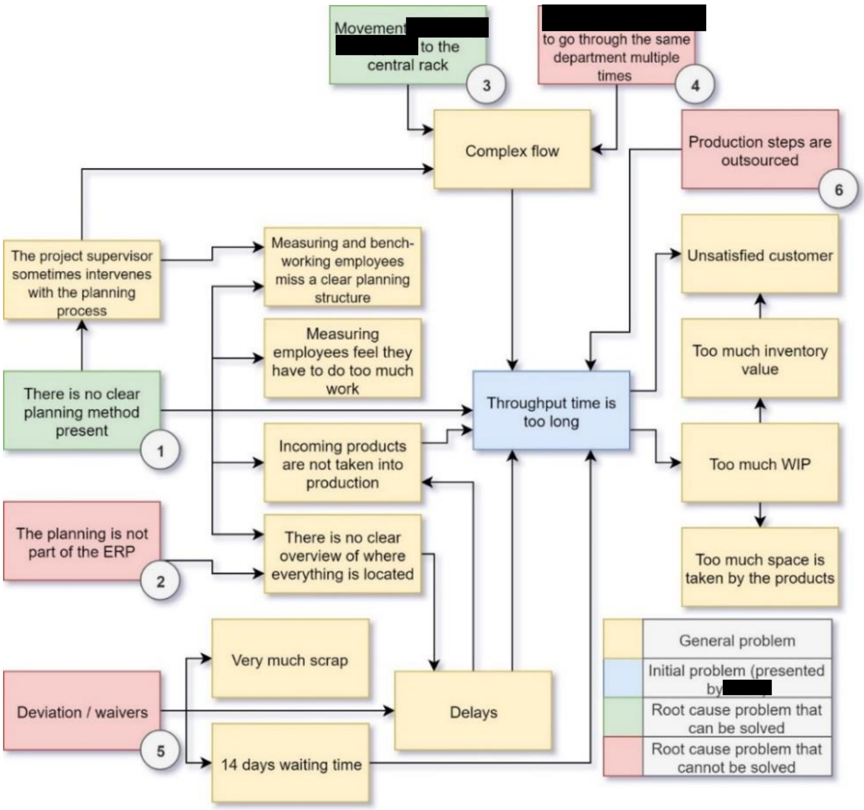

Figure 2: Problem cluster of the production of product A.

Root cause 1: no clear production planning

First, many problems occur because there is no clear production planning. Currently, it is decided to plan certain production steps in a week. The next week, the following chain of production steps will be done and so on. This is not an efficient method since it results in a lot of waiting time from week-to-week. However, one look at the planning shows that this approach is also not strictly followed. This makes the planning process a bit arbitrary and hard to follow as an outsider. Discovering how the current planning approach exactly works (if present) and what the restrictions are, will also be part of this thesis (see: *section 2.2*). Planning in this way is currently done in order to easier adapt to potential deviations in the product that are still present but will be solved. In addition, the current production output is not that high yet, so it is sufficient for the situation at hand. Lastly, some departments also work on other products. With this planning, the departments have more freedom to choose when they will process product As. The current planning results in longer throughput time, because certain production steps could also be done within one day, based on their throughput time. According to the planner, production planning has not really been a topic that was thought about yet. Measuring and bench working employees acknowledge this. The interventions in the production of product A by the project supervisor also underline this. If a clear planning method was present, there would be no reason to interfere. The fact that the project supervisor sometimes intervenes with the production planning, results in a more complex flow since it is not communicated what was done and thus the regular flow is interrupted. The measuring employees also feel they have to do too much work (not only to produce product A). It should be investigated if this is true or because the jobs are not scheduled right. According to the planner, enough capacity is present. However, this should be investigated. Because there is no clear planning method, certain incoming products A were simply not taken into production because it was forgotten and because there were delays. With a clear planning structure, this would have been shown. In addition, because of the delays, other products A were not taken into production since the delayed products should first be processed. Lastly, the lack of a clear planning method contributes to the fact that there is no clear overview of where every product A is located. If the planning was right, it would show exactly where in the process the products should be. The intractability of products A results in delays (and thus a longer throughput time) since the products first have to be found before they can be processed.

Root cause 2: the production planning is not part of the central ERP
Second, the production planning of product A is not part of the central ERP-system. This also contributes to the fact that there is no clear overview of where everything is located. This intractability takes time (see before). In addition, in this way, the occupation of departments by other products for different customers are not considered. Therefore, it could be that too many products are scheduled on a certain day for a certain department. Lastly, it also brings less flexibility. Currently, the project supervisor and the planner update the planning manually, while an ERP-system can usually do this automatically.

Root cause 3: unnecessary movement of product A
Third, because of likely space constraints, no WIP is stored in front of machines or departments. Every product A goes back to a central rack in the middle of the hall. Moreover, workstations are not placed directly after each other, but throughout the entire production hall. This results in a lot of movement and this movement takes time. It should be investigated if the space constraints are actually present and what could be done about it in order to reduce movement. In addition, this movement contributes to complex flow. This complex flow takes time which again results in longer throughput time.

Root cause 4: product A needs to go through the same department multiple times
Fourth, products A need to go through many of the same production steps because of quality issues. For example, the product needs to be measured and cleaned multiple times. This again results in a complex flow since the product does not flow smoothly to the next department, but often needs to go back to an earlier department. As said, this complex flow takes time. Examples of these steps are inspection, measuring, and, deburring which are all recurring steps.

Root cause 5: deviation/waivers
Fifth, the many deviation and waivers are still present because the product is still quite new to COMPANY A. Deviations and waivers are basically production errors. For example, certain tolerances are not met, or the product is slightly damaged. Many causes of deviations and waivers have been solved already, but there are still a lot of problems present that are slowly getting solved. Not many new problems emerge. These deviations result in scrap or delays because customer X must determine if the product can still be used or not. These deviations mainly influence the output of the process, however, it also influences the throughput time. This assessment of the customer X takes time (delay), resulting in longer throughput time. If the product cannot be used anymore, the product will be disposed. One of the deviations are tears in the material after grinding. Because of this, the first following 100 products must wait for two weeks to relax, resulting in longer throughput time.

Root cause 6: outsourcing of production steps
Sixth, the products are outsourced for tear inspection. This is being outsourced since it is too expensive for COMPANY A to do for themselves. Another student had investigated this. Doing this in-house would cost around €100, - per product A, which would not leave enough profit margin for COMPANY A. Doing tear inspection in-house is expensive since COMPANY A is simply not capable of doing this by themselves. This outsourcing results in an increase of the throughput time by two weeks. Sandblasting is also currently outsourced. This also takes one week, resulting in longer throughput time. However, sandblasting will be done in-house somewhere in the 2nd quarter of 2019. The machine is already bought, delivered and placed.

The action problem: causes and consequences of the throughput time
Concluding, outsourcing, delays in the process, complex flow, and the lack of a planning method contribute to the initial fact that the throughput time is too long. Moreover, as mentioned before, some products that come in are not taken into production, already resulting in a longer throughput time from the start. The long throughput time and the delays make the customer unsatisfied. A longer throughput time has disadvantages for both the customer and COMPANY A, as outlined before. The customer has set a goal of a throughput time of 4 weeks.

1.3 Choosing the core-problem and research question

As shown in figure 1 above, the cluster traces back towards six potential core problems. However, if the checklists (Heerkens & van Winden, 2012, pp. 47-50) are used, only two core problems remain.

The problem about the outsourced processes sandblasting and tear inspection cannot be influenced or is already getting solved. As mentioned, sandblasting will be taken into production somewhere in the 2nd quarter of 2019, resulting in a reduction of the throughput time of approximately one week minus its process time. Nevertheless, tear inspection cannot be done in-house since it would not leave enough profit-margin, as shown by previous research done by a colleague-student. The only thing that can be done to reduce the lead time of outsourcing, is ordering more frequently with small batches from the particular company. However, this costs money. In addition, this is again part of production planning.

The fact that the product needs to go through so many redundant production steps, especially regarding measuring, cannot be solved because of quality certification and the fact that the customer needs to guarantee this quality. This is a familiar phenomenon in the aircraft component industry.

The number of deviations and problems can be solved, which is currently done by the quality manager. This is a familiar problem for companies that take a product into production for the first time (Steenhuis, 2015). Especially the steps with the ring on the product still result in a lot of problems for COMPANY A. However, to help to solve these problems, more technological knowledge is needed which is beyond the scope of this thesis. Moreover, it will take too much time since COMPANY A is already working two and a half years on these problems. A quality manager is looking at these problems from a different perspective. He tries to change certain things within machines, processes, and production steps in order to prevent deviations and waivers.

The fact that the production planning is not part of the ERP-system also has to do with the fact that the product is still in an introductory phase. In the future, when the deviations within the production are solved, it will be implemented in the ERP-system (according to COMPANY A). Currently, it is not efficient to implement it now since it will need multiple adaptations. The details and conditions first need to be right before implementing it in the ERP-system. Moreover, focusing on this problem requires
IT-knowledge. It would be a relevant problem for an IT-thesis but not for an Industrial Engineering and Management thesis, so this will not be done.

To conclude, this leaves two chosen core problems that are solvable in 10 weeks of time:

1. *There is no clear production planning method for the production of product A*
2. *There is considerable movement present in the production of product A*

As mentioned, there is no clear planning method present. In the current situation, a certain production chain has one week to finish a batch of products A. This leads to a longer throughput time since products are waiting too long, whereas they can probably be processed much earlier. In addition, even this approach is not strictly followed. This is considered 'not clear'. 'Clarity' is not measurable yet. This will be done in step 1 of the problem approach, which will be explained later. In this phase, restrictions and KPI's will be identified in order to assess and measure a planning method for COMPANY A. A clearer planning approach could be an approach with clear consequent steps and more visibility, that at the same time scores 'sufficient' on the determined KPI's *(see section 4.1)*.

The movement-problem also has been mentioned. This is mainly because of a central rack in the middle of the hall where all products A go to. It should be investigated if this can be done in a different way. Movement can be measured in distance, time, the number of locations where products A are located, heat maps, etc.

It has been determined to first solve the planning-method problem. This has been decided together with the director of COMPANY A. Based on the problem identification, we believe that solving this problem is more effective than solving the movement problem. The problem-cluster underlines this since the planning method leads to more problems. Moreover, it is not certain if a solution to the movement problem is that effective because there is little different shaped space in the production hall. It is probably still valuable to investigate and map this.

Based on the core-problem the following research question can be constructed:

*How should a **production planning approach** be **applied at COMPANY A** such that the **relevant characteristics** and **restrictions** of the **production** are satisfied to reduce throughput time?*

1.4 Theoretical perspective and scope

In this section, the scope and theoretical perspective of the main constructs in the research question will be outlined. This is done to provide insight into the main concepts and the way they will be used within this research. The definition of throughput time has already been explained.

First, this research will only focus on improving the situation for product A. In order to keep this thesis manageable, other products will not be considered during the planning. This is difficult for departments that are not only working on products A but also on other products. Second, this research will only provide ways and information to plan the production of product A. It will not provide applications or tools. Third, this research will not be focusing on current production errors. It assumed that these problems will be solved soon resulting in a smooth flow of product A.

The planning problem will be approached with the theoretical perspective of operations management and operations research. Operations management "is about how organizations create and deliver services and products" (Slack, Brandon-Jones, & Johnston, 2013, p. 4). Operations research is "a scientific approach to decision making that seeks to best design and operate a system, usually under conditions requiring the allocation of scarce resources" (Winston, 2003, p. 1). Within these broad fields, relevant theories can be found.

Theories to monitor and control operations are pull control, push control, the drum, buffer rope concept (also called bottleneck control), and workload control. These theories will be used in order to find a planning and control approach. In a pull system, the pace and specification of what is done are set by the consequent workstation which pulls work from the previous workstation. Pull control is often used in lean synchronization in order to match supply and demand (Slack, Brandon-Jones, & Johnston, 2013, p. 478). In addition, multiple planning approaches rely on pull principles. Two famous approaches are Kanban and constant work in progress (ConWIP). Kanban controls the transfer of items with cards and signals. It instructs the previous workstation to send new work. (Slack, Brandon-Jones, & Johnston, 2013, p. 478). ConWIP sets a limit on the total WIP in the entire system (Koh & Bulfin, 2004). On the other hand, in a push system, the activities are scheduled by a central system and completed in line. An example of such a system is the material requirements planning (MRP). A central system for planning and control is currently also in place at COMPANY A. The workstation pushes work to the consequent station, without considering the number of products already present at the next step. An example of a system that can accommodate both pull and push systems is Paired Cell Overlapping Loops of Cards with Authorization (POLCA). POLCA also uses cards to show the free capacity between two working cells instead of stations (like with Kanban). Another theory is the drum, buffer rope (DBR) concept, from the Theory of Constraints (ToC). According to this theory, the bottleneck of the process (the slowest link in the process) should be the control point of the whole process. A buffer should be placed in front of this bottleneck (Slack, Brandon-Jones, & Johnston, 2013, p. 312). Workload control focusses on load-based order release mechanisms. The aim is to stabilize workloads in accordance with the output rate (Thürer, Stevenson, Silva, & Qu, 2017). Analyzing these planning and control approaches and their applicability to COMPANY A will be part of this thesis, which will be outlined in *chapter 3* and *chapter 4.*

Production planning can be defined by using the book of Slack, Brandon-Jones, and Johnston (2013). They call this "planning and control of operations". They do not make a distinction between planning and control since theory and practice are not clear about the division between planning and control. According to Slack, Brandon-Jones, and Johnston, planning and control is "concerned with the activities that attempt to reconcile the demands of the market and the ability of the operation's resources to deliver" (Slack, Brandon-Jones, & Johnston, 2013, p. 290). It involves scheduling, coordinating, and organizing operations activities. A distinction is based on long-term, medium-term and short-term planning and control. The scope of this thesis will be on long-term planning, using aggregate demand and resource forecasts, with long-term objectives (Slack, Brandon-Jones, & Johnston, 2013). Production has been deliberately added in order to specify the term. For example, it is no use if a patient planning is found since such a planning has completely different restrictions and will be of no use.

Under *approach,* optimization techniques or heuristic algorithms are considered. The current planning method that is in place is also a planning and control approach, however, it is far from optimal. For this, "optimization technique" has been added. An optimization technique will give values for decision variables that optimize an objective function within its given constraints and the set of all values (Winston, 2003, p. 2). However, sometimes the number of variables and constraints can be so large that it might be difficult for computers or people to find an exact solution. In this case heuristics (or heuristic algorithms) can be used (Winston, 2003, p. 75). These can be described as 'rules of thumb' in order to search for a reasonable solution, but not optimal (Slack, Brandon-Jones, & Johnston, 2013, p. 209). However, these will also improve the situation.

Relevant characteristics of the current production of COMPANY A are product-flow, bottlenecks, planning, capacity at work-stations and department-specific throughput times. Of course, there are much more characteristics of a production process like inventory, layout, people, etc. (Slack, Brandon-Jones, & Johnston, 2013). However, these seem to be the only relevant characteristics for the problem at hand. This might change after the interview with important stakeholders. I want to know these topics since they are input for planning method and simulation model (outlined later). *Restrictions of the current production* can be seen as so-called non-compensatory criteria. These are attributes that the planning method should have, otherwise, it cannot be taken into consideration (Heerkens & van Winden, 2012, p. 90).

The last construct in the research question considers the *application at COMPANY A*. I want to point out that "implementation" will not be part of this thesis. Multiple planning approaches will be outlined. All these approaches will be scored on key performance indicators (KPI's), that all have a certain weight. In this way, scores can be given such that the right method will be *applied.* This method is quite familiar and outlined several times in literature. For example by Heerkens and van Winden (pp. 81-90), but also by Winston (pp. 785-792).

1.5 Sub-questions

To answer the overall research question, sub-questions will have to be answered. These are based on the key-constructs of the main research question. First, the main constructs of the sub-questions will be explained and if possibly operationalized. After this, the sub-question will be divided into multiple smaller questions. The motivation, data gathering and data analyzing of these questions will be outlined under the questions. Lastly, some reliability, validity and limitation issues of all sub-questions will be outlined.

1.5.1 Sub-question 1: restrictions and characteristics of the production process

1. *What are the **restrictions and characteristics** of **the production** of product A?*

In this phase, all relevant characteristics of the production process should be outlined and data should be gathered. With relevant characteristics, recall that the following is meant (see: *section 1.4*): product-flow through the process (1.1), planning (1.2/1.3), throughput time (1.4), capacity at workstations (1.5), and bottlenecks (1.6). These seem to be the only relevant characteristics for the problem at hand. I want to know these topics since they are input for planning method and the simulation model. The restrictions (1.3) can be seen as non-compensatory criteria. This research is descriptive since the characteristics of the production will be investigated. The questions will deliver both qualitative and quantitative data. The sub-questions are:

- 1.1 What are the current production steps of product A?
- 1.2 How is the production planning of product A done?
- 1.3 What are restrictions for a planning method?
  - 1.3.1 What is the weekly input?
  - 1.3.2 What should be the weekly output?
  - 1.3.3 Is a certain transport-day present?
  - 1.3.4 Other restrictions?
- 1.4 What are the essential parameters and/or potential distributions of the throughput time for each production step?
  - 1.4.1 What are the main activities in each production step?
  - 1.4.2 What are the waiting times in the current production process?
  - 1.4.3 What are the move times in the current production process?
  - 1.4.4 What are the process times in the current production?
  - 1.4.5 What is the set-up time for each production step?
  - 1.4.6 Are the production times on paper right about the throughput time?
- 1.5 What is or should be the capacity at each production step?
  - 1.5.1 Is there enough capacity to produce the specified weekly input?
    - Should extra people be hired in order to continue?
    - Should extra machines be bought in order to continue?
  - 1.5.2 Is this step completely reserved for product A?
    - How much time is present to work on product A?
    - When does this step have time for product A?
- 1.6 What are the bottlenecks within the production?

Question 1.1 can be identified by following the product through the production process and interviewing relevant shop-floor workers while doing this. **Question 1.1** is important in order to make a planning method that meets reality. The production steps will be checked by the project supervisor such that I know for sure that it is the real situation. **Question 1.2** can be acquired by interviewing the planner. Knowing the current method well is important to identify places for improvement and potential difficulties when constructing a planning method. **Question 1.3** covers the restrictions of a planning method. Examples of certain restrictions have been outlined under **question 1.3**. A distinction is made between input and output. In a perfect situation, this would be equal. However, since it is known that there are deviations and scrap this could be different. Should I consider this, or not? **Question 1.4** can be identified by asking the production planner and shop floor workers about the time they are working on a step. This can be seen as an expert opinion. Moreover, by acquiring data from the ERP-system, probable throughput times can be acquired. These datapoints will be analyzed with Excel and SPSS, involving statistics. There might be too little data points within this ERP, so it is uncertain if this is useful. In addition, all activities in each production-step are known and written down since this is a requirement for aircraft components. This can also be used to assess the throughput times. The analysis of these multiple sources should produce throughput times acknowledged by all sources. Furthermore, to construct each 'total throughput time', the framework of Johnson (2003) is used, resulting in the extra sub-questions (1.4.2. till 1.4.5). **Question 1.4.6** has been added to check if the production papers are right about the production times. It might be that my analysis contradicts this time. The eventually chosen throughput times will be discussed with the stakeholders in order to assess if they are reasonable. **Question 1.5** is asked to assess the capacity of the production steps. The capacities of the machines and the conditions for this capacity should be

determined. Some departments might not even have enough capacity to produce the specified amount of **question 1.3.** This was discovered when interviewing the project supervisor of product A and by looking into documents. If capacity currently is insufficient in a production step, I should assess what is needed according to the director and use this as initial values. For example, an extra machine should be placed, an extra worker should be hired, etc. These initial values can also be experimental factors in the simulation model later. If the production steps do not have enough capacity, no assessment of a planning method and the throughput time can be made. In addition, recall that several departments are completely reserved to produce product A (for example turning and milling) while other departments (for example bench working) also have to work on other products. It should be assessed how much time these departments have left to work on product A and when. This is difficult to assess. If it turns out that it is too difficult to assess, simplifications should be identified. For example, by saying that there are always X number of employees available for product A. However, the more simplifications, the more the quality of the research will decrease. **Question 1.6** is important because it can display weaknesses of the production process, which again could be used as an input for the planning method, for example by bottleneck control methods. By the gathered data, this question can easily be answered. Eventually, a thorough production flow map will be drawn together with a table that outlines all production steps and their activities together with the throughput times. This will be based on
'input-transformation-output'. The table and the map should be the input for the new planning method.

1.5.2-Sub question 2: KPI's to apply a production planning at COMPANY A

2. *What are the **important KPI's** for a production planning at COMPANY A?*

In order to assess and measure a planning method (*application*), KPI's will have to be determined. One of the KPI's will definitely be the throughput time consisting of set-up time, processing time, move time and waiting time (Johnson, 2003) since it is the main reason for starting this thesis. Other KPI's could be lateness, value-added time (time for processes that improve products), inventory, costs. This descriptive research will deliver qualitative results since KPI's of a planning method will be identified. The sub-questions are:

- 2.1 What are important KPI's for a planning method at COMPANY A?
- 2.2 What are the individual weights for these KPI's?
- 2.3 How can we assign scores to the KPI's?

The most important KPI's for COMPANY A will have to be identified. This will be done by interviewing all relevant stakeholders: the planner, the director, and product A project supervisor (research population). At first, I will not give the stakeholders any examples of KPI's. If they are not able to come up with some KPI's, I will give them a list with KPI's in a random order from which they can choose. It is important to assess the importance of individual KPI's. So, the weights should also be asked. This could be done with the AHP-method (Winston, 2003, p. 785) to make a well-founded decision. However, this is not the initial plan because it is time-consuming. Eventually, all stakeholders should agree with the chosen KPI's and their weights in a meeting. Eventually, tables should be made that determine a score for a certain KPI. Doing this in advance will be beneficial because I will not be biased by certain findings in a later stage. With the scores and weights, eventual grades can be given to several planning methods and it will help to assess the importance of the different planning methods. To conclude, this sub-question should deliver a scoring template in order to assess the different planning methods in a later stage. These KPI's will be irrelevant for the simulation model (that will be explained later) since in a simulation model multiple KPI's can be tracked.

1.5.3 Sub-question 3: literature study for production planning approaches

3. *What production **planning and control optimization techniques or heuristic algorithms** can be found in literature and how can they be **applied in practice?***

In order to make a good planning, a list of planning methods is needed to make a good decision. This knowledge question has two constructs of the main question, covered by the sub-questions namely: "planning and control optimization techniques or heuristic algorithms (3.1, 3.2, and 3.3)" and "application in practice (3.2, 3.3, 3.4, and 3.5)". Both constructs have been outlined in *section 1.4.* The sub-questions are:

3.1 What are the main types of methods in literature to improve a planning method?
3.2 What are the advantages of each type?
3.3 What are the disadvantages of each type?
3.4 How does each method score on the chosen KPI?
3.5 How does each method fit the restrictions?

The research population will be literature. By conducting a systematic literature review, sources will be found in databases (descriptive research yielding qualitative results). Based on these sources, main production planning types should be identified and outlined such that a choice can be made during the problem approach. Each method should fulfill the restrictions, otherwise, it cannot be used (as mentioned at sub-question 1). The advantages and disadvantages of each method should be summarized. In addition, by describing how each method performs on the chosen KPI's, should provide an overview of which methods to use. Other researchers with different KPI's and restrictions could also use this overview to make a decision for their problem at hand. These planning approaches will not be investigated outside of the scope of the outlined theoretical perspective.

1.5.4 Validity and reliability issues

In the research, several reliability, validity, and limitation issues might occur. Many of them have already been discussed. A few highlights and how I want to solve them:

1. **Lack of data points regarding throughput time in the ERP**

The first step is extracting data from the ERP. If the ERP does not provide enough data points, multiple shop-floor workers can be interviewed as 'expert opinion'. If their answers agree with each other, it can be assumed as a reasonable time. Thirdly, production papers outline the time for a certain production step. This can also be an extra source of information. In addition, the initial sources for this determination on the production paper can be requested. Lastly, I can measure certain production times by myself. This is not desirable since it is time-consuming. The multiple sources of information can also be used as an extra validation of findings.

2. **Determining final KPI's and their weights**

It has already been outlined how KPI's will be acquired. However, if multiple KPI's are selected, what will be final KPI's? Why should the one KPI be excluded, while the other should be included if there are too many KPI's? In addition, how can the final weights be determined? For this, the AHP-method can give a quantitative argument about why certain KPI's and weight should be chosen. As said, this is time-consuming, so this is not desirable. In order to solve this, I will first interview the planner and product A project supervisor. I will share these results with the director and ask about his opinion. Eventually, the director will determine the final weights and KPI's.

3. **Discrepancy between paper and reality**

In multiple steps, there might be a discrepancy between paper and reality. This was already encountered when making this project proposal. Therefore, results based on documents should always be checked by one of the stakeholders before using them. In addition, if a discrepancy between my measurement and a document is found, it should be discussed how this is possible. This will prevent me from proceeding with the wrong data.

4. **Capacity at work-stations**

This issue has already been discussed. Probably, some production steps might not have the amount of capacity to produce the specified amount. By interviewing the director, it has been determined to assume the capacity that is needed. In addition, measuring the time left for product A at production steps that are not completely reserved for product A is difficult. For this, simplifications could be made, for example by priority rules and assuming that there is enough capacity. More simplifications and assumptions will, however, decrease the quality of this research.

5. **Conditions in literature**

In literature, multiple planning approaches can be found. Usually, these sources also make assumptions and simplifications. Moreover, these sources are applied to a certain environment with certain characteristics. These conditions should be identified before consulting these sources. Otherwise, the results might not be applicable to my case.

1.6 Problem approach and objective

In order to answer the research question, the following problem approach has been constructed together with its objective.

Step 1: data gathering and analyzing
Data gathering and analyzing in this phase basically means answering sub-questions one and two. As mentioned, this step will produce a scoring template for the different KPI's in order to structure the literature study. In addition, restrictions together with the production map and the production table with all relevant parameters will be constructed.

Step 2: literature study
In this phase, sub-question three will be answered. This has also been outlined above. This step will produce an overview of different planning methods with advantages, disadvantages, and assessment of the different KPI's. This assessment helps to structure the literature study by summarizing how each planning method performs on the KPI.

Step 3: choosing and outlining a planning method for COMPANY A
Based on literature and data-gathering it is time to outline the overall planning methods that can be used by COMPANY A. All needed data and knowledge should be present at this point. In addition, a decision on which planning approaches to use in the simulation model should be taken based on the overview of sub-question three. It should be assessed how the constructed planning methods score on the KPI's and if it meets the restrictions. This phase should outline multiple planning methods that can be used by COMPANY A.

Step 4: solution testing in a simulation model
In this step, a simulation model will be built in order to test the different multiple planning methods. The planning methods have been assessed in step three, however, a simulation mode will give extra proof. It was decided to use a simulation study, which is a method that is usually suitable for

manufacturing systems. Simulation has multiple advantages and disadvantages (Robinson, 2014, pp. 13-17). The first reason for choosing simulation is the fact that I can keep track of many KPI's. The second reason for simulation is the fact that it is easy to experiment within a simulation model, without changing a lot. The third reason is visualization. It will be easier to show the results of my study if it is clearly visualized, like in a simulation model. The last reason is the fact that it is easier to model variability with simulation, which will certainly be present in my research. This phase will consist of four sub-steps:

1. Making a conceptual model

In this phase, a conceptual model will be made based on Robinson's framework (Robinson, 2014, p. 97). This framework consists of five activities of which two (understanding the problem identification and determining the modeling and general objectives) have already been done in step one. Thirdly, the model's output should be clearly described, based on the first steps and KPI's. Fourthly its inputs, the experimental factors, should be determined together with potential sensitivity analysis. Determining these experimental factors requires (again) an interview with the relevant stakeholders. The number of experiments should be limited because of time constraints and interaction effects. Lastly, the model content should be outlined. This includes simplifications and assumptions that will have to be made.

2. Implementing the conceptual model: programming the simulation model

In this phase, the simulation model will be programmed. In other words, the conceptual model will be implemented in a computer program. The program that will be used is Tecnomatix Plant Simulation. This program has been chosen since I have experience with this program, because it is user-friendly, and because a tutorial about this program is present (from the university).

3. Verification and validation

The next step is verifying the simulation model. Verifying means that the conceptual model has been transformed into a computer model with enough accuracy. The last step is validation. Validation is the process of ensuring that the model is sufficiently accurate for the purpose at hand (Robinson, 2014, p. 252). Robinson's methods will be used for this. However, the right methods should be chosen based on the available data from step one. This could involve statistics but also expert opinions.

4. Experiments

In this step, the experiments determined in the conceptual model, will be conducted within the simulation model. Several planning methods will be tested within the simulation model in order to identify the consequences of the different methods. For this, the experiments should be properly prepared. This includes determining warm-up periods or initial conditions, batch sizes or the number of replications and the run length. Based on these experiments, data should be gathered from the simulation model and analyzed with statistics. This step should produce proper results on the planning approaches. Next to the planning approaches, other planning-related subjects will be tested like transporting and adding extra machines.

Step 5: conclusions, recommendations, and discussion

Based on the results of the simulation model and the assessment in step three, conclusions can be drawn. The performance of the different methods should be assessed. Based on these conclusions, recommendations can be given to COMPANY A about which planner to use. Just like every research, this research will probably also have some assumptions, simplifications and probable shortcomings (for example in the conceptual model). The influence of these topics on the results will also be discussed.

Objective
To summarize the above research questions and problem approach, the objective of this research is to provide a planning that meets the restrictions and criteria provided by COMPANY A while reducing the throughput time of product A. This should be achieved by planning the production in a more sophisticated way than is currently done. The simulation model will provide extra proof for a chosen method.

1.7 Deliverables
By conducting this research, the following will be delivered to COMPANY A:

- An overview of the production process of product A (sq 1).
    - Including an assessment of the process time of multiple production steps.
    - Including an assessment of the (needed) capacity.
- An overview of important KPI’s and their weights in order to make a distinction between their importance (sq 2).
- An overview of planning methods in literature and an assessment of their importance based on the KPI’s and restrictions of COMPANY A (sq 3).
- Multiple improved production planning approaches that satisfy the restrictions given by COMPANY A.
- A simulation model of the production of product A.
- Advice about which planning method to use based on the earlier assessment and results of the simulation experiments.
- Results and advice based on the other experiments within the simulation model.

In order to acquire all deliverables, a planning has been made which can be found in *appendix A.2.* In this appendix, also the realized planning is displayed. This included a short reflection outlined in the same appendix.

1.8 Summary and conclusions for chapter 1
The core contributions to a long throughput time are the current planning, movement within the production of product A, production errors, outsourcing, and the fact that the planning is currently not part of the ERP-system. It is believed that solving the planning problem is the most effective way to reduce throughput time. For this, a problem approach has been constructed. By gathering data from COMPANY A, doing a literature study, and, eventually testing the planning approaches within a simulation model, the planning should be improved.

Chapter 2: Characteristics of the production of product A

In this chapter, all relevant characteristics (for this thesis) to produce product A will be outlined and analyzed. These include the production route, current planning, throughput times, demand for products A, transport-days, and costs. Since current capacity is not sufficient to produce the required and assumed demand, a capacity analysis will be done for all departments. This chapter will be concluded by analyzing potential bottlenecks. Other theses might need different production characteristics for their problem.

2.1 Production steps of product A

In order to improve anything regarding the production of product A, the production process should be well understood. In this step, the production steps have been studied and outlined. In *appendix B*, a map and a table can be found. The map displays all internal processes regarding the production of product A. The table outlines each production step by explaining the operation, the working instruction, its location, and its output. In this section, a short summary will be given.

To start, product A consists of two types. Type AC (Airbus-Comac) and type B (Boeing). The ratio AC:B is approximately 1:3. On an arbitrary day in the week, several products A come in. This number varies from five to twenty. The expedition receives the products and puts them in the right place. The attached papers are delivered to the business office. The business office checks these documents, makes an order in the computer systems, and prints all needed documents for the production. These two steps are done for the entire batch that comes in. Afterward, the products continue according to one-piece flow.

When all documentation is attached to the pallet, part marking adds a unique mark to the product, whereas expedition adds another label and a production card, and puts them in plastic pallets with edges. Next, quality control checks the casting, weighs it, removes potential scratches and etches, and adds a measuring pin in order to measure the product. If everything is right, the product will be turned and milled on the Machine 1 machine in several programs. These programs are longer for the AC-type product A. The product will be measured two times during turning and milling: between the programs and at the end of all the programs. Because turning and milling create burs on the product, the products needs deburring by bench working, who also add another mark to the product. Moreover, the product will be cleaned in a washing machine. Consequently, the measuring room checks the work of all aforementioned production steps, before it is sent to the outsourcing company THE OUTSOURCING COMPANY for a week, that does a tear inspection on the product. The expedition takes care of the receival and delivery to THE OUTSOURCING COMPANY. If the product is approved by THE OUTSOURCING COMPANY, it is sent back to COMPANY A, and a visual inspection will be done. At this stage, the so-called “dash six” is ready. This used to be the end-product because COMPANY A had difficulties with doing the consequent steps, however, currently, COMPANY A is capable to also do the consequent production steps.

The first consequent step is heating and shrinking a ring to product A. Because of the material of this ring, the product needs to be greased with anti-corrosion material after each consequent step. Following, the product will be ground on the so-called Machine 2 machine, which again creates burs on the product, that need to be removed by bench working again. In addition, it also needs cleaning again, which will be done in a different washing machine since the product is less polluted than after turning and milling. Going on, quality control checks if everything is still right before it will be sent to THE OUTSOURCING COMPANY for another week by the expedition (again). After approval of the tear inspection by THE OUTSOURCING COMPANY, the product comes back and will be visually inspected. Next, the type-B products A will be sandblasted. This used to be outsourced, but COMPANY A is planning to do this themselves somewhere in the second quarter of 2019. Next, the product will be cleaned and tested on their cleanliness. This cleanliness test is currently done on every product but will be done on one out of every ten products. If the product is clean, the B-type products A will get inserts. Finally, the product will be checked for the last time. If everything is right, the product is ready to be delivered. The business office takes care of the delivery in the computer programs, while the expedition takes care of the physical delivery. The so-called “dash zero” is finished.

Reflecting on the production process

Based on the summary above and the production table, COMPANY A can be seen as a make-to-order company. COMPANY A receives the castings (orders) and starts production. COMPANY A does not process multiple castings and then waits till the customer buys them like in a make-to-stock environment. The castings are the property of customer X. The production layout can be described as a product (line) layout (Slack, Brandon-Jones, & Johnston, 2013, p. 197), also called a flow-shop. Stevenson, Hendry, and Kingsman also make a distinction between a general and a pure flow shop, as described above. Since products A travel in one direction, through a sequence of work centers in a strict order, the situation can be described as a pure flow shop.

This flow-shop approach is not familiar to COMPANY A. COMPANY A is more used to small batch production with some customization for the customer. This customization results in variable production routes. In addition, the demand for these products was really fluctuating. For these products, the production is designed differently. Product A, in that regard, is completely different. The route of each product A type is known. In addition, customization is not applicable. This is in line with the direction in which COMPANY A wants to go, also with other products. Nevertheless, it shows again the difficulties for COMPANY A and the production of product A.

In reality, the production process is a bit different from the production process outlined above. First, there are still some deviations and waivers present as a consequence of production. Therefore, some steps must be redone again. Second, sometimes the route is done in a different order. However, this is not preferred by COMPANY A. Third, the Machine 1 operator does not always measure the product by himself. This is also done by the quality control operator. Lastly, not all departments are completely focusing on product A. The business office, expedition, part marking department, quality control, bench working, inspection, and insert-assembly also need to do other products.

The fact that products are not delivered on a regular basis and in different numbers, makes processes almost unplannable. It is difficult to anticipate in order to reserve enough capacity. Suddenly multiple products A can be delivered by customer X, resulting in a sudden WIP increase for COMPANY A. As explained by the director, COMPANY A could at the one moment be busy with the delivered products A while at another moment almost no department is working on products A. So, the goal is to acquire more stable delivery intervals and numbers. These fluctuating delivery intervals and numbers will be one of the experiments in the simulation model. This is important in order to show customer X the effect their delivery policy has on COMPANY A. Moreover, it can also show the advantage that they will acquire by delivering differently.

Multiple causes and consequences of the long throughput time, outlined in *chapter 1*, are being underlined by the outlined production steps. Since the production chain is so long, a lot of WIP can build up between processes. In addition, a lot of movement is present since (as described in the production table) every product needs to be delivered to the central rack. This movement takes time. The production table also shows that some departments are recurring production processes, while some departments are only surpassed once.

2.2 The current planning algorithm

By identifying the current planning method, potential difficulties and places for improvement can be identified. The current planning algorithm is displayed in a diagram, which can be found in *section B.3*. It is based on the model that the project supervisor made for his business school project, so it is not designed by me.

In the diagram, the weeks are displayed. Within these weeks, multiple production steps are scheduled for the entire batch that comes in at week 1. So, for week 1 all products A that come in should have finished receival of casting, order intake, part marking, product preparation, and inspection. For week two, the entire batch should have finished turning and milling, and so on. In week 4 and week 6 the products are outsourced. Products that are not finished by that time, will not be outsourced. So, for example, if the transport to THE OUTSOURCING COMPANY is on a Monday afternoon, products that will be finished that morning will not go into the truck. The receival of castings and order intake are the only two processes that will be done for the entire batch. After these steps, products A move on one product at a time between stages, but in batches between weeks.

Reality vs. paper

Even though this is the plan, the reality is different. A quick scan of the planning can identify that this method is not applied regularly. Usually, products are just pushed on (and not waiting) if there is room in the next department. In addition, currently, a lot of deviations and waivers are present in the production process. These products are on hold, waiting for an assessment of customer X. However, every moment these products can go back into production, disrupting the current flow. In the current production process, these waivers first have to be solved. So, the current planning is somewhat reactive instead of proactive. It is reacting to the current status of the system and it adapts to it if possible. In the past, product A project supervisor used to do this daily. However, currently, rescheduling is done weekly. This rescheduling takes a lot of time.

Reflecting on the current planning method

Currently, a planning plan structure is present, but often there is deviated from the initial plan in order to adapt to the situation. A lot of waiting time is present in this schedule because of week-to-week scheduling. Products that finished their week-plan early in the week need to wait for quite a while in order to move on. This could be done earlier if the next department is not occupied. In addition, waiting for the transport day can also take a considerable amount of time.

Next, there are still a lot of products with waivers/deviations present in the production. These waivers/deviations are now still quite unpredictable. COMPANY A is working hard on solving all these production issues (for multiple years now) and almost all these issues are solved or getting solved (as mentioned). After this, the waivers/deviations will probably become more predictable such that they can be taken into consideration in a planning. However, unpredictable production errors will always be present. This is familiar for any production environment. Furthermore, multiple products are still on hold because of a waiver/deviation. Thus, they are part of the WIP somewhere between two production steps. If they are taken back into production, they interrupt the flow of other products. To conclude, in order to apply a production planning method, the unpredictable production errors will have to be minimized (what is currently done) and the products with deviations and waivers that are still in the WIP will have to be processed first.

In addition, a lot of tasks are not scheduled in the same order. For example, measuring is sometimes done after bench working, but sometimes before. This gives on the one hand flexibility, but on the other hand also a more complex flow. You do not know which production steps are finished and which are not.

The planning approach can be specified as a normal MRP, but with different process times as usual. Instead of using the process times, multiple steps are combined and are said to take one week. Since the MRP is not linked to any other system (like for other products), it needs this weekly updating, which takes considerable time.

So why did COMPANY A even implement this week-to-week planning? Well, the week-to-week planning brings certainty, something that is wished by COMPANY A. Giving the workers a longer period in which they can produce product A, increases flexibility for them. For example, the deburring department also has to work on other products. In this way, they can first finish small batches of these products and finish product As later. By giving this large time-period, COMPANY A can almost certainly say that the batch will be completed within this week, even if processing times deviate. This is not completely true for 'week 5' though. As shown in the diagram, the number of production steps in this week is quite long. Therefore it is uncertain if a larger batch can be completed within this week.

The planning is sufficient for the current situation since the production numbers are not that high yet. Adapting the planning weekly is also still doable. This is needed because of the waivers and deviations. However, if in the future these issues are solved and the production numbers will increase, the production planning will have to be improved. The week-to-week planning will not be sufficient to cope with larger batches since the throughput time is quite long and a large WIP will build up.

2.3 Throughput times

In this step, the throughput times for each production step will be acquired and analyzed. This will be done in such a way, such that the throughput times can be used as input for a simulation model. This also makes the throughput times usable for other methods like queueing or dynamic programming. The goal is to get reasonable distributions or approximations of the throughput time such that they can be modeled in any system.

Sources of data

In order to acquire throughput times of each production step, multiple sources have been used. Robinson (2014, p. 121) defines multiple sources of data. Available data is defined as category A data. An example of category A data is data of the throughput times within the ERP system. For every product that COMPANY A makes, the processing times are clocked by the shop floor workers. This data can be analyzed by checking the fit between a probability density function and the data. If this fit is not present, this data can still be used by making an empirical distribution, a trace or approximate distributions (Robinson, 2014, pp. 125-133). Unfortunately, the ERP-data was not as good as expected. Not every production step clocked its operation, or wrongly clocked its operation. The steps that clocked their operation were turning and milling (060), secondary operations (070), part marking (080), cleaning (090), assembly of the ring (130), grinding (140), and secondary operations (150). The planning officer gave me an indication of which steps could be rightly clocked, which were uncertain, and which were unreliable. More category A data was present within the ERP-system. Estimated throughput times were also calculated to determine the costs of production and eventual losses or profits. These estimated times have been constructed by the calculators. Next to this, product A project supervisor made some files in which some estimates of throughput times were added. This can be seen as an 'expert opinion' about the possible throughput times.

However, basing the throughput times on just these few sources is, in my opinion, too unreliable. Because of this, new data was collected. Robinson (2014) defines this data as category B data. First, product A supervisor was interviewed to explain his estimates and to determine on what assumptions the estimation was based. Next, the shop-floor workers were interviewed in order to acquire more 'expert opinions'. The shop floor workers work with the product daily. Therefore, their estimate is probably one of the most reliable estimates. The shop floor workers were asked about their activities in order to assess if it corresponds with the activities that are outlined in this thesis. Next, a minimum, mode, and maximum were asked in order to approximate the throughput time with a triangular distribution. The triangular distribution is useful for an approximation (Robinson, 2014, p. 133). Many shop floor workers were able to give estimates about the minimum, mode, and maximum time. Some shop floor workers were not able to give the three parameters. However, they were able to give an approximation with a certain range of deviation. Eventually, approximations based on 'expert opinion' were collected for every production step.

Another way of collecting data could be clocking certain production steps by myself. It was decided to not do this. Clocking data by myself would cost too much time because of the multiple production steps. Furthermore, it would only deliver a few data points (approximately one to five), and what is the value of just a few data points? I consider the expert opinion (i.e. shop floor workers) to be more valuable. In addition, approximations could also be made by making lists on which shop floor workers could clock their operation themselves. However, if currently clocking within the ERP-system is already problematic, why would writing it down suddenly do the job? Moreover, in order to acquire reliable data, it should be explained when to start and stop the clocking, which would again take a lot of time regarding the number of steps that are present. Lastly, it is uncertain when new products A come in. So, perhaps I must wait for a long time in order to even acquire times.

Data that is not available and not collectable is defined as category C data (Robinson, 2014, p. 121). This data is present for one production step, namely sandblasting. As mentioned, sandblasting will be done in-house in the second quarter of 2019. Sandblasting is taking one week because of outsourcing. So, it is not known exactly how much time this would take to do at COMPANY A. Robinson (2014, pp. 122-123) outlines multiple ways on how to treat this data. In this thesis, product A supervisor was again asked for an approximation. He knows what is done during the sandblasting step. Moreover, he visited the company that currently does this for COMPANY A so his estimate can be seen as reasonable. This corresponds with Robinson's opinion: "discussion with domain experts, such as staff and equipment suppliers, might provide reasonable estimates" (Robinson, 2014, p. 123).

Data analysis

The collected data of the multiple interviews and the data points of the ERP-system can be requested by contacting the author. Eventually, all collected data was analyzed. First, the ERP-data were analyzed by using descriptive statistics. This included summaries with numerical measures (e.g. mean, standard deviation, kurtosis, skewness, etc.), box plots, the 1,5 x IQR rule, Q-Q plots, and comparing histograms. If these seem promising, a goodness-of-fit test was conducted to determine if the activity-time could be approached with a certain statistical distribution. This analysis took a lot of time. The entire analysis can be found in *appendix C.1.*

All sources were included in one table. So, the data estimate of product A supervisor, calculated times, the ERP average, the assessment of the planning officer about the reliability of the ERP data, and my opinion mainly based on the descriptive statistics and the persuasion of the shop floor worker. This table can be found in *section C.3*. Eventually, product A project supervisor and I sat down and decided on how to determine the throughput times based on this table. The eventual argument for this decision can be found in *section C.4.*

The throughput time of the Machine 1 machine has been determined in a different way. The way this was done can be found in *section C.2.*

Reflecting on the throughput times

Eventually, the following throughput time distributions have been determined for each production step.

Table 1: Determined throughput times for each department.

#	Operation	Decision (minutes)
	Reception of products	Uniform 5-7 (receiving)
	Order intake	Uniform 10-15.
10	Documentation/instructions	
20	Part marking	Uniform 5-10.
30	Sawing/material inspection	Uniform 15-25.
50	Inspection	Uniform 15-20.
60	Turning-Milling machine	B 360 ± 15%: uniform AC 405 ± 15%: uniform
70	Secondary Operations	Gamma distribution (10,885;0,279) hours.
80	Marking	Gamma distribution (4,16;010) hours.
90	Cleaning	Uniform 5-10.
100	Inspection	Uniform 5-10.
110	THE OUTSOURCING COMPANY	Uniform 10-14 (loading and receiving)
120	Visual inspection	Uniform 15-20.
130	Assembly	Gamma distribution (4,03;0,19) hours.
140	Grinding (Machine 2)	Normal distribution (2,31;0,90) hours, with limits to prevent extreme values.
150	Secondary Operations	Triangular distribution with 20, 25 and 30.
160	Cleaning	Uniform 10-20.
170	Inspection	Uniform 5-10.
180	THE OUTSOURCING COMPANY	Uniform 10-14 (loading and receiving)
200	Visual inspection	Uniform 15-20.
190	Sandblasting	Uniform 60-90.
210	Cleaning	Uniform 10-20.
205	Visual inspection	Triangular with 90, 120, and 140, for 1 out of 10 products.
220	Assembly	Uniform 8-12
230	Final inspection	Uniform 10-20.
	Delivery (administration)	Uniform 15-25.
	Delivery (expedition)	Uniform 10-20 (loading).

Multiple uniform distributions have been chosen. This is because little is known about these values, other than a likely range. In this case, Robinson advices the uniform distribution (2014, p. 351). It has been determined to choose for a continuous uniform distribution since it is about activity time in which between full seconds/minutes/hours activities can be completed. As explained for the Machine 1, a constant processing time is assumed with variations based on a smooth run-time or not. The analysis of the statistical distributions has been discussed. Lastly, for several steps, the triangular distribution is assumed. In this case, the likely range and a most likely value were known by the shop floor workers. In this way, the throughput time can be approximated a bit more accurate than with a uniform distribution (Robinson, 2014, p. 134).

Based on the chosen distributions, two things stand out. First, it seems that the calculated throughput times in the ERP-system are different from the eventually determined throughput times. Sometimes steps are combined in the ERP-system while in this thesis these steps are treated separately. However, for some steps where the same activities are assumed, the calculated time is still not that accurate. The calculated times are both estimated higher and lower for separate production steps. However, by adding all averages of the chosen distributions (1009), adding the calculated times (1215), and comparing them, a difference of 206 minutes can be observed. So, there is an undercalculation of approximately 206 minutes (!) per product A. Therefore, I advise COMPANY A to reconsider these calculated times since they can give a wrong picture of the estimated costs. I am not saying that my approximations are completely right, but I think they are closer to reality than the calculated times.

Second, except for the Machine 1 machine, it seems that clocking an operation is quite reliable. The clocking times are quite in line with the estimations given by the experts. So in order to get more reliable data, I would advise COMPANY A to start clocking of all the operations and use averages of these times as calculated times. If done properly, it seems to give quite reliable data. It is also useful for further modeling purposes.

2.4 Other production characteristics

Next to the steps, planning, and throughput times, multiple other smaller characteristics are of interest for this thesis. These will be outlined in the following section, consisting of the demand, transport-days, and costs estimations.

Demand for products A

For this thesis, the demand for product A calculations of COMPANY A have been used. Doing a thorough demand forecast is beyond the scope of this thesis. It is also not needed since COMPANY A expects its calculations to be reliable.

Table 2: The demand for products A.

[censored]

This demand is based on aircraft sales with these particular engine types, displayed in the first ([censored]) and second row ([censored]). However, not all products A will be processed by COMPANY A. For customer X to spread its risk, multiple suppliers are chosen to process product A. COMPANY A is one of these suppliers. As agreed, COMPANY A will fulfill approximately 40% of the demand.

2019 has already started and the desired output numbers of around 16 per week are not met. Customer X will acquire these products A elsewhere. Catching up in the second half of the year will be undoable. Therefore, the real 2019 numbers will be lower.

Transport-day to THE OUTSOURCING COMPANY and delivery of new castings and acquiring finished products A

Currently, the transport day to THE OUTSOURCING COMPANY is usually on Wednesday, but it could be any other day. Doing any work on products A that need to be transported on that day, is not desired. Though, this still happens. Every transport-day a truck brings back products that were outsourced, and acquires products A that will be outsourced. The transport to THE OUTSOURCING COMPANY takes approximately three hours and outsourcing takes a week. It has been decided that this transport day is done weekly. However, it is no restriction. Driving two times would reduce the throughput time, but it comes with a cost. This is possible since the tear inspection only takes approximately one to two hours. COMPANY A believes that this can be done by THE OUTSOURCING COMPANY.

As mentioned, delivery of new castings is done quite randomly by the customer. So this could be any day. Moreover, acquiring of finished products A is also done when enough products A are finished. Preferably, the customer brings new castings, and at the same time, acquires finished products A.

Costs

Based on cost-calculations of COMPANY A, the following costs have been determined. These are the tariffs that COMPANY A calculates with. Therefore, these costs will also be applied to this thesis. The costs will not be re-evaluated or analyzed.

- Transport costs:
  - [censored]
- Employee costs:
  - [censored]
- Machines:
  - [censored]

The machine costs can be estimated yearly. The machines are bought and leased at the same time. So, every time COMPANY A pays for the machines, they automatically buy a part of it (just like a mortgage when you buy a house).

- WIP value:
  - [censored]
- Other costs:
  - [censored]

2.5 Capacity analysis

Currently, there is a certain capacity present at COMPANY A. However, this capacity is not enough to produce the demand numbers in the previous section. I discussed with the director what should be the starting situation for my thesis. It was decided to calculate the required amount for each department. Therefore, the main question in this section will be: *what should be the capacity, to produce the required number (as mentioned in the previous section)?* The findings will be the start-values for the eventual simulation model.

In this section, buying extra machines is not yet considered for the Machine 1 (turning and milling), Machine 2 (grinding), and sandblasting machines. Hiring extra employees and having different shifts, might be interesting. In a later stage, during experimentation with the simulation model, it should be considered if this is cheaper than buying an extra machine. The disadvantage is, that this extra machine will perhaps need an extra worker.

Since in the simulation model only the first 26 weeks of 2019 will be modeled, 2019 will not be considered. COMPANY A has calculated some the capacities already for themselves and customer X in order to show that they can produce the required amount of products A. The base numbers for this analysis are:

Table 3: Base numbers for the capacity analysis.

[censored]

As shown, COMPANY A assumes an utilization of 85% which is quite high. Moreover, they assume 24 days off for employees, which includes illness. I will use these numbers for this capacity analysis. It can be questioned if these numbers are plausible. However, just like with the numbers for the total demand and cost, doing a thorough investigation about these numbers will almost require an entire second thesis. As displayed, with these numbers, the department is only working 5 days per week, 8 hours per day. It might be that this capacity is not sufficient, such that a 16 or 24-hour shift is needed. Moreover, these are the numbers for just one employee or machine. The maximum capacity per year doubles if the number of employees/tools/machines is doubled.

Based on the demand in the *previous section* and the average process time of each production step shown in *section 2.3,* the needed yearly capacity can be calculated by multiplying the two. This will be done for every department. The goal is to find the minimum number of hours for which the required amount of products A can be produced. Since maintenance, efficiency problems, holidays and other non-working days are all considered, the required amount should be close to 100%. Perhaps a bit more, perhaps a bit less.

The Machine 1 Machine (Turning and Milling)
For the Machine 1 machine, it immediately becomes clear that working 8 hours per day, 5 days per week, will not be sufficient to produce the required amount, resulting in utilization of 357,7%-372,5% (2020-2022). So, the number of hours should be more than tripled. This can be done by running 24-hour shifts. However, this is also not enough. Only by adding a 24-hour shift on Saturday (or Sunday) will result in enough hours to produce the required amount, resulting in utilization of 97,7%-101,7%. This is 1,7% too much. However, perhaps some gains can be acquired in the process times, maintenance, efficiency, etc. So, this shift will be used as a starting value. The simulation model will have to point out if this is enough to produce the required amount.

Deburring
For the deburring department, 8 hours per day, 5 days per week, with one employee will also not be sufficient to produce the required amount of demand, resulting in utilization of 198%-205,8%. This is mainly since the deburring department is visited twice by product As, namely after turning and milling and after grinding. However, since tools are available to produce with two people, working in shifts is not necessary. Therefore, two people will need to be present in the deburring department, in order to produce the required amount, resulting in a utilization of 99%-102,9%. The simulation will again have to point out if this is enough to produce the required amount.

Machine 2 (Grinding)
For the grinding machine, 8 hours per day, 5 days per week with one employee will not be sufficient to produce the required amount of demand. This results in utilization of 131,6%-136,8%. Therefore more hours should be used. This can be done by working on Saturday. However, this would result in utilization of 62,6%-65,1%. Therefore, working on Saturday morning or one Saturday every two weeks might also be sufficient, resulting in utilization of 84,9%-88,2%.

All other departments
All other departments can produce the required amount of demand by working 8 hours per day, 5 days per week. Namely, if the processing time is below 101 minutes, the utilization will be below 100%. This is the case for all other departments, except for the cleanliness test which takes on average 120 minutes. However, the cleanliness test is only performed for one out of ten products. So, this will also be doable.

To summarize the initial capacity values:

Table 4: Capacity decision for capacity-constrained departments.

Department	Capacity decision
Machine 1 (Turning and milling)	Working 24 hours per day, 6 days per week.
Deburring	Working 8 hours per day, 5 days per week with two full-time employees.

Machine 2 (Grinding)	Working 8 hours per day, 5 days per week and working 4 hours per day, 1 day per week.
All other departments	Working 8 hours per day, 5 days per week.

2.6 Bottlenecks in the production

The production bottleneck is the workstation with the highest utilization (Lödding, 2013; Hopp & Spearman, 2008) or the bottleneck is the longest task in the process (Reid & Sanders, 2013; Slack, Brandon-Jones, & Johnston, 2013). Using Plant Simulation (the simulation program I work with) the bottleneck is the workstation that works the highest portion of the time. That is, it is not waiting, blocked or paused. Moreover, the waiting time of a workstation behind the bottleneck is relatively high (Kikolski, 2016). Another characteristic of a bottleneck is a long queue in front of the bottleneck. Combining all statements, there are multiple characteristics of bottlenecks. Therefore it is too easy to say workstation X is the bottleneck because it has characteristic Y. Nevertheless, based on the statements, the following four production steps seem to be potential candidates for the bottleneck (in arbitrary order):

1. Outsourcing to THE OUTSOURCING COMPANY
2. Machine 2 (grinding)
3. Machine 1 (turning and milling)
4. Deburring

THE OUTSOURCING COMPANY has the longest processing time since it takes a week. Therefore this can be classified as a bottleneck. However, THE OUTSOURCING COMPANY is part of the process two times. Is the first time product As will be outsourced the bottleneck? Or the second time? Or both? Nevertheless, even though outsourcing takes a week, it does not have a constrained capacity. That is, almost always the required number of products A can be sent to THE OUTSOURCING COMPANY. In this thesis, it is assumed that there is no limit on this. For other departments, this is not true. As shown in the previous section, the Machine 1, deburring, and Machine 2 need extra capacity to process the number of products A. Their estimated utilization are relatively high, which results in queues and thus longer throughput times. Lastly, in this thesis, production errors, failures, and maintenance are not considered extensively in this thesis since data about this is missing. So, this definition cannot be used. It is difficult to conclude this section with just one bottleneck. Therefore, the bottleneck will be part of the simulation study. Not in the sense that it is my goal to determine a bottleneck since this is not that important. But in the sense that changing different things regarding different departments (potential bottlenecks) will result in different outcomes. Based on this, the most successful changes can be determined. Think about outsourcing two times per week instead of one time, changing Machine 1 and Machine 2 shifts, and bottleneck control planning and control approaches (outlined later).

2.7 Summary and conclusions for chapter 2

1. Product A project is somewhat different for COMPANY A since COMPANY A usually produces in small batch quantities with some variety.
2. The production chain of product A is quite long, resulting in a lot of WIP.
3. The current planning algorithm is difficult to outline and is therefore also not strictly followed in practice.
4. The current planning algorithm leads to a lot of waiting time for products A. Though, it brings certainty within the production.
5. The calculated process times are different from the actual process times.

6. Clocking the process-time gave valuable data that can be used to analyze the process. If clocking was done right, it was often in line with the given estimates.
7. All departments can work normal office hours with one employee or one machine to produce the required amount of products A. Though, the turning and milling machine and grinding machine, need to work in different shifts, whereas the deburring department needs two employees.
8. Potential bottlenecks are outsourcing to THE OUTSOURCING COMPANY, the grinding machine, the turning and milling machine, and the deburring department.

Chapter 3: Production planning and control and simulation study (literature study)

This chapter will include a literature study about both planning and control and a simulation study. In the planning and control section, one of the sub research questions of this thesis will be answered. In the simulation study section, the key concepts of simulation, applicable to this thesis, will be outlined.

3.1 Production planning and control

In this section, answers to the following question will be researched within literature:

What production planning and control optimization techniques or heuristic algorithms can be found in literature and how can they be applied in practice?

The theoretical perspective will be similar as in *section 1.4*. In addition, the constructs in this research question can be described similarly as the overall research question, and thus, the key constructs are also already defined in that *section 1.4*. "The application in practice" is defined as the application to COMPANY A, which will be assessed in *chapter 4, w*here KPI's will be determined and the different planning approaches will be scored on these KPI's.

In this section, the key fundamentals of planning and control will be outlined. First, the key principles of planning and control will be outlined in order to understand important aspects of planning and control approaches. Second, push and pull control will be outlined and compared. These two approaches form the fundamentals of many planning and control approaches. Some of these approaches are outlined in the last part of this section. Due to time constraints, not all approaches could be outlined. This selection has been made, based on the review of Stevenson, Hendry, and Kingsman (2005).

The subject of planning and control has been recurring in several other theses and case studies. Noordhuis (2018) did a similar master-thesis about implementing planning and control approaches in a production environment. In his thesis, workload control was advised to the company. It showed significant improvements in the simulation model, together with a guide for implementation. Another master thesis, of Heutink (2017) advices the COPACABANA planning and control approach. This approach is less famous than the usual approaches. Maarleveld (2015) recommended a hybrid push-pull approach. This will have to improve lead times, decrease WIP while maintaining throughput. Concluding, the implementation of a planning and control approach can provide significant benefits, according to the theses. This is also shown in several case studies. For every planning and control approach, the results of case studies for different planning and control approaches will be discussed.

3.1.1 Production planning and control

Planning and control can be described, using the definition of Slack, Brandon-Jones, and Johnston: "***Planning and control*** *is concerned with the* ***activities*** *that attempt to reconcile* ***the demands of the market*** *and the ability of the* ***operation's resources to deliver***" (2013, p.290). This definition consists of four constructs which will be explained separately:

Planning and control has already been discussed in *section 1.4*. However, for completeness, it will shortly be repeated. Planning and control will be used as one term since the division between the two terms is not clear in reality and practice. However, when the terms are discussed separately, planning usually refers to a plan, something that is intended to happen in the future. Control, on the other hand is concerned with coping with varieties within a production process. In other words, making quick and small adaptations if the planning was not right about a situation, in order to still achieve strategic objectives (Slack, Brandon-Jones, & Johnston, 2013, p. 290). Planning and control can be done on the long-term, medium-term, and short-term. Long-term planning uses aggregate demand forecasts, determines resources in aggregate form, and sets objectives in largely financial terms. Short-term planning, on the other hand, uses disaggregated demand forecasts, or even actual demand, intervening resources to correct deviations from long-term plans, and ad hoc decisions (Slack, Brandon-Jones, & Johnston, 2013, p. 291). Consequently, control usually refers to short-term planning whereas planning is usually about long-term planning. Medium-term planning is between these two extremes. For the remainder of this chapter, planning and control will be used interchangeably.

An important aspect of the **operation's resources to deliver** is the volume and variety in which products are made. This determines how an organization is organized (Reid & Sanders, 2013, p. 578). These processes usually have different objectives and characteristics, also regarding planning and control. High-volume operations, described as flow, or (product) line organization have repetitive operations with low variety. High-volume operations usually use fixed routings, where activities are performed in the same way, in a fixed sequence of workstations. On the other end of the spectrum, there are low-volume, high-variety operations. These operations usually make customized products of higher quality in a so-called job-shop. Consequently, these companies use a process layout (layout arranged by equipment), with highly skilled employees, and general equipment, because the tasks differ per (group of) products (Reid & Sanders, 2013, pp. 578-579).

The **demand of the market** is also an important aspect of production planning and control. Demand is usually uncertain, and planning and control should be able to cope with this uncertainty. This uncertainty depends on multiple factors. One of these factors is dependent or independent demand. Dependent demand can be predicted with more certainty. Dependent demand depends on another variable that is known. For example at COMPANY A, they know that a certain amount of aircraft is ordered for the coming years. Since they know how many of their parts will be present in these aircraft, they can calculate the demand for their part. On the other hand, independent demand does not depend on other products. Therefore, demand is more difficult to predict (Slack, Brandon-Jones, & Johnston, 2013; Reid & Sanders, 2013).

Another important aspect of demand forecasting is the length of time between the receipt of the order and its shipment (Lödding, 2013, p. 21). In low volume, high variety operations, the entire production process from design to delivery is done after a customer order. This is so-called *customized non-repetitive production*. On the other end, high volume, low variety operations produce to stock. This is called *make-to-stock production*. Between these extremes, two other systems can be observed, *assembly-to-order* assembles sub-assemblies but does not create the end-product until the order is received. So, the product can still be slightly customized. The last configuration is called *make-to-order (MTO)* where manufacturing only starts after an order is received. The difference between MTO and customized production is that an MTO environment usually starts with some already bought resources, materials, etc. Other books, like for example the book of Slack, Brandon-Jones, and Johnston (2013) define even more types, making the differences between the types even smaller. Literature usually only refers to the main types outlined in this paragraph.

The decision on when to start to produce has a big impact. Empirical studies show that companies with short delivery times grow more quickly and achieve higher profits than those with longer delivery times (Lödding, 2013, p. 21). This is (in my opinion) easy to understand. If all other specifications of a product are equal, everyone would buy the product with the shortest delivery time. Thus, this can be seen as another competitive factor. However, shorter delivery times also bring the risk of not selling the already produced stock, or in case of food production, obsolete products.

Planning and control has to do with **four main activities**: loading, sequencing, scheduling, and monitoring and control. These activities are overlapping, and different books use different terms for the concepts. Nevertheless, the four activities are essential for planning and control.

Loading

Loading has to do with the amount of work that is allocated to workstations (Slack, Brandon-Jones, & Johnston, 2013, p. 299). If a machine is available for X number of hours a week, it does not mean that the machine can be loaded that many hours. There are six big losses of loading time (Muchiri & Pintelon, 2008):

1. Equipment failure (maintenance effectiveness)
2. Set-up & adjustment (maintenance effectiveness)
3. Idling & minor stoppages (production effectiveness)
4. Reduced speeds (production effectiveness)
5. Defects in the process (quality effectiveness)
6. And reduced yield (quality effectiveness)

Subtracting these losses from the loading time leaves the valuable operating time, which can be loaded by planning and control.

Loading can be divided into finite and infinite loading. Finite loading does not load more than the available capacity on a workstation, based on an estimate of the available capacity. On the other hand, infinite loading does not limit accepting work. Based on the characteristics of the load, it must be determined which type to use (Matsuura, Tsubone, & Kataoka, 1995). The characteristics depend on if the load can be limited, if this is necessary, and if the costs of limiting the load are low. The latter means that setting a limit should not have negative consequences (Slack, Brandon-Jones, & Johnston, 2013, pp. 300-301).

Sequencing

Sequencing is about the order in which to do all jobs in each workstation. It is part of short-term planning. In order to determine this, priority rules exist. With priority rules, orders are given a certain priority in order to determine their sequence. Priority rules can be divided into local and global priority rules. Local priority rules set priority based on jobs waiting at a certain work center, whereas global priority rules set priority based on information from not only this particular work center but also other work centers (Reid & Sanders, 2013, p. 584). Well-known priority rules are summarized in the following table:

Table 5: Familiar priority rules in literature.

Priority rule name	Type	Idea (based on Reid & Sanders, 2013)
First come, first served (FCFS)	Local	First order in will be processed first.
Last come, first served (LCFS)	Local	Last order in will be processed first.
Earliest Due Date (EDD)	Local	Jobs are sequenced according to when it is due.
Shortest processing time (SPT)	Local	Jobs with the shortest processing time for this workstation will be processed first.
Longest processing time (LPT)	Local	Jobs with the longest processing time for this workstation will be processed first.
Critical Ratio (CR)	Global	Jobs with the lowest ratio due date minus current date (time remaining to due date) divided by the remaining processing time will be processed first.
Slack per remaining operations (S/RO)	Global	Jobs with the lowest ratio time remaining to due date divided by the number of operations remaining will be processed first.

However, sometimes the customer determines the priority. Usually, orders of more important, larger customers have priority over other orders. Priority may also be based on physical constraints (Slack, Brandon-Jones, & Johnston, 2013, p. 301). From these priority rules, multiple other rules are derived. These are usually more complex, but in several situations also more effective.

Blackstone, Phillips, and Hogg (1982) wrote a famous article in which they compared the different dispatching rules. In this analysis, SPT (and a variation of SPT) scored the best. EDD, slack per remaining operation, critical ratio, and FIFO followed (in this order). Their analysis was based on manufacturing job shops. If strategic costs are assumed for late orders, other priority rules perform better. Especially the rules that take these costs into account (Vepsalainen & Morton, 1987). This analysis was also based on a job shop. Baker (1984), on the other hand, comes to different conclusions. In other words, there is no one-size fits all for a priority rule. Companies should set their strategic objectives and determine which priority rule scores best on these objectives.

Scheduling

Sometimes operations want a timetable that shows the work and the sequence of this work. However, sometimes this is not always possible in the short-term sense. The general formula for the number possible schedules is (n!)*m, where n is the number of jobs and m the number of machines. Thus, the number of possible schedules can become quite large, even for small operations (Slack, Brandon-Jones, & Johnston, 2013, p. 307).

Another aspect of scheduling is forward and backward scheduling. By forward scheduling, the processing starts immediately when an order is received, not concerning its due date. In this way, the orders are completed on the earliest possible date. However, if jobs are finished early (before its due date), the operation will build-up inventory. Backward scheduling calculates when a job needs to be started such that it is completed on its due date. This prevents inventory from building up when jobs are finished. However, forward scheduling provides slack: time in which a job can be delayed such that it is still on time for its due date (Li & Willis, 1992).

There are many famous examples of schedules such as Gantt charts including load charts and progress charts, shift scheduling, materials requirements planning, Kanban walls, etc. Different schedules have different advantages and disadvantages. These will not be discussed in this chapter.

Monitoring and control
The last activity concerned with planning and control is monitoring if all loading, sequencing, and scheduling is following the initial plan. The world is stochastic, so planning and control systems need to cope with deviations from plans within a certain timescale. Controlling is not always routine. According to Hofstede's typology for management control (1981), the type of control is based on if the objectives are unambiguous, outputs are measurable, effects of interventions are known, and if the activity is repetitive.

- *Political control* is needed if objectives are not unambiguous and if this ambiguity cannot be resolved. By political control, objectives are set by higher authorities in the company hierarchy such that objectives become unambiguous for those lower in the hierarchy.
- *Judgmental control* is needed if objectives are unambiguous and outputs are not measurable. It basically is a subjective judgement
- *Intuitive control or trial and error control* is needed if objectives are unambiguous, measurable, but the effects of the interventions are not known. Intuitive control is conducted if the activity is non-repetitive, where a person needs to be found who can intuitively find the proper form of intervention needed. If the activity is repetitive, the organization can learn the intervention by experience via trial and error control.
- *Expert opinion or routine control* is needed if objectives are unambiguous, outputs are measurable, and the effects of interventions are known. If the activity is non-repetitive an expert can do the control since it is a repetitive task for that person. If the activity is repetitive routine control can be used, with systematization skills.

Hofstede displayed the needed control in a flow chart. So, for a better understanding of the different types of control, I refer to his article (Hofstede, 1981).

Applying the principles of production planning and control to COMPANY A
With the theory above, the production planning and control system of the production of product A can be classified according to the constructs mentioned. The current system uses short-term demand since products come in at an uncertain moment in an uncertain batch size. The planning is made based on the delivered products A. However, the situation in the simulation model uses aggregate demand, where a certain weekly demand is assumed based on forecasts. These forecasts are based on dependent demand since a certain number of aircraft are ordered with this type of engine. As mentioned in *section 2.1*, most of the time COMPANY A produces in a high variety, low quantity products whereas product A production is a low variety, high quantity process. The production process of product A can be classified as make-to-order. The priority rule that COMPANY A uses is FIFO. Finite loading is used in order to not overload work centers or machines within the production. The schedule that COMPANY A uses is a table with products A as rows and the production steps as columns. Within these rows and columns, dates are filled-in. These dates indicate when product A in the row should have completed the production step. Lastly, control used to cope with deviations at COMPANY A, is based on a combination of routine or expert control. For example, when there are deviations in the product, a quality manager (expert) needs to decide how to cope with it. However, for the planner, a deviation has more often occurred, and he needs to re-plan the work (routine).

3.1.2 Push vs. pull control
An important aspect of planning and control is if the work is pushed or pulled through the process. This is an element of control that triggers and determines when an order is sent to another department.

One of these triggers is push control. By push control, work is sent to the next department without checking if the other department can process it. A central planning system usually determines planning and control. An example of such a system is a material requirements planning (MRP). The MRP schedules the release of work based on demand. However, actual conditions can differ from such a system, resulting in queues, idle time, inventories (Slack, Brandon-Jones, & Johnston, 2013, p. 311). Another trigger is called pull-control. In a pull system, the pace and specification of what is done are set by the consequent workstation which pulls work from the previous workstation if it finished a job. Pull control is often used in lean synchronization in order to match supply and demand (Slack, Brandon-Jones, & Johnston, 2013, p. 478). A system that uses pull control is the Kanban system.

So, an MRP schedules work based on demand, whereas Kanban authorizes the release of work based on the status of a system. The critical distinction between pull and push control is that pull systems set a limit on the WIP while a push system does not (Hopp & Spearman, 2008, p. 358). Such a WIP limit with emphasis on the flow between processes results in several benefits, as outlined by Hopp and Spearman (2008, pp. 359-363).

- **Pull control reduces manufacturing costs**
  WIP limits make sure that disruptions like machine failures do not cause the WIP to grow even further. If a disruption happens in a push system, WIP has already been build up until this disruption is detected whereas with a pull system the WIP limit already acted.
- **Pull control reduces variability**
  WIP limits make sure that cycle times are less variable than in a pure push system. Cycle times increase with WIP levels (Little's law, 1961), and pull systems make sure that this WIP is always within a certain limit, therefore reducing variability in cycle times.
- **Pull control improves quality**
  Quality inspection is more effective in a low WIP environment (Hopp & Spearman, 2008, p. 362). If WIP levels are high and queues are long, quality assurance inspection may not identify a problem until a large batch has already been produced. Whereas with a short queue only a few products might have been produced.
- **Pull control maintains flexibility**
  Push control pushes orders in a perhaps already congested line. This results in less flexibility because of several reasons. First, parts that have been partially completed cannot easily be changed. Second, schedules in a long queue might need constant updating because of priority rules. Third, because of high WIP levels, products need to be released earlier in advance of their due dates, resulting in a longer planning horizon, increasing uncertainty.
- **Pull control facilitates work ahead**
  Since pull systems take into consideration the system status, and orders are released based on the WIP level, good luck can be exploited. For example, if for a while no machine breaks down, more might be produced than anticipated. A push system, on the other hand, does not take the status of the system into consideration, so it will not release orders earlier.

Push and pull control is in reality also used in a combination. This is called a hybrid system (Hopp & Spearman, 2008, p. 356). It tries to combine the best of both push and pull control.

3.1.3 Push and pull production planning and control approaches

In literature, multiple production planning and control systems can be found. These methods use push, pull, and a hybrid approach. Many of these approaches have been included in the Handbook of Manufacturing Control of Hermann Lödding (2013). In this book, production planning and control methods are described for generating and releasing orders, sequencing orders, and controlling the operations. Describing all of them will take too much time and is already done in the book. However, Stevenson, Hendry, and Kingsman (2005) reviewed key concepts of production planning and control for the make-to-order industry, like the situation at COMPANY A. Therefore, these concepts will be outlined in this section.

Describing the method will be done by outlining the key characteristics of each planning and control method, the steps that are needed when executing the method, the advantages of each method, and the disadvantages of each method. Lastly, an example of an implementation in literature will be outlined for each method. For this, no simulation studies, queuing or other models will be used. This is done on purpose since I want to discover the effects of the method in a real environment when implemented. During the analysis of the method, multiple cross-comparisons with the other methods will be outlined.

Material Requirements Planning (MRP)

MRP is "an approach to calculate how many parts or materials of particular types are required and what times they are required" (Slack, Brandon-Jones, & Johnston, 2013, p. 456). Based on back-scheduling, MRP determines when each part is required. This back-scheduling considers the time it takes to conduct each step. The MRP is based on demand forecast, bill of materials, and inventory records. MRP requires information concerning independent demand from the so-called master production schedule (MPS), in which the requirements and current inventory are displayed. This MPS should include all sources of demand. The current inventory consists of scheduled receipts and on-hand inventory. The bill of materials displays the relationship between finished items and their parts, so-called lower-level items. These lower-level items depend on the demand of the end-items. Next to the inventory records of finished items, the MRP also needs inventory records of parts such that the right number of parts are ordered. This again consists of on-hand inventory and scheduled receipts.

MRP consist of the following five steps (Hopp & Spearman, 2008, p. 117):

1. Determine the net requirements. Calculate what is needed minus the scheduled receipts and the on-hand inventory. If this number becomes negative, new items must be ordered. For end-products, this is based on the MPS, whereas for parts this is based on the demand for end-products and its level in the BOM.
2. Based on the net requirements, lot-sizes should be determined since not all parts can be ordered in the exact numbers.
3. Based on the lead times of each production step, start times should be determined.
4. By using the level of the part in the BOM, requirements, start-times, and lot-sizes for each component can be determined.
5. Go on until all levels are processed.

Based on the outlined steps, MRP can be seen as a push system since it schedules products into a production process based on demand.

Before MRP, reorder points were used for every part and end-products. As it turned out, this approach was more suitable for end-products only. MRP provided the key link between independent demand (of end-products) and dependent demand (of parts). Today, MRP is still the core of many ERP systems (Hopp & Spearman, 2008, p. 114). However, some problems occur when using MRP (Hopp & Spearman, 2008, pp. 135-139):

1. The MRP assumes infinite capacity. Therefore, the MRP can create infeasible plans. It needs additional systems to cope with this, like rough-cut capacity planning or capacity requirements planning.
2. There are many pressures to increase planned lead times in an MRP system. This causes a higher WIP. This problem gets even bigger since MRP assumes constant lead times whereas real lead times are variable. Therefore, planners usually plan much longer for a certain production step. This again leads to higher WIP.
3. Nervousness, which can lead to strange effects. This happens when a small change in the MPS results in a large change in planned order releases.

After a slow start for MRP, it got popular around 1972. Currently, sales of MRP software and implementation has exceeded more than 1 billion dollars. As mentioned, almost every current ERP has an MRP system as its main component. Therefore, almost all managers know the MRP system (Hopp & Spearman, 2008, p. 114). However, currently many other approaches are known, and MRP also has significant disadvantages (see above).

Kanban

Kanban is a way to make pull-control work in practice. Kanban is a part of the larger lean synchronization theory. With Kanban, cards control the timing of pulling work from one station to another. The Kanban (whatever it is, a card, a ball, etc.) triggers the movement, production, and supply of units (Slack, Brandon-Jones, & Johnston, 2013, p. 478). Usually, a card is used, containing the relevant workstation, job type, lot size, and card number.

In order to make the idea clear, the simplest form of Kanban (one-card Kanban) will be explained. With Kanban, every product on a workstation has a defined number of Kanbans. This card moves back and forth between the workstation and the output store. If the output store completes the job, the Kanban will be returned to the workstation. Based on these fundamentals, the following procedural rules describe how one-card Kanban works (Lödding, 2013, p. 186):

1. A workstation (let's call it workstation B) may only start production when the Kanban for this job type is present.
2. If there are multiple jobs and job types, the job with the highest priority is chosen. This is based on the chosen priority rule (see: *section 3.1*).
3. Workstation B checks if all materials are present for the product. If so, workstation B picks the material from the preceding workstation (let's call it workstation A) and returns the Kanban to station A. If the materials are not present because workstation A has been disrupted, another job should be chosen. This should not happen too often. The system is blocked if none of the materials for any job are present.
4. If all materials and the Kanban are present, the workstation will produce the job. It brings the job with the Kanban to the output store.

Kanban can take multiple forms, for example by using two-card Kanban in which transport-Kanbans triggers the transport and production-Kanbans trigger the production. This is especially relevant if there is a considerable distance between the two workstations. Other forms are visual Kanban or bin Kanban.

People that are familiar with certain stock systems will see similarities between stock systems and Kanban. Kanban is a special case of the so-called Order Point System. In an order point system, a purchase order is placed if the number of units on hand falls under a certain value. In order to make Kanban similar, the parameters of the order point system should be as follows (Lödding, 2013, p. 196):

1. Fixed order quantity
2. Order point = maximum stock – 1

In order to analyze the benefit of Kanban regarding MRP, the same advantages of pull over push control can be mentioned. This is because Kanban is one of the most typical pull-systems whereas MRP is one of the most typical push-systems. In addition, Kanban stimulates communication between departments. Even though there are many ways to do this, Kanban certainly helps. Kanban also supports sharing a resource among different routes.

Nevertheless, Kanban certainly also has its disadvantages (Hopp & Spearman, 2008, p. 502):

- It is quite complex to determine all Kanban cards per department.
- Operators have less flexibility, by not being able to work ahead and extra pressure to produce when a consequent station needs something.
- If multiple parts are present, multiple containers must be stored at each workstation.
- It can only accommodate a small product mix since cards are product specific.
- Kanban is not suitable for small, infrequent jobs.

In literature, several examples of implementation of a Kanban system can be found. One implementation was reviewed at John Deere, in the Waterloo Works department where casted iron cases for tractor transmissions are made. Implementation of Kanban reduced inventory value from $300k to $100k. In addition, delivery of products has significantly been improved (Spencer & Larsen, 1998). In addition, Kanban implementation in a tire manufacturing plant also showed really successful as it saved 315.500 INR per annum, due to the reduction of WIP, the increase of output, reduction in set-up and changeover time, increase in machine uptime, and reduced defects (Mukhopadhyay & Shanker, 2005). These examples show that Kanban can be successful when rightly implemented.

ConWIP

Constant Work in Process (ConWIP) is a pull control that tries to maintain a constant WIP level in a production line. ConWIP is a special case of Kanban (Thürer, Stevenson, & Protzman, 2016). Therefore, it has similar rules, but this time for the entire production line. ConWIP releases an order if the WIP of the entire production line is below a certain level. If this happens, the order with the highest priority (based on the priority rule) is chosen (Lödding, 2013, p. 335). This WIP is measured in number of parts or in planned hours. Planned hours of an order can be measured as:

- The sum of planned times of its operations
- The planned times of the not yet completed operations
- The time planned on the bottleneck station

Hopp and Spearman (2008, pp. 369-381) have compared ConWIP with both Kanban and MRP. Their analysis results in a few interesting findings. The proof of these findings will not be discussed here but are outlined in the book. Their findings of comparing ConWIP to MRP:

- A push system (like MRP) is more difficult to optimize since the parameter of a push system is directly observable, namely its WIP. Throughput (parameter used in a push system), on the other hand, is not and needs to be calculated by estimating capacity. This is more difficult.
- A pull system is more efficient than a push system. They even come up with the following law: "For a given level of throughput, a push system will have more WIP on average than an equivalent CONWIP system" (Hopp & Spearman, 2008, p. 370). Or using Little's Law, for a given level of throughput, the cycle times in a ConWIP system will be lower.

- As mentioned, a constant WIP reduces variability.
- The key advantage according to Hopp & Spearman is the robustness of a ConWIP system. They state: “A CONWIP system is more robust to errors in WIP level than a pure push system is to errors in release rate” (2008, p. 372).

And their findings on comparing ConWIP to Kanban:

- Kanban requires setting more parameters. Kanban needs cards for every workstation whereas ConWIP only needs one parameter: the WIP limit for the entire production line. In addition, Kanbans are part number specific, meaning that Kanbans are specifically for each type of product, whereas ConWIP selects the next order based on a release list, based on a priority rule.
- ConWIP can cope with variations in volume and product types much better than Kanban.
- Regarding people, ConWIP introduces less pacing stress in the first station than a Kanban line.

So based on the analysis of Hopp & Spearman, ConWIP is better than push systems and has some advantages regarding a Kanban system. However, when order generation is independent of department capacities and the flow is complex, departments with a method that uses individual load limits will attain a higher output rate with a comparable WIP level (Lödding, 2013, pp. 345-346). Examples of such methods are Kanban and Workload Control (outlined later). In addition, when utilization rates are low, it is not necessary to implement ConWIP. This can even lead to higher WIP levels (Lödding, 2013, pp. 345-346). Lastly, with ConWIP and Kanban, two additional potential problems arise (Hopp & Spearman, 2008, p. 503):

1. Bottleneck starvation due to a failing machine behind a bottleneck. Because a machine is failing, WIP builds up and no new order is released with ConWIP. However, the bottleneck might be empty.
2. Premature releases such that the WIP level remains constant. So even if a part’s due date is far ahead, it still might be released. This reduces flexibility since parts that already have been processed cannot be modified that easily.

Slomp and Bokhorst (2009) did a case study about implementing ConWIP in a business unit. This business unit produces a high variety of products in low volumes. Implementing ConWIP had resulted in a reduction of 4,2 days of flow time to 1 day of flow time for a part of the business unit. Though, the overall flow time in the unit was not reduced. Nevertheless, the ConWIP approach was liked by the workers and supervisors since it resulted in a better overview (Slom, Bokhorst, & Germs, 2009). In another case study at Vard Group AS, a designer and shipbuilder from Norway, several concepts were implemented together with a FIFO sequence, a stable workforce, and grouping of units. The situation can be described as an engineer-to-order environment. Implementing ConWIP positively influenced the throughput and the predictability of lead times (Kjersem, Halse, Kiekebos, & Emblemsvag, 2015).

POLCA

Paired cell overlapping loops of cards with authorization (POLCA) is a card-based system just like Kanban. A POLCA card is allocated to a specific pair of production cells. These cards authorize the production of orders and rotate between these cells. Within the cells, any other of the aforementioned production control methods can be implemented (Lödding, 2013, pp. 419-433), like an MRP. In that case, POLCA can be seen as a hybrid push-pull approach. Like Kanban is part of lean manufacturing theory, POLCA is a part of the larger quick response manufacturing, based on cell-layouts. Basic POLCA is includes the following elements:

- A release list: with all orders that can be released, defined by a higher-level planning and control system.
- POLCA cards. As mentioned, assigned to an originating and destination cell.
- Release date: determined with the aid of backward scheduling based on the planned end, by a higher-level planning and control system.

Basic POLCA consist of the following rules:

1. An originating cell is only allowed to process an order when the release date of the order has been reached. In addition, a POLCA card should be present (just like with Kanban). If both conditions are not true, the order is blocked. This does not work for the first and the last cell in the production line. The first cell can use the planned start date as a release date, whereas the last cell does not need a POLCA card.
2. If an order is blocked, the cell searches for another order that can be processed.
3. When an order is started by an originating cell, the POLCA card is attached to the order. This POLCA card is freed until the destination cell finishes its last process.

POLCA authorizes production within cells. It is especially suitable for systems with non-repeat production, focusing on operating at a steady capacity (Stevenson, Hendry, & Kingsman, 2005). However, just like with ConWIP, when order generation is independent of department capacities and the flow is complex, departments with a method that uses individual load limits will attain a higher output rate with a comparable WIP level (Lödding, 2013, p. 432). Moreover, if the material flow is highly complex, the method leads to blocked WIP and thus, a loss of efficiency. Lastly, if finite scheduling is applied (*section 3.1)*, planned WIP of a manufacturing cell can be temporarily higher than the set limit such that goals are still not met. This can also happen for ConWIP, however, for POLCA these effects occur more often (Lödding, 2013, p. 432).

Suri and Krishnamurthy (2009) did three case studies about the implementation of POLCA in a production environment: a manufacturer of aluminum extrusions, a manufacturer of motor control centers, and a manufacturer of machined parts. These facilities improved the efficiency of their operations and employee satisfaction. The case studies showed that POLCA can be promising, especially for high variety or custom engineered products (Krishnamurthy & Suri, 2009).

Workload Control

The basic idea of workload control (WLC) is holding back orders which would be proceeded to the consequent step. The order is held back since the consequent step is already overloaded. So, WIP is the key parameter. Basic WLC is based on the following aspects and rules (Lödding, 2013, pp. 365-381):

- A release list: which contains known but not yet released orders.
- The WIP account of the workstations: the work content of a department. Orders are added to this account if they are released and removed if they are finished. So, a WIP contains direct WIP (directly in front of the department) and indirect WIP (WIP that is in a preceding department but will come on the workstation in the future).
- WIP limits of the workstation. If the WIP account exceeds the WIP limit, the release of all orders routed through this department is blocked.

The order release can be event-based or based on a periodic order release. Just like with POLCA, WLC tries to attain steady utilization (Lödding, 2013, p. 380). WLC is specially designed for MTO-type production environments. It is an effective method to reduce WIP and to control lead times for non-repeat production and variable routings. However, just like Kanban, the method must set WIP limits per department (Stevenson, Hendry, & Kingsman, 2005). In addition, the method causes a large amount of variability in the input of a system, and thus variance in output lateness if processed in a FIFO sequence, therefore, another priority rule should be used. Furthermore, the method is not suitable if:

- A lot of complexity is present in the material flow, such that it is difficult to set a workstation-specific load balance.
- The positions of the workstations in the order throughput are changing (Lödding, 2013, p. 380).

In the famous article of Hendry, Huang, and Stevenson (2013), where WLC was implemented in a high variety, low volume make-to-order company (name of the company is not mentioned). Data showed that when WLC is implemented successfully, it can lead to reductions in lateness and tardiness, reduced overtime costs, and improved coordination between sales and production without increasing capacity or reducing the workload processed (Hendry, Huang, & Stevenson, 2013).

Nevertheless, there is one substantial remark regarding the results of workload control. Empirical research reports observed a reduction in total work-order throughput time of 40-50%. However, other research reports mention only a reduction of a few percent or even an increase. This is referred to as the workload control paradox (Stevenson, Hendry, & Kingsman, 2005). Multiple articles and research contribute to this paradox, including the article of Hendry, Huang, and Stevenson. Further details of this paradox will not be outlined in this thesis. Though, it shows that positive results by implementing workload control are not certain and environment-specific.

Bottleneck control

Let's start with this chapter by outlining that multiple names are used for this concept. Bottleneck control (Lödding, 2013) is also called pull-from the bottleneck (Hopp & Spearman, 2008) or drum buffer rope (Slack, Brandon-Jones, & Johnston, 2013). With bottleneck control, the WIP is only regulated up to the bottleneck of a production line. Bottleneck control is similar to ConWIP, in the sense that it releases an order if the WIP falls below a certain level. The difference, however, is that not the WIP in the entire production line is considered, but the WIP in the line until the bottleneck. This method can be supported by bottleneck cards that regulate the release of orders (Lödding, 2013, pp. 347-349).

If multiple bottlenecks are present (which is the case for COMPANY A), multiple variations to the method can be chosen (Lödding, 2013, p. 350):

1. Only consider the WIP of one workstation.
2. An order is released if the WIP of all bottlenecks falls below a certain value. So, for an order to be released, it needs bottleneck cards from all bottlenecks.
3. The order is released if the WIP of any of the bottlenecks falls below a certain value. So, one bottleneck card is enough for an order to be released.
4. The sum of the WIP before all bottlenecks is added. If this WIP falls below a certain value, the order is released.

Bottleneck control prevents bottleneck starvation (as outlined in the ConWIP section), which is a big advantage of bottleneck control (Hopp & Spearman, 2008, p. 504). Conditions to implement bottleneck control are similar to ConWIP. Though, a clear bottleneck must be present in the production, in order to make it work. If so, the output rate can be higher than ConWIP, with a comparable WIP level (Lödding, 2013, pp. 358-359).

Bottleneck control was implemented in a large multinational enterprise. The enterprise provides structures for vehicles (the name is not mentioned in the article). The implementation proved to be successful as the total work content was reduced by 56%. (Darlington, Francis, Found, & Thomas, 2014).

3.1.4 Concluding remarks

In this section of the chapter, the main constructs of planning and control have been explained. The constructs should always be considered when constructing a planning. Therefore, these constructs have been applied to the situation of COMPANY A and product A. In addition, some approaches have been outlined. There are numerous other approaches and variations on the mentioned approaches. Most of them are outlined in the book of Lödding (2013). Due to time constraints, not all of them can be analyzed. The base approaches are summarized in the following table:

Table 6: Summarizing the main planning and control approaches within this thesis.

Planning approach	**Main idea**	**Main advantages**	**Main disadvantages**	**How to use**
MRP	Schedule when each part should be produced, based on back-scheduling.	1. Provide key link between dependent demand of parts on independent demand of the main product. 2. Determine exactly when, what, and how much is required.	1. Uses push-control which is usually outperformed by pull control. 2. Is more difficult to optimize since the parameter is not directly observable. 3. Needs additional systems to make feasible plans.	MRP-tables or including it in an ERP-system. Based on inventory records, demand forecasts, and bill of materials activities are scheduled in advance.
Kanban	Regulate WIP between two departments.	1. No growing WIP between stages. 2. Less variability. 3. Flexible for disruptions. 4. Relatively constant cycle times.	1. Multiple parameters need to be set for every workstation. 2. Pacing stress for workers. 3. Small product mix possible. 4. Not suitable for small infrequent jobs 5. More blocking of jobs between departments.	Kanbans (usually cards) regulate the flow of products. Every department has a certain amount of Kanbans. Production may only start if Kanban cards are present. Kanbans are released when the next department starts an order.
ConWIP	Remain a constant WIP in the entire system.	1. Robustness. 2. Only one parameter needs to be determined. 3. Less pacing stress (regarding station-specific approaches). 4. Can cope relatively well with fluctuations in volume and product types.	1. Bottleneck starvation. 2. Premature releases. 3. Only suitable if utilization is high.	Release a new order when the WIP-level in the system falls below the limit.
POLCA	Regulate WIP between two manufacturing cells.	1. Suitable for non-repeat production. 2. Steady utilization.	1. Multiple parameters for each manufacturing cell. 2. Lower output than approaches with individual load limits.	POLCA cards regulate the flow of products. POLCA cards allow production in a cell to start. The cards remain attached to the product until the cell finishes its production.
Workload Control	Set WIP-limits per department, including direct and indirect WIP.	1. Steady utilization. 2. Designed for MTO environment. 3. Control lead times. 4. Control non-repeat production and variable routings.	1. Multiple parameters need to be set for every workstation. 2. Lower output than approaches with individual load limits. 3. WLC paradox. 4. Variability in the input and output of the system.	An order should be released if the WIP account falls below the department-specific WIP limit. This WIP account considers direct and indirect WIP.
Bottleneck control	Remain a constant WIP up until the bottleneck in the production.	1. Similar advantages as ConWIP. 2. No bottleneck starvation.	1. Clear bottleneck should be present.	Release a new order when the WIP-level in the system up until the bottleneck falls below the limit.

It seems to be that pull-control methods usually outperform push-control methods according to literature. Therefore, considering the methods that try to integrate pull-control in the production are an interesting alternative for any organization that is currently using push-control. The methods mentioned are quite straightforward when implemented with the right parameters. But it is the determination of parameters, rules, and practical consequences what makes the implementation of pull-control difficult, together with explaining it to the shop-floor.

There are numerous articles about the effects of different planning and control approaches. These included queueing models, simulation models, DP-models, etc. However, this is the theory. As mentioned, for every approach I tried to look for implementation in practice. It turned out that there are little articles about the implementation of these methods. In my opinion, much more research should be done about the practical effects of planning and control approaches such that their effect is also proven in reality. Moreover, it should be researched if the theoretical assumptions still hold in practice.

To conclude, there is no ‘one-size fits all’ planning and control approach. Moreover, even though multiple articles, like for example the article of Stevenson, Hendry, and Kingsman, attempt to link preferred characteristics to a planning method, the choice for a method is not that straightforward. It needs thorough consideration of what the effects of each method will be, preferably with testing it in a model before implementing it. This is exactly what will be done in this thesis. The consideration of each approach will be discussed in the next chapter, whereas the simulation model will be outlined in the following chapters.

3.2 A simulation study

In this section, some key-concepts of simulation studies will be outlined. The goal of this chapter is to provide a quick overview of the relevant subjects for this thesis regarding simulation. This section does not outline a complete simulation study guideline. It highlights a few of its components. For a complete overview of all the steps of an entire simulation study, I refer to the books of Robinson (2014) and Law (2015). The approaches outlined in this chapter are also from these books. The books from Robinson and Law are seen as ‘bibles’ for a simulation study. As an additional source, the lectures and tips from Dr. Ir. M.R.K Mes are used. In addition, in this chapter, only a few examples of techniques and approaches are outlined whereas in literature numerous other approaches are present. Furthermore, definitions and techniques will not be described in detail. For techniques, only their purpose and main guidelines will be described.

First, an elaborate definition of a simulation will be given, to explain what the concept includes:

“Simulation is the process of designing a model of a system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system” (Shannon, 1975).

To supplement this definition, simulation involves an imitation on a computer, as it progresses through time. In literature, multiple other definitions are described. However, I believe that this definition includes most concepts of simulation.

3.2.1 Simulation model types and programs

Simulation can be done in different ways. Therefore, multiple types and programs have been developed over time. There are numerous simulation model types. Some examples are described by our lecturer, Dr. Ir. M.R.K. Mes (2018):

Table 7: Different simulation types.

Simulation type	**Definition**
Discrete event simulation	An approach for modeling queueing systems. Entities (e.g. patients, products) flow from one activity to the other. If entities arrive at a faster rate than the processing time, queues build up.
Agent-based simulation	Using agents with individual behavior, that interact over time to see if patterns emerge.
Monte-Carlo simulation	Using a set of input distributions, in order to determine some output. Especially useful for finance.
Continuous simulation	If variables change continuously over time, based on differential equations (e.g. water levels, cars moving on a road).
System dynamics	Systems are modeled as stocks and flows. Flows adjust the level of stock whereas stocks are the entities. This is a continuous simulation.

These simulation types can be programmed in multiple simulation programs. There are numerous simulation software packages present. There is no 'best software' package. This depends on the type of simulation, its purpose, the experience of the modeler, and several other factors.

3.2.2 Describing the model on paper: conceptual modeling

When doing a simulation study, the modeler should not directly start coding. Usually, a lot of preparation is done before a computer is used. One of these things is conceptual modeling. Based on the simulation type, a conceptual model is made. A conceptual model is a non-software specific description of the simulation model, usually defined as the paper-model. Robinson (2014, pp. 96-118) made a framework for a conceptual model. The conceptual model consists of five main parts:

- *The problem situation*
  The problem should be understood by the modeler. This is like multiple other problem identification methods, as outlined in Heerkens and van Winden (2012) or Cooper and Schindler (2014).
- *The modeling and general objectives*
  The conceptual model should include the objectives of the problem-owner. According to Robinson (2014, pp. 100-102), three aspects should be considered by determining the objectives. Namely, the wish of the client, the level of performance, and the constraints.
- *The inputs*
  The model's input are the experimental factors. The factors that will be experimented within the simulation model.
- *The output*
  The output are the KPI's on which the different scenarios will be compared.
- *Identifying the content*
  The model's content are the details of the model, the assumptions during modeling, and the simplifications. Simplifications are made for more rapid model development, whereas assumptions are made in order to fill gaps in our knowledge.

To conclude, the conceptual model basically describes all the contents of the simulation model, such that any modeler with an arbitrary suitable simulation program can program the model. Usually, the conceptual model is changed during coding or when discussing it with key stakeholders. So, usually, the conceptual model will change as the simulation study progresses (Robinson, 2014, p. 109).

3.2.3 Verification and validation of a simulation model

When the paper model is implemented in a computer model, it is not necessarily accurate for the purpose at hand. To check this, the model should be verified and validated. Verification and validation basically determine if the simulation model is an accurate representation of the actual system being studied. Verification tries to determine if the paper model has been translated into a computer model accurately enough. Validation tries to determine if the simulation model is an accurate representation of the system, for the particular objectives of the study (Law, 2015, pp. 246-247).

For verification, three methods are outlined (Robinson, 2014, pp. 254-260). Namely, checking the code, visual checks, and inspecting output reports.

For validation, multiple types of validation are described in the following table:

Table 8: Different validation approaches.

Type of validation	**Meaning**	**Methods**
Data validation	Data validation is based on sufficiently accurate content, assumptions, and simplifications. In other words, is the conceptual model detailed enough (Robinson, 2014, p. 254)?	General data-gathering and analyzing techniques.
Conceptual model validation	"Determining that the content, assumptions, and simplifications of the proposed model are sufficiently accurate for the purpose at hand" (Robinson, 2014, p. 254).	Have conversations with subject-matter experts (Law, 2015, p. 256). Circulate the model among those who have a detailed knowledge of the system.
White-box validation	Just like verification, white-box validation checks little parts of the model. However, white-box validation checks if parts of the model represent reality with sufficient accuracy, whereas verification checks the model against the paper model.	Checking the code, visual checks, and inspecting output reports (Robinson, 2014, pp. 254-260).
Black-box validation	Black-box validation considers the overall behavior of the simulation model (Robinson, 2014, pp. 260-263).	Compare to real-world or other models, if the real situation does not exist (Law, 2015, pp. 256-257).
Experiment validation	Experimentation validation is about the procedures taken for providing the results. In order to acquire sufficient results, the warm-up length, number of replications, and run-length will be determined (Robinson, 2014, p. 254).	See next section.
Solution validation	Compare the solution model to the implemented solution in the real world (Robinson, 2014, p. 254).	Similar to black-box validation.

Validation makes sure that the model is an accurate representation of reality or problem at hand such that the eventual conclusions make sense and are substantiated.

3.2.4 Experimental set-up within a simulation model

When the model is validated, experiments can be run. However, the model is not ready to directly run experiments yet. For this, the experimental set-up must be determined. But first, it will be explained why this is necessary.

Simulation output

The output of a simulation model is stochastic. This simulation output can be transient or steady-state. With transient output, the distribution of the output is constantly changing. With steady-state output, the output is changing according to some fixed distribution. Steady-state output is 'moving around' a certain value (Law, 2015, pp. 491-492). Next to these two familiar output types, other types have also been identified, like steady-state cycles and shifting steady-states. I will not describe these, but they are a variation of the main types (Robinson, 2014, pp. 368-371). Next, a simulation can be terminating or non-terminating. A terminating simulation stops at a natural endpoint. For example, a supermarket closes at the end of the day. A non-terminating simulation does not have such a natural endpoint (Law, 2015, pp. 491-493).

Usually, it takes a while before the model is in a steady state. For example, when a simulation is started there is no WIP in a production hall, whereas, in reality, WIP is present. This is the so-called initialization bias. In order to obtain accurate simulation results, multiple actions should be taken. Usually, simulations try to obtain an accurate estimate of mean performance. To acquire this, the initialization bias should be ignored, by determining the length until the model is in steady-state and removing data obtained in this period (warm-up period) or by setting initial conditions.

In addition to removing the initialization bias, sufficient data should be acquired such that a proper estimate can be calculated. Sufficient data can be acquired by multiple replications or a single long run. With multiple replications, the model is run multiple times with different random number streams, such that the sequence of random events also changes (Robinson, 2014, pp. 173-174). For both methods, the run length should be determined. By using replications, the replication run-length should be determined. Likewise, for a single long run, the length of this long run should be determined. For a terminating simulation, the run-length does not have to be determined since this is determined by a natural endpoint.

Dealing with the initialization bias

As mentioned, the initialization bias can be removed with a warm-up period or by setting initial conditions (or a combination of the two). A warm-up period can be determined with multiple methods. Hoad et al. (2010) identified 44 different methods and classified them under five headings

- Graphical methods: involving visual inspection of time-series together with subjective judgment.
- Heuristic approaches: simple rules for determining the period.
- Statistical methods: statistical principles for determining the period.
- Initialization bias test: iterative ways together with other methods to determine the period.
- Hybrid methods: a combination of methods.

Not all approaches are equally good. The marginal standard error rule (MSER) performed consistently well. In addition, it does not rely on assumptions, parameters or complex calculations (Hoad, Robinson, & Davies, 2010). The aim of the MSER is to minimize the width of the confidence interval of the mean by deleting initial observations. The MSER value can be calculated as follows:

$$MSER(d) = \frac{1}{(m-d)^2} \sum_{i=d+1}^{m} \left(Y_i - \bar{Y}(m,d)\right)^2 \qquad \text{Equation 1}$$

Where d is the proposed warm-up period, m the number of observations, and $\bar{Y}(m,d)$ the mean of the observations Y_{d+1} to Y_m. The MSER value is calculated for every value of d up until m-5, so the last five values are not used. The value for d that minimizes the MSER value, is the warm-up period. If this value is higher than half of the used days, the conclusion for the warm-up period is rejected.

If a model has more than one output (KPI), the warm-up length should be determined for every output. The maximum warm-up length for each KPI should be chosen as warm-up length. Moreover, the warm-up period should also be chosen for every input (experiments). In practice, this can become quite burdensome. Therefore, the warm-up length should be overestimated a little bit (Robinson, 2014, p. 179).

As an alternative to a warm-up period, initial conditions can be set by identifying values in the current real system or by determining the values of the system after the warm-up period. Initial conditions can be useful if the runtime of the simulation model is quite long.

The run length and number of replications

After a method for removing the initialization bias is found, the run-length and number of replications should be determined. The aim of both is to obtain sufficient output data from the simulation model. The number of replications will first be discussed.

For determining the number of replications, Robinson (2014) outlined three methods:

1. *Rule of thumb*
   "At least three to five replications are performed" (Law & McComas, 1991). This rule shows that multiple replications should be run, however, it does not consider differences between models.
2. *Graphical method*
   With the graphical method, an X number of replications should be run. The number of replications should be plotted against a cumulative mean, for example, the average internal throughput time. The point where the graph becomes flat should be chosen as the number of replications.
3. *Confidence interval method*
   With the confidence interval method, the width of the confidence interval, relative to its average, should be sufficiently small. For this, a relative error should be determined which is usually 0,05. Eventually, the minimum number of replications for which the estimated relative error is smaller than the relative error (0,05) should be chosen. In formula form:

   $$n^* = min\left\{ i \geq n: \ \frac{t_{i-1,1-\alpha/2}\sqrt{S_n^2/i}}{|\bar{X}_n|} \leq d \right\} \qquad \text{Equation 2}$$

   Where n = the number of replications, t the value from the students t-distribution, S the standard deviation from the replications, X the average output data from the replications, i the replication number and d the chosen allowed relative error.

The run length of the simulation should be much longer then the warm-up period. According to our lecturer DR. IR. M.R.K. Mes: "Say at least 10 times longer (2018)". For determining the run-length, also a graphical approach can be used. This is similar to the graphical approach for the number of replications. In this approach, an X number of replications should be run (let's say 3-5) within the simulation model. The run-length should be sufficiently long. Eventually, the point where the graphs of the replications become flat should be chosen as run-length. This is like Robinson's method for the run-length (2014, p. 191). With the type of simulation determined, initialization bias removed, the number or replications chosen, and the run-length set, experiments can be run within the simulation model.

3.2.5 Comparing scenarios

When full experiments are run, the results need to be reported. This is based on reporting results of a single scenario, or reporting results of comparing scenarios.

Reporting results of a single scenario

Reporting results of a single scenario involves basic statistics. For this, the estimators of the mean, sample variance, sample standard deviation can be used. Moreover, confidence intervals of the mean should be constructed. A confidence interval of the mean is an interval in which the mean parameter lies, with a certain level of confidence. Other interesting values are the mode, median or percentiles. The number of observations are equal to the number of replications. Other parameters are the same as usual. These basic statistics are explained numerous statistics books, but also in simulation-specific books, for example, Law (2015) or Robinson (2014).

Reporting results of two or multiple scenarios

When comparing two or multiple scenarios, a modeler cannot simply say scenario X is better than scenario Y since the mean is higher (or lower, depending on the objective). This does not take variability and the number of used replications into account. Two compare two scenarios, two methods are mentioned in both Law (2015) as Robinson (2014). Both methods are based on confidence intervals.

If the same number of replications are used, and common random numbers within the simulation, the pairwise-t approach should be used. In this case, the observations (replications) are not independent. The formula:

$$CI = \bar{D} \pm t_{n-1,1-\frac{\alpha}{2}} \frac{S_D}{\sqrt{n}} \qquad \text{Equation 3}$$

Where $\bar{D} = \frac{\sum_{j=1}^{n}(X_j - Y_j)}{n}$ and $S_D = \sqrt{\frac{\sum_{j=1}^{n}(X_j - Y_j - \bar{D})^2}{n-1}}$. X_j are the replications of scenario X, Y_j are the replications of scenario Y, n is the total number of replications (equal for scenario X and Y), t the value from the students t-distribution, D the mean difference between scenario X and Y, and S_d the standard deviation of the differences.

If the same number of replications are used, and different random numbers within the simulation, the confidence interval for the difference between two means should be used. In this case, the observations (replications) are independent. The formula:

$$CI = \bar{X} - \bar{Y} \pm t_{2n-2,1-\alpha/2} \sqrt{\frac{S_X^2 + S_Y^2}{n}} \qquad \text{Equation 4}$$

With $\bar{X}$ the mean output data from scenario X, $\bar{Y}$ the mean output data from scenario Y, and S_x and S_y are the standard deviations from respectively scenario X and Y. The other variables are the same as the aforementioned confidence interval.

Three outcomes are possible, with the following results:

Table 9: Analysis of results from the pairwise-t approach or the confidence interval for the difference between two means method.

The confidence interval is completely to the left of zero	It can be concluded with a specified level of confidence that the true mean of scenario X is less than the true mean of scenario Y.
The confidence interval includes zero	It can be concluded with a specified level of confidence that the true mean for scenario X is not significantly different the true mean for scenario Y.
The confidence interval is completely to the right of zero	It can be concluded with a specified level of confidence that the true mean for scenario X is greater than the true mean of scenario Y.

Moreover, "the extent to which an interval misses zero provide additional information on the size of the difference" (Robinson, 2014, p. 214). There are multiple other approaches to compare two systems, but these will not be discussed here. For example, the two-sample t-approach is a test when the number of replications are different (Mes, 2018). In order to compare more than two scenarios, these tests should be compared for all scenarios. This can be done by doing pairwise comparisons between all scenarios.

3.2.6 Concluding remarks

Simulation can be done in multiple ways. First, the simulation should be described on paper such that the contents are described, understood, and agreed upon. This conceptual model should be validated and eventually be programmed within a computer program. Consequently, this model should be verified and validated. This can be done with multiple techniques. If the model is verified and validated, experiments can be run after the experimental set-up is determined. This experimental set-up is needed in order to acquire reliable results from the model. Lastly, the results from the experiments can be analyzed with statistical tests.

Chapter 4: Planning and control method selection for COMPANY A

In this chapter, KPI's for assessing a certain planning and control approach will be determined. Moreover, weights will be attached to these KPI's. Based on an assessment of opinions in literature, certain scores will be given for each KPI, for each planning approach such that eventually three planning approaches can be chosen to test in the simulation model.

4.1 Assessing and selecting production planning and control approaches

In the previous chapter, several planning and control approaches have been mentioned. In order to assess their applicability to COMPANY A, KPI's need to be determined. In a meeting with the project supervisor and director of COMPANY A, the following restrictions and four KPI's for a planning approach were selected.

1. System output/Throughput time

System output was defined as the number of finished products A per unit of time. This output should be high, preferably as high as possible. Planning systems try to increase this output. For example, bottleneck control systems are useful for increasing system output (Stevenson, Hendry, & Kingsman, 2005). Another important aspect is a constant output. The customer preferably has a steady supply of products instead of a fluctuating output. In this way, the customer can anticipate on the delivered products A.

The main goal of this thesis is to reduce the throughput time for product A. So, this goal should not be forgotten by the production planning method. A planning method can heavily influence the throughput time. For example, MRP-systems that not always generate feasible plans can lead to high WIP and long cycle times (and thus a longer throughput time) (Kanet, 1988).

Before continuing, COMPANY A and I proposed these two KPI's (and their weights) separately. However, if the throughput time reduces, system output per unit of time will increase (other factors constant), as shown by Little's law. Therefore, throughput time and system output more or less indicate the same thing. So these KPI's will be combined into one KPI with the added individual weights. This has been approved by COMPANY A.

2. Applicability and implementation to COMPANY A, including communication

This is also a non-compensatory criterion. The planning approach should be applicable to COMPANY A. However, there is a difference between the ease of implementation between the one and the other method. For example, the Constant Work In Process (ConWIP) is suitable for a general flow shop (where work travels in one direction, but jobs are allowed to visit a subset of work centers for limited customization), whereas the Kanban method is more suitable for a pure flow shop (where work travels in one direction through a sequence of work centers in a strict order). The applicability should be assessed (Stevenson, Hendry, & Kingsman, 2005) and compared to the situation at COMPANY A.

As described, the situation of COMPANY A can be described as a make-to-order company, with a product (line) layout, also called a pure flow shop. COMPANY A can be classified as a small to medium-sized enterprise (SME). So the applicability will be tested against these characteristics.

An important aspect of implementation, according to COMPANY A, is communication. The planning method should be understood by shop floor workers and people in the business office. It must be easy to explain and to work with. Next, for multiple methods, different parameters need to be determined. However, for some methods, this is more complex. For example, Kanban needs to determine parameters for every workstation. Since COMPANY A has so many workstations, multiple parameters need to be determined. ConWIP on the other hand only has one parameter for the entire system (Lödding, 2013). The complexity and amount of work determining these parameters will also be considered.

3. Adaptability

Adaptability is defined as the way the system can cope with changes in the environment. For example, a changing input in the system, a different day that products are delivered, changing capacity because of illness, breakdowns, etc. As mentioned by Slack, Brandon-Jones, and Johnston: "A planning and control system should be able to detect deviations from plans within a timescale that allows an appropriate response" (2013, p. 311). There is, however, a difference in how each method reacts. For example, a material requirements planning (MRP) system is not flexible in a dynamic environment (Rupp & Ristic, 2000), whereas POLCA is much more flexible to cope which such changes (Stevenson, Hendry, & Kingsman, 2005).

4. Utilization

Utilization is described as the actual output divided by designed capacity of a certain department (Slack, Brandon-Jones, & Johnston, 2013, p. 331). Utilization levels should usually be high. If the utilization is low, the machine or operator does not have much to do. An empty machine or an operator that does not have to do much, costs money. This idle time should, therefore, be reduced. However, utilization should not be too high. Because of variability in the process, a utilization that is too high can result in long waiting times (Slack, Brandon-Jones, & Johnston, 2013, p. 118). It can be assumed that a reasonable level of capacity is between 70-90 percent. It is also important to have steady utilization rates, such that the system can cope with this variability. This was also underlined by the director of COMPANY A. An example of a planning approach with an emphasis on utilization is paired-cell overlapping loops of card with authorization (POLCA) (Stevenson, Hendry, & Kingsman, 2005).

In order to assess their importance, weights have been added to the KPI's. The following weights have been chosen based on the meeting with the director and product A project supervisor. We want to have weights since they show a difference in their importance for COMPANY A.

Table 10: The chosen KPI's and their weights for COMPANY A.

KPI	Weight
System output / Throughput time	0,35
Applicability	0,30
Adaptability	0,25
Utilization	0,10

As mentioned, system output and throughput time combined have the highest weight. COMPANY A wants to maximize its product A output since it is almost certain that the customer will use all output. Increasing this or decreasing the throughput time was the initial goal of this project. Second, it has been decided to give the applicability the highest individual weight. The director and the project supervisor believe this is important in order to make a planning approach work. If the planning approach is not easily applicable to COMPANY A and the shop-floor, it will be of no use. Third, adaptability is seen as an important factor. Since the environment is changing, the planning approach needs to be able to adapt to a changing situation. Lastly, the utilization should not be too high or too low and stable.

Next to the KPI's and the weights, restrictions have been determined. These are non-compensatory criteria. The planning method should fulfill these in order to be chosen.

1. The priority rule should be first-in-first-out (FIFO). Orders are always processed in the sequence of their input for each department.
2. It should be applicable to COMPANY A. Recall that this is also a KPI. However, if the method is not applicable at all it should not be considered.
3. Data should be available. Some methods require data. This data should be present. There is no time to acquire any new data in this time period.

The KPI's, their weights and the restrictions help by choosing the eventual method to apply at COMPANY A. Eventually, two or three methods will be chosen to test in a simulation model.

4.2 Planning and control perspectives in literature

The outlined planning approaches will be scored on the four KPI's described above. This will be done on a scale of 1-10 (poor-good). Eventually, a weighted score will be given. This weighted score will provide an extra argument next to the other arguments for the choice of a certain planning method. For the simulation model, the weights will not be used since multiple KPI's can be tracked at the same time. Note that scoring of the different approaches is based on statements from literature and the description of the KPI's. However, the selection remains an individual assessment of me. Someone else might come up with different scores. Therefore, this method of selection is subjective. The impact of this problem would be reduced if scoring tables would be provided. In this way, people would use the same guidelines by scoring the applicability. However, due to time constraints, this is not done.

Scoring the MRP on the KPI's of COMPANY A

According to Petroni (2002), MRP has great potential to increase the productivity of the firm. By back-scheduling the MRP calculates when each department needs to do perform its activity, therefore finishing all parts as soon as possible. Thus, the output seems really promising. However, MRP-systems that do not always generate feasible plans can lead to high WIP and long cycle times (Stevenson, Hendry, & Kingsman, 2005) and thus longer throughput times (Little, 1961). In addition, as discussed in the previous section, it is believed that pull systems acquire a lower throughput time for a similar output. So, the output/throughput time of MRP is scored with a 7.

Since demand forecasts are quite predictable in the aircraft manufacturing industry, this aspect of the MRP will be quite reliable. Moreover, the number of orders per week can be agreed upon with customer X. Even though the customer sometimes still deviates from this plan, demand is consequently quite predictable. Moreover, the production of product A is quite standard and the bill-of-materials is quite small since only one ring needs to be attached. The MRP, therefore, seems applicable to the situation at COMPANY A. Preferably the MRP should be combined with an ERP system in order to make it work even better (Stevenson, Hendry, & Kingsman, 2005). However, MRP and ERP implementation seem to be quite difficult for small and medium-sized firms. Not many small and medium-sized firms implemented the MRP successfully (Petroni, 2002). Though, this was in 2002, now the MRP is a well-known concept in many companies. For example, the current planning method can be seen as an MRP-system (see *section 2.2*). Furthermore, a new ERP is currently implemented at COMPANY A, so this part might also be integrated into the new system. Because MRP seems applicable to COMPANY A, the applicability of the MRP system will be scored with an 8,5 even though Petroni (2002) argues that implementation is quite hard. Moreover, ERP/MRP is a well-known system for COMPANY A, whereas all other systems are new to the company.

One criticism of the MRP is its flexibility. As mentioned, a material requirements planning (MRP) system is not flexible in a dynamic environment (Rupp & Ristic, 2000) and needs constant updating. The MRP does not always provide feasible plans (Stevenson, Hendry, & Kingsman, 2005). To check this, other systems are needed. So, the applicability is scored with a 4.

Lastly, the MRP system does not adequately support capacity decisions (Stevenson, Hendry, & Kingsman, 2005). For this, additional systems are needed resulting in, again, a low score of a 4 for utilization.

Scoring Kanban on the KPI's of COMPANY A

As discussed, with Kanban and pull control, the exact amount is produced as requested by the customer (Slack, Brandon-Jones, & Johnston, 2013, p. 478). In addition, Kanban and pull control decreases throughput time and reduces inventories (*see previous chapter*), so the output/throughput time scores good (8) (Slack, Brandon-Jones, & Johnston, 2013, p. 478).

Since demand variability and the number of parts are low, and the batches of products A are large, the applicability seems suitable (Stevenson, Hendry, & Kingsman, 2005). In addition, production of product A is designed according to the one-piece-flow principle (moving one workpiece at a time between operations), which is an essential element of Kanban (Lödding, 2013, p. 183). However, set-up times are quite large for some departments at COMPANY A, which makes Kanban less suitable (Lödding, 2013, p. 183). Furthermore, just like with the MRP system, literature suggests that Kanban is hard to implement (Stevenson, Hendry, & Kingsman, 2005). However, when implemented communicating it is quite simple.
As outlined by Hopp & Spearman (2008, p. 502) determining the number of Kanban cards can be difficult since it has to be done for every station. This is especially difficult for COMPANY A where the number of workstations is quite large. In addition, multiple departments are surpassed multiple times which makes the situation even more complex. Furthermore, determining the number of cards in itself is fairly difficult. In literature, simulations are often used. This is again difficult since the number of cards for station i influence the number of cards for station i+1. Therefore, considerable experiments should be conducted. Lödding (2013) uses a different approach, but for this more data is necessary than is currently available at COMPANY A. Other books, for example Reid and Sanders (2013), use formulas. But usually, these are too simplistic or again too complex, which would need more data just like in Lödding's book. So, to conclude, determining the number of Kanban cards would almost require an entire extra thesis. So, despite all advantages when Kanban is implemented, the implementation itself is so hard that the applicability scores poor (4).

A critique of the Kanban system is the fact that it does not take varying processing times into consideration (Lödding, 2013). Moreover, Lödding (2013) argues that Kanban needs an extra system in order to be more flexible. Especially, if capacity is calculated on the small side. So, this part scores poor (4).

Kanban does not balance load as efficient as other approaches. Just like MRP, it needs other systems to determine the loads of departments, resulting in the same grade. Though, it delays the processing of materials for which no Kanbans are present. So, Kanban somewhat balances capacities but not as efficient as other approaches (Lödding, 2013, p. 198), resulting in a 6 for this part.

Scoring POLCA on the KPI's of COMPANY A

Since quick response manufacturing focusses on throughput time reduction, POLCA scores well on throughput time reduction. The analysis of Lödding (2013, p. 433) underlines this. Companies that implemented POLCA reduced throughput time considerably. However, Lödding (2013, p. 432) also argues that when order generation is not coordinated and the material flow is complex, approaches with a workstation-specific load balances will attain a higher output rate than POLCA. POLCA also causes more blockades within the process because it can refuse orders (Lödding, 2013, p. 424). So, this part will be given a 7.

POLCA is made for manufacturing in cells, with small batches, high routing variability and high product variety (Stevenson, Hendry, & Kingsman, 2005). Manufacturing of product A is not done in cells. In addition, none of the mentioned things are quite applicable to COMPANY A. Even though the production of Products A is according to one-piece-flow, which POLCA assumes. Furthermore, like with Kanban and MRP, the implementation is often problematic (Tubino & Suri, 2000). Again here, determining the number of cards is difficult. Since the implementation is so difficult, and the characteristics of COMPANY A are quite different as the desired characteristics for COMPANY A, this part scores poor (3).

Just like with Kanban, POLCA needs additional systems in order to be more flexible (Stevenson, Hendry, & Kingsman, 2005). It also does not consider processing time variability. Numerous control loops also make the system less flexible (Lödding, 2013, p. 432). Regarding flexibility, POLCA does not seem to differ much from Kanban, resulting in the same grade (4).

POLCA focusses on operating at 70%-80% of capacity (Stevenson, Hendry, & Kingsman, 2005). This is a good utilization rate to strive for. In addition, with POLCA the utilization rates are quite constant which. Therefore this part scores very well (9).

Scoring ConWIP on the KPI's of COMPANY A

ConWIP can provide greater throughput than Kanban (Spearman & Zazanis, 1992) since the Kanban systems blocks parts more often. As mentioned, pull control decreases throughput time and reduces inventories, so this KPI scores good (8,5) (Slack, Brandon-Jones, & Johnston, 2013, p. 478).

ConWIP can be applied if routes are constant and processing times are similar. The route should not be variable and quite short, so a pure flow-shop seems to fit the ConWIP approach (Thürer, Stevenson, & Protzman, 2016). Processing times are definitely not similar at COMPANY A. However, it is uncertain how big the difference should be. Furthermore, the route of COMPANY A is long. So, the ConWIP does not seem to fit the environment of product A. The implementation of ConWIP is quite easy since only one parameter needs to be determined. This is doable since the parameter does not have to be determined for each separate station and product, and thus no interdependency is present. Lödding describes multiple methods for this. However, one method requires Logistic Positioning with Logistic Operating curves, which is again a substantial task for which new data needs to be gathered. Another method is setting a WIP limit and slowly reducing it. This is doable in a simulation model. To conclude, the applicability is scored with a 7 since not all characteristics are suitable for the method but the implementation is quite easy.

Like many of the approaches, ConWIP needs an extra system to cope with backlogs (Lödding, 2013, p. 340). Moreover, it does not consider process time variability (Thürer, Stevenson, & Protzman, 2016). However, since the WIP is constant for the entire production line, the throughput times of the orders can be predicted quite well. Furthermore, the constant WIP is beneficial for COMPANY A since all WIP is stored in one place, no matter what stage of the production. So, this part is on the one hand like the Kanban approach, but it also has some additional advantages resulting in a 6.

Since ConWIP does not consider individual load balances but only load balances of the entire system, the utilization can be quite low for specific workstations. However, it is possible to extend ConWIP in order to balance the loads. Nevertheless, the utilization scores poor (4).

Scoring WLC on the KPI's of COMPANY A

The method's output is quite variable, which is not wished by COMPANY A (Stevenson, Hendry, & Kingsman, 2005). In addition, wrong estimates of the method can heavily influence the output of the system (Bertrand & Van Ooijen, 2003). However, in a study by Bertrand and Wortmann (1981), it was shown that the average throughput time was reduced by using workload control (Lödding, 2013, p. 380). Moreover, as mentioned in the previous section, Stevenson, Hendry, and Kingsman (2005) underline that empirical research projects reduce throughput time. Though, in theoretical reports, reductions of only a few percent or even an increase can be observed (Stevenson, Hendry, & Kingsman, 2005): the WLC-paradox. So, it is unsure what the real effect will be. All positive and negative effects combined, it was decided to score output and throughput time with a 5,5.

Stevenson, Hendry, and Kingsman (2005) consider WLC most suitable for a general flow shop and job shop in a make-to-order environment. It can cope with non-repeat products with variable routings. However, the situation at COMPANY A is more or less a pure flow shop environment with repeating products and one route. Moreover, the varying approaches and performance of WLC in every situation make the choice more difficult. Nevertheless, WLC is specifically designed for the MTO-industry. Another aspect for WLC, like Kanban, it is quite difficult to determine its parameters. Lödding (2013) again describes methods for which more data is needed. Considering the number of workstations at COMPANY A (again), this can become a tedious task. Moreover, another method is using simulation, which again would almost be another thesis since the parameters need to be determined for every workstation and there is interdependency between these stations. Using the same reasoning as with Kanban cards, since WIP limits are essential for the method's performance, wrong estimates can lead to bad performance (Bertrand & Van Ooijen, 2003). Lastly, next to determining the WIP-limits, WIP accounts need to be updated constantly with direct and indirect WIP. Since no system is present at COMPANY A that can do this, this will take a lot of time for a single employee to constantly update this account. Consequently, this will cost a lot of money. Taking everything into consideration, the applicability to COMPANY A is scored with a 3 since the characteristics of COMPANY A are not quite suitable for WLC, determining the WIP limits is difficult, and WIP accounts need to be constantly updated.

The flexibility of WLC seems promising: "unexpected changes to quantity and design specifications can be accommodated at less inconvenience" (Stevenson, Hendry, & Kingsman, 2005). In addition, the method stabilizes incoming orders, making it independent for variations. Therefore, the adaptability of WLC has been scored as high (8).

The aim of WLC is a steady utilization of workstations. Since this is the aim of WLC, this KPI scores well (9) (Lödding, 2013, p. 380).

Scoring bottleneck control on the KPI's of COMPANY A

Bottleneck control attains a higher output than ConWIP in multiple simulation studies. This output rate is higher if the bottleneck is at a later stage in the production line and the utilization of other workstations is quite low (Lödding, 2013, pp. 353-354). Though, it is uncertain if this is true for COMPANY A. Furthermore, bottleneck control concepts have improved throughput time in many cases. In the article of Mabin and Balderstone (2003), 59 out of 81 companies improved the throughput time. Their analysis shows that bottleneck control likely reduces the throughput time (Mabin & Balderstone, 2003). Combining all arguments, output and throughput time of bottleneck control has been scored with a 9.

Bottleneck control is only practical if there is a clear bottleneck in the production process. In *section 2.6*, potential bottlenecks have been analyzed. So this can be tested for COMPANY A.

Implementation, therefore, seems to be no problem. In addition, it is suitable for a pure flow shop (Stevenson, Hendry, & Kingsman, 2005). Determining the parameters for bottleneck control is similar to the CONWIP approach. In the basic bottleneck control approach, only one parameter needs to be determined, however for more complex bottleneck control approaches multiple parameters need to be determined. This will be more difficult because of interdependency. Since the characteristics of COMPANY A seem suitable for a bottleneck control, and parameter determination is not too difficult the applicability will be scored with an 8.

Just like with ConWIP, due to constant WIP, the order throughput time can be predicted quite well, resulting in high delivery reliability. In addition, the 'rope' communicates with prior activities such that they are not overproducing (Slack, Brandon-Jones, & Johnston, 2013, p. 313). However, bottleneck control does not have any systems for coping with backlogs, just like ConWIP (Lödding, 2013, p. 353). All in all, the adaptability of the system is similar for bottleneck control and ConWIP (6).

"If the non-bottleneck workstations of a production line are also highly utilized then the output rate advantage of Bottleneck Control disappears and ConWIP may even attain a higher output rate" (Lödding, 2013, p. 354). In other words, either the utilization of only the bottleneck is high and the utilization of the other departments is low or ConWIP is better and the utilization of the other departments are similar. Therefore, the utilization scores poor (4).

4.3 Comparing the planning and control perspectives

Based on the argument given, scores were given. These scores together with their weights resulted in the following weighted averages.

Table 11: The assigned scores and eventual scores for the potential planning approaches for COMPANY A.

	Output/Throughput time	Applicability	Adaptability	Utilization	Score
MRP	7,0	8,5	4	4	**6,4**
Kanban	8,0	4	4	6	**5,6**
POLCA	7,0	3	4	9	**5,3**
ConWIP	8,5	7	6	4	**7,0**
WLC	5,0	3	8	9	**5,6**
Bottleneck Control	9,0	8	6	4	**7,5**

As shown, MRP, ConWIP, and bottleneck control all have the highest weighted score. Due to time constraints, it has been chosen to only consider three planning approaches for COMPANY A. So, for COMPANY A, the performance of the top 3 will be tested within the simulation model. For this, the exact method will be outlined in the next section in order to apply it to COMPANY A.

ConWIP and bottleneck control score much better than the other approaches. As shown, most methods have been scored relatively high on increasing the output of the system, since it is the main goal of many approaches. However, the implementation for some approaches is difficult whereas for other approaches this is relatively easy. This is the main reason why ConWIP and bottleneck control score much higher than the other approaches. The choice of the top 3 is quite robust: increasing or decreasing any score in the table with 0,5 points will not change the choice of the top 3.

4.4 The planning approaches for COMPANY A

In this section, the three chosen planning approaches will shortly be explained for COMPANY A. The details of the approaches are a bit different when the three approaches will be applied to COMPANY A. In *section 3.1.3* sequential procedures of the approaches have already been explained.

MRP

The MRP is a bit different for COMPANY A. Product A does not consist of many parts. Therefore, the bill of materials is small since it only consists of two parts (a ring and inserts). So small, that it is not considered in this thesis. Moreover, demand is quite certain, and a weekly demand of approximately 18 products A per week can be assumed in this thesis. Therefore, the inputs of the MRP are available. But since the parts are not considered, the MRP-table only consists of an MPS table scheduling 18 products A per week. Currently, as described in *section 2.2*, the planning does the same. However, it uses week-to-week scheduling instead of just letting the parts move through the process. To improve the MRP even further, capacity requirements planning should be used, to check if the MRP plans are feasible and if enough work is scheduled. The MRP might be elaborated even more by using an ERP-system that is up-to-date.

ConWIP

ConWIP is also quite different for COMPANY A since it cannot pick up its materials from a warehouse and start producing, as is normally assumed in literature, it must order part quantities. However, when products A go out, new products A come in. The number of finished products A that will go out can be resupplied by reordering the same number of castings in order to remain the WIP at a constant level. Depending on when this order must be made, it should be estimated how much will be finished when the truck arrives. This estimate might be off one or two products A, resulting in a slightly higher WIP than allowed. These products A should be stored and not be taken into production, until the next order arrives. Within the ConWIP-system, any other system can be used. A ConWIP system would not make much sense if the current planning approach is used. To attain the required outputs for AC-type products A and B-type products A, both an AC-type WIP-limit and B-type WIP-limit will have to be set. Setting these WIP limits is quite difficult and should be considered with care. This cannot be done based on the current system since the production numbers are much lower. Therefore, setting the parameters will also be part of the simulation study.

Bottleneck control

Bottleneck control is like ConWIP, in the sense that it cannot pick up its materials and should order products A. Based on where the bottleneck is in the process, the order should be increased by one if a product A leaves the bottleneck department. Again, based on when the order must be placed, an estimate should be made of how many products A will be finished at the time when the order arrives. Again, for both types of products A, WIP limits will have to be set. Within the bottleneck control system, an MRP-system can be used. Setting the parameters and determining the bottleneck will be part of the simulation study.

4.5 Summary and conclusions for chapter 4

MRP, ConWIP and bottleneck control are planning approaches that seem to suit the environment of the production of product A. This is mainly because the implementation of these systems is relatively easy compared to other approaches. The MRP-model is actually like an MPS-model when applied to COMPANY A.

Chapter 5: The simulation model

In this chapter, the simulation model of this thesis will be described. This will be done by first making a conceptual model of the simulation model. This conceptual model will be implemented in a computer program. Lastly, the programmed simulation model will be verified and validated.

5.1 The conceptual model

This section describes the conceptual model of the simulation model. This will be based upon the key concepts of a conceptual model, as described in the previous chapter.

5.1.1 Understanding the problem situation and objectives

Based on the outlined chapters above, a problem identification has been outlined in *chapter 1.* Moreover, in *chapter 2*, the production process, the planning, and all relevant characteristics have been determined. So, this step of the conceptual model has already been conducted.

Just like understanding the problem situation, the three aspects of objectives have also been described in *chapter 1* and *chapter 4*. Preferably, the initial goal was to reduce the throughput to four weeks (level of performance). However, the director believes that this will be somewhat higher in reality. This will be done by experimenting with multiple factors (which will be outlined in the next section) of which one is the planning and control method.

Lastly, multiple restrictions will be applicable to the simulation study:

1. The priority rule should be first-in-first-out (FIFO). Orders are always processed in the sequence of their input for each department (as mentioned).
2. The WIP level should be within a certain boundary. In that sense, that it is no hard restriction, but WIP levels should be plausible in practice.
3. The run-speed should not be too long since multiple experiments with multiple replications and a significant run-length will have to be run.
4. The simulation model should be easy to understand and to communicate. So visualization is an important factor.

5.1.2 Scope of the simulation model

This section will describe the experimental factors and reports from the simulation model.

Inputs (experimental factors)

Using the simulation model, multiple experiments will be conducted, all related to planning and control. There are multiple levels with different factors. Making all combinations will be too much to experiment with. However, to solve this, one-factor-at-a-time method (OFAT) will be used. By using this method, factors will be varied per level and the best factor per level will be selected. The results, however, will not be completely reliable since factors influence each other: the so-called interaction effect. It will be assumed that the interaction between experimental levels will be minimal and will therefore not be considered. However, as mentioned, this is actually not true.

- **Production planning and control methods, with different parameters**
    - The current ‘weekly’ planning as outlined in *section 2.2,* this is the base model.
    - MRP-model.
    - ConWIP control.
        - For this model, the optimal card number will first be determined.
    - Bottleneck control.
        - For this model, the optimal card number and optimal bottleneck will first be determined.

How the different models are programmed, will be outlined in *section 6.2.*

- **Influence of transports once or twice per week and the optimal transport days to the outsourcing company.**
    - First: transport once per week and the optimal day.
    - Second: transport two or three times per week and the optimal combination of days.
- **Influence of fluctuating delivery numbers and intervals from the customer.**
    - First: influence of fluctuating delivery numbers
    - Second: influence of fluctuating delivery intervals
    - Third: influence of fluctuating delivery intervals and numbers
    - Fourth: influence of little fluctuating delivery intervals and numbers.
- **Adding extra machines**
    - Comparing scenarios for adding an extra Machine 1 (turning and milling).
    - Comparing scenario for adding an extra Machine 2 (grinding).
      Since an extra machine is added, the working-shift of these machines can also be adapted. Based on the change in shift, different scenarios will be outlined and compared.
- **Influence of transports once or twice per week and the optimal transport days to customer X.**
    - First: transport once per week.
    - Second: transport two or three times per week and the optimal combination of days.

Outputs (reports)

Based on the different experiments, different outputs are interesting to analyze. However, the main KPI's on which the models will be compared are:

- Internal average throughput time: the total time from the arrival of a product A up until it is finished, minus the two weeks of outsourcing. Though, waiting for the truck to outsourcing is included in this time.
- Internal average throughput time incl. THE OUTSOURCING COMPANY: the total time from the arrival of a product A up until it is finished, including the two weeks of outsourcing.
- Total average throughput time: the total time from the arrival of a product A up until it is back in the truck to customer X.
- Average daily WIP: the average daily WIP level, updated every day.
- Total output: the total output acquired during the run time.
- Weekly output: the average weekly output, measured every week.
- Weekly AC-type output and weekly B-type output: the average weekly output for each type (AC-type and B-type products A), measured every week.

The output is interesting in order to compare the different simulation scenarios. For example, the model acquires a much lower total throughput time if the output is only 12 products A per week instead of 18. Therefore, the output numbers should always be similar. In addition, the ratio AC-type:B-type should also be similar to analyze the results. The total process time of the AC-type is much shorter. So, a scenario is automatically performing better if more AC-types are scheduled.

Other interesting KPI's, dependent on the experiments are:

- Waiting times for a product A (based on potential bottlenecks)
    - Average waiting time for THE OUTSOURCING COMPANY (so waiting for the truck to the outsourcing company)
    - Average waiting time in front of Machine 1
    - Average waiting time in front of Machine 2

    - Average waiting for deburring
    - Average waiting for the delivery truck to customer X
- Occupations of machines (based on potential bottlenecks)
    - Machine 1 machine
    - Machine 2 machine

For example, it is of not that relevant if the Machine 1 occupation is included in an experiment about a transport-day. Though, it is quite relevant if an extra Machine 1 is added.

5.1.3 The model content

In the model content, the scope, assumptions, and simplifications will be discussed.

Scope and details of the base model

The following things will be included in the base simulation model. This model will be used as the base scenario, in which each level of experimentation will be executed.

- The **production route** as described in *section 2.1.* A simplification is made regarding the order of routes. The route is fixed for each product A type and there will not be deviated from this route. In practice, a different order is sometimes applied. The route for product A AC and B will be different, as described. The processing time on the Machine 1 for type AC will be longer and type AC will skip the processes sandblasting and assembly of inserts.
- The weekly **planning** as described in *section 2.2* will be used. So, products A also move from week-to-week. A weekly trigger moves products A that are finished to the next production chain in the planning. Therefore, products A that did not finish their week-to-week planning remain in the production chain for another week.
- The **processing times** as described in *section 2.3*.
- The **demand** as described in *section 2.4*. It will be assumed that based on this demand, a certain weekly quantity will be delivered to COMPANY A. However, for 2019, the situation will be a bit different. Since the demand in 2019 will not be acquired (as explained in *section 2.4*), it is assumed that the weekly demand will start after 26 weeks. So, for the first 26 weeks, the delivery quantity of 2019 will be assumed. Moreover, for 2019, this weekly demand would be 16 instead of 18. It is believed that this will only disturb the obtained values from the simulation model. Therefore, for 2019, also a weekly demand of 18 is assumed. Product As will be delivered as different types. These types will be defined within the model. The ratio is 1:3 since six AC-types will be delivered and twelve B-types will be delivered weekly.
- The **delivery day** is assumed to be on Monday at 13:00. It is assumed that the truck will be unloaded with castings and loaded with finished products A at the same time.
- All **relevant data** per product A will be stored in a table in order to calculate KPI's and analyze the outputs. Moreover, also daily statistics and weekly statistics will be stored in order to calculate the weekly and daily statistics. Depending on when possible KPI's need updating, KPI's are updated. For example, when a product A leaves to THE OUTSOURCING COMPANY, the internal WIP will be updated. When a day ends, the daily stats will be updated, etc. This is all based on using functions on the tables that store the data, just like you would do in Excel files.
- One out of ten products will be **inspected on its cleanliness**. This cleanliness test will usually take 90 minutes and does not depend on product A type. This is done by checking for every entry in the cleanliness inspection if it is a multiple of ten. If this is true, product A moves to the cleanliness test. If this is not true, it moves to the assembly of inserts (if it is a B-type) or the final inspection (if it is an AC-type).

- **Shifts** have been included in the model. All departments initially have a normal office shift from 7:00 till 16:00, Monday to Friday with breaks (9:15-9:30, 12:00-12:30, 14:30-14:45). The Machine 1 has an adapted shift of 24 hours, including Saturday, without breaks since the programs can run while the operator can take a break. This is not completely true, for example when a program stops during a break. But this does not happen often, and if it happens the production will only be delayed by a few minutes which is included in the variation of the processing time. Furthermore, the machine 2 (grinding) has an extra working day on Saturday with the same working hours as a normal day. The Machine 1 and Machine 2 have these shifts in order to cope with the specified demand. If the capacities are not increased, the WIP will build up infinitely high in front of these machines. Consequently, throughput times will also become longer. With these numbers, the models cannot be analyzed, so a certain capacity should be assumed. These shifts differ from initial capacity analysis. This difference will be explained in the side note at the end of this section.
- **Deburring** is combined in one cell. Products that have finished turning and milling (P60) and grinding (P140) will enter this cell. This is done since waiting times will be longer if deburring is combined into one department instead of two separate departments. Moreover, based on where the products come from, the process times will be defined. If the products come from the Machine 1, the process times will have a gamma distribution, whereas products that come from the Machine 2 will have a triangular distribution (as described with the parameters of *section 2.3).* This is because deburring after turning and milling takes much longer than deburring after grinding. The deburring department has two operators present, that work in a normal shift.
- **Outsourcing** is included in the model. The products leave on Monday at 8:30. The products that go to THE OUTSOURCING COMPANY for the first time and for the second time are stored in the same queue, such that all products leave at the same time. Next week, the truck comes back and delivers the products to COMPANY A. Based on the number of times they are outsourced already, product As will continue their route. After the first outsourcing, products will continue with P120, whereas after the second outsourcing products will continue with P200.
- The production processes all have one **operator or machine** during their shift, except for the deburring department where two operators are present (and thus two toolsets).
- The **machines cannot pause their activity** if a shift interrupts this activity. In practice, this results in the fact if it is late in the afternoon, an operator will likely not even pick up a new product A. Therefore, it is assumed that the Machine 2 operator will not pick up new products A after 14:00, since its shift ends on 16:00 and its average processing time is 2 hours and 18 minutes. So, after 14:00, the entrance of the machine 2 is locked. It could be, that the machine 2 is still processing after 16:00. For example, when the operator picks product A on 13:45, and the processing time is longer than 2 hours and a quarter. In that case, it is assumed that the operator will finish its activity in overtime.
  The same idea has been programmed for sandblasting. Though, for sandblasting the entrance is locked after 14:35 since its average processing time is 75 minutes.
  This idea has not been programmed for the Machine 1. This is not completely true, as will be discussed in the simplifications.
- If the truck arrives at 13:00 (Monday), **all products A will first be unloaded**. Moreover, all administration (P10) will be done for all products A. After this, product As will move on one-by-one.
- If departments are empty, a **set-up** time will be assumed. The Machine 1 has a set-up time of 90 minutes if it is empty. If the Machine 1 is not empty, no set-up time will be assumed since

the operator can set-up the machine while the program is running (*section 2.3).* Any other departments have 15 minutes of set-up time if it is empty. This set-up time can be anything, from signaling the operator, to getting the tools, looking for documentation, etc. This set-up is not assumed when the operator is already working on a product A since the operator is at its place, with the tools.

Other simplifications

- Production route is fixed. There will not be deviated from the initial plan, as mentioned.
- Move times are included in the process times. These will not be modeled as separate set-up times. In addition, set-up time for the Machine 2 and Sandblasting, next to getting the tools, documentation, etc. are included in their process time.
- In the model, putting products in the truck is done before the truck arrives. This is, of course, not possible. This is because this production step also includes some sort of material inspection next to loading product As. However, the main reason this is done, is because during loading no new products will enter the THE OUTSOURCING COMPANY-queue. This is not allowed. Only products that are finished when the truck comes will be loaded. This is also the reason that the truck is only present for one minute in the model, and the dwell time for the queue is one minute.
- Departments like cleaning, inspection, etc. that are actually not separate departments are modeled separately. This is done for three reasons. First, because the processing times are relatively short and utilization is low. Therefore, waiting times are low in front of these departments, even if they would be combined. Deburring is combined since the processing time is quite long and utilization is quite high. Therefore, the waiting time is also much longer in front of the deburring department. Second, the model will be difficult to follow if all departments are anywhere in the model. This will decrease visualization drastically. Third, modeling this takes some time. So, not combining these departments will result in more rapid model development.
- Weekly demand will be fixed as explained in the model contents. This is still fluctuating just like the delivery intervals. However, COMPANY A wants a steadier supply of customer X in the future. One of the purposes of this model is to show what kind of effect the fluctuating quantities and intervals have.
- Holidays (2 weeks) are not modeled. Product As that are in the process at a holiday time will have a longer throughput time. This is not modeled since it would only disrupt data. In reality, this does not matter that much since during the holidays the entire company is closed and no new products A will be delivered. Moreover, maintenance, failure, and repair to machines are not taken into consideration. Since product A is quite new to COMPANY A, data about these subjects are not that accurate yet. Moreover, failures are still quite unpredictable. Therefore, modeling these would only disturb the model. Later, when failures occur in a more frequent pattern, it will be easier to model maintenance, failures, and repairs such that it can be included. To cope with these variations, departments should not have a utilization higher than a certain value. A rule of thumb is that utilization should be between 70%-90%. As discussed with the director, the value has been set to 85% for COMPANY A. This is, in my opinion, still quite high.
- The machine 2 and sandblasting are locked late in the afternoon (as explained), however, the Machine 1 is not. This is because the throughput time of the Machine 1 can be divided into separate programs (*section 2.3).* So, it is assumed that if it is late in the afternoon, the operator will likely use a shorter program instead of a long program.
- Sandblasting is done in-house. This is currently not the case, however, soon it will be done in-house so it is reasonable to assume that this will be the case.

Assumptions

- Product As have a prioritization. Multiple departments are also busy with other products. It is assumed that when a products A comes to these departments, they are immediately processed, except for the set-up time when the department was empty. In reality, this is different because products A are often waiting to be processed since departments are still working on other products. Probably, the set-up time would, therefore, be longer.
- There are no production errors. Products are always finished according to the normal production route. No extra repairs, assessments, or inspections are necessary. So, in the model, no delays will be observed due to production errors. Moreover, no products A will become scrap because they are too severely damaged. Therefore, the input is equal to the output (except in the end since there are still products in the WIP). Of course, in reality, this is not true. But as mentioned, data about these things are still lacking.
- THE OUTSOURCING COMPANY (the outsourcing company) can handle any batch size, as long it is a reasonable batch size. Moreover, they can also handle fluctuating numbers. In reality, a company would have a certain maximum batch size that they can produce in a week. However, it is not known how much they can process. Therefore, it is assumed that THE OUTSOURCING COMPANY can handle any number, as long as it is realistic. In addition, in reality, a company would also have a lot of trouble with handling constant fluctuating batch sizes.

Side note

The shift for the machine 2 of the model is different from the calculations made in *section 2.5.* As starting values the numbers of the capacity analysis were used. As it turned out, the Machine 2 could not cope with the required amount and the model would “explode”. Therefore, the shift was increased by also working a full day on Saturday. The machine 2 could not cope with this demand in the simulation model since it is locked after 14:00, leaving even less available hours than initially considered.

Moreover, the utilization output is different in the simulation model. Where does this difference come from? As mentioned, the simulation model does not take into consideration holidays, non-operating days, maintenance, and other efficiency issues. The capacity analysis did, therefore resulting in higher utilization. As mentioned, to cope with this difference, it is assumed that machines are not allowed to work on a utilization higher than 85%, which is still quite high.

Lastly, “variability in a process acts to reduce its efficiency” (Slack, Brandon-Jones, & Johnston, 2013, p. 117). The simulation model takes into consideration variability of process times, while the excel-sheet does not. This is another reason for the difference in utilization numbers.

Flow charts

In *appendix D.2,* flow charts are displayed. These flow charts explain some basic logic behind some coding within the simulation model since sometimes a flow chart says more than a thousand words. However, some things are just easier to explain than draw. This was the case for some parts of the model. This explanation is already included in the *model content* of this chapter. Lastly, some of the coding seems simple in hindsight. Though, most codes include a lot of trial-and-error, taking days before they finally worked. Furthermore, in the program, they are a bit more complex than displayed in the flow charts. The flow chart about the planning approaches will be explained in *section 6.2.*

5.2 Implementation, verification, and validation of the simulation model

In this section, the paper model will be translated into a computer model. After this is done, the simulation model will be verified and validated.

5.2.1 Implementation of the simulation model

The conceptual model has been coded in a discrete event simulation-type. The program that is used, is Tecnomatix Plant Simulation, developed by Siemens PLM software. Plant Simulation was chosen since it was taught to us during our bachelor-education. In addition, the university provides the software for free to its students. I believe that other simulation programs would do just as good as Tecnomatix Plant Simulation. However, compared to other simulation tools, “Plant Simulation supports a flexible way of working with the model” (Bangsow, 2016, p. VI). The following model has been coded:

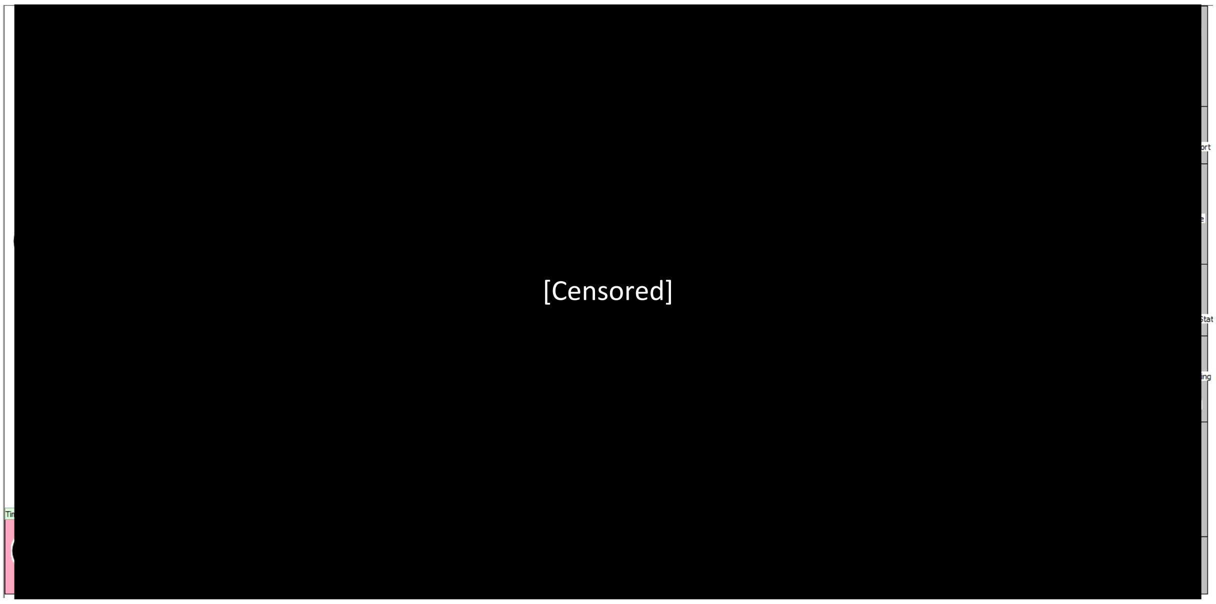

Figure 3: Screenshot of the simulation model.

The contents of the simulation model already have been explained in the conceptual model. In this section, it will be explained what is simulated where. For a more detailed explanation, I refer to the model itself. All methods are explained step-by-step with pseudocode within the simulation model. Some extra screenshots of the model are provided in *appendix D.*

The white area (1) basically describes the production line. It is like the figure in *appendix B.3.* Every line within the simulation model is similar to the planning in that week. Only the deburring department and THE OUTSOURCING COMPANY are not displayed in that way since they need to be modeled as separate departments, as explained in the conceptual model. THE OUTSOURCING COMPANY is modeled in the yellow block (3), whereas the deburring department is modeled in the light brown box (2). Between every week, two queues are present. If a new week starts, products are moved to the next line. Trucks are displayed with truck icons. It was tried to display the simulation model according to the diagram in *appendix B.1* or according to the blueprint of the production hall. In my opinion, this made the model only more complex, so this idea was abandoned.

The pink area (4) shows a lot of KPI’s. Most of these KPI’s will not be analyzed since they are not relevant for the research at hand. They were mainly programmed for coding purposes. In this way, the influence of new codes could easily be observed, which is part of black-box validation (see next section). The most relevant KPI’s are internal throughput time, total throughput time, average total WIP, weekly output, and total output.

Storing information, and all logic of the simulation model is basically present in the grey part of the model (8). In the tables, all relevant data is getting stored in order to calculate KPI’s, run experiments, and eventually analyze all results. Generators call a certain method at a specified interval. For example, the “GeneratorDay” stores data for every day. Methods perform all coding. They are called by processes, generators or buttons. The logic within the methods is explained in the conceptual model. Different methods have different functions, as displayed in the pseudocode.

The blue block (7) basically describes all shifts as explained in the conceptual model. Two shifts are a bit odd: the “THE OUTSOURCING COMPANYtruck” and “FinishedproductAsupports” shifts since they only take one minute, as described in the conceptual model. The green block (5) only contains the Eventcontroller that basically takes care of running the model. Lastly, the dark brown/orange box contains objects in order to more easily run experiments with the model (6). It can also obtain modifications to the base model. Displaying this in a separate frame immediately shows the changes to the model for that experiment.

5.2.2 Verification of the simulation model

The three methods for verification have been conducted continuously throughout the modeling of the simulation. During programming, a diary was kept in which every step was written down when it was coded. Parts were only written down if they were checked. In this way, every part of the model was verified. This checking was done by first writing down the code. Usually, this already gave some errors and the simulation was stopped. By using debugging and setting stoppers in the code, all problems were solved. However, sometimes the model did not give an error, the simulation continued, but it did not do want I wanted it to do. Again, stoppers and debugging was used to solve this.

If everything ran smoothly, the model was visually checked in order to check if the flow of the products was going right. For this, debugging was used. By using this, you stop the process, predict what will happen, and check if it happens. If this was not the case, the model was changed. This was specially done for departments that are more difficult to code, like THE OUTSOURCING COMPANY.

After all KPI’s had been modeled, the results could be checked. This was done in an early stage of modeling, such that this could also be checked. Sometimes, extreme or wrong values were observed in the tables. This was not observed when the KPI’s were not modeled. For example, in this way, it was discovered that the THE OUTSOURCING COMPANY truck should not be present in the model longer than a minute because otherwise products A would quickly ‘jump’ into the truck, which is not allowed.

To conclude, I think the paper model is translated into a computer model accurately enough to continue.

5.2.3 Validation of the simulation model

In this section, the simulation model will be validated with the methods outlined in *section 3.2.3.*

Data validation

Gaining data has been done *in chapter 2* of this thesis. During this phase, all relevant data for the simulation model was gathered from multiple sources. When collecting this data, multiple meetings with product A project supervisor and the director were planned. After every meeting, it was approved or disapproved to continue with the data. In this way, I knew if my data was right or not. Eventually, conclusions were drawn for all data. The director and project supervisor approved to continue with the chosen data.

Conceptual model validation

During several meetings with the project supervisor, the model content, assumptions and simplifications were discussed. These were the same meetings as in which the data was validated. Sometimes reality was too difficult to model, for example regarding the current unpredictable production errors. In such a case, an assumption was made. In this case, it was assumed to not consider these errors in the model. Eventually, step by step the conceptual model was created and validated.

Eventually, the conceptual model was given to the director of COMPANY A. For me, he should give a green light in order to continue with the model (or not). Two questions were asked, after he read the model, with the actual answers he gave attached to the questions:

Do you think the conceptual model (paper model) describes reality accurately enough?
"Yes, I am convinced that all steps would be made for an actual result of the daily operation. This will give Company A a clear and global vision on which we can improve ourselves. Further detail is not, for this moment, interesting."

Do you think the conceptual model (paper model) is useful for the problem at hand?
"The main problem is that the lead time is too long at this moment (9 weeks) with as result that too many Products A are in our WIP which takes too many operating space. Too reach eventually 18 – 20 Product A as delivery we need to get our lead time as short as possible. So yes, I am convinced that this conceptual model will be useful for the before mentioned problem."

To conclude, I consider the conceptual model validated.

White-box validation
For white-box validation, multiple things were checked. First, the timings were checked. Are departments taking as long as you would expect? This was difficult to model for the Machine 1 (turning and milling) and the deburring department since the processing time depends on characteristics of product A. Eventually, all throughput times seem reasonable. Second, the flow was checked. Especially for outsourcing and deburring. Third, the arrival numbers and delivery numbers were checked. Lastly, some extreme values were used, for example by delivering 30 products per week. It was checked if the model reacted as you would expect it to react, and it did. For example, stations like the Machine 1 and Machine 2 (grinding) could not handle this demand as you would expect.

Furthermore, during coding, an intermediate meeting was planned with the project supervisor and director. The model was shown, together with showing the flow of the products through the process. This was done by running the simulation slowly and explaining step for step what is happening at which time. The model still missed some details during this meeting, some of which I had already written down. When I asked which details needed to be included, multiple things were mentioned:

- Expedition and the business office first finish all products A in a batch (step 1 and 2). From there on, they move according to one-piece flow.
- Set-up time of 15 minutes for departments that are empty.
- Add WIP value as KPI, this is interesting to track.
- Delivery and acquiring time of the customer is on Monday at 13:00 instead of 8:00. The THE OUTSOURCING COMPANY truck will also come on a Monday, at 8:30.
- Deburring should be one department since this department is quite busy. You can leave the other departments as they are.
- Occupation of departments should be below 85% in order to cope with holidays, maintenance, etc.

- Machines cannot pause their work. If their shift ends, they will finish their current operation. Moreover, it is believed that they will not even pick up a new product A at the end of the afternoon since they will risk working in overtime.
- The model should be structured more nicely (visualization).

It was good to see that multiple things that I had already considered were also mentioned. These were added to the conceptual model later. Eventually, all these small things were added as extra details. Eventually, the following question was asked to the director:

Do you think that the products flow logically through the process? *"Every step made in the process is logically to reach the finished product. It is even impossible to do it in another way."*

To conclude, I believe that the separate parts of the model are accurate to describe the real world, except for the simplifications and assumptions made.

Black-box validation

Let's start this section by outlining that real-world output data is not present. Of course, COMPANY A has delivered products A already. But as explained multiple times in this thesis already, there were multiple production mistakes or other things such that this is not a reliable data point to compare against. This is all because product A was in an introductory phase. This does not display the future. Therefore, the model should be compared with other models.

First, the model was checked against adding all averages of the throughput times for each department. For the AC-type product A, this would result in a total throughput time of 1467 minutes (no inserts, no sandblasting, no cleanliness test, 15 minutes set-up time per department, 90 minutes set-up for Machine 1). Corresponding to 24 hours and 27 minutes (excluding two weeks of outsourcing). Consequently, the model was run for one product A type AC in a simplified model. In this model, all shifts were non-active, delivery to THE OUTSOURCING COMPANY was done directly (so no waiting for the truck), and the entire system was empty, so no waiting time was observed. In addition, the
week-to-week-planning was removed. This was done such that the two situations can be compared. The total internal throughput time (excluding two weeks of outsourcing) was 31 hours and 47 minutes. Why is this difference so big? Well, in the simulation model, the product had to wait in front of the machine 2 because it was locked. This waiting took 6 hours and 50 minutes. Subtracting this from the total throughput time, resulted in 24 hours and 57 minutes. So a difference of approximately 30 minutes is observed. This is plausible since process times in the model are not fixed but random according to a certain distribution. Similarly, the sum of the averages of the B-type was calculated (no cleanliness test, 15 minutes set-up time per department, 90 minutes set-up time for Machine 1) resulting in 1537 minutes. Corresponding to 25 hours and 37 minutes (excluding two weeks of outsourcing). Recall that this difference with the AC-type is present because the AC-type does not have sandblasting, assembly of inserts, and a longer process time on the Machine 1. The total internal throughput time in the simulation model was approximately 33 hours and 29 minutes (excluding two weeks of outsourcing). However, the B-type was waiting 7 hours and 34 minutes in front of the Machine 2. Subtracting this from the total would result in 25 hours and 55 minutes. Again a little difference is observed, which can be due to the fact that process times in the model are not fixed. It can be concluded that the process times in the model correspond quite accurately to the process times that were determined in section *2.3.*

Second, based on the *appendix B.3* an observed total average throughput time of approximately 9 weeks would be expected. However, if the model is run for 3,5 years (including warm-up period, this period will be determined in the next section), the average total throughput time is around 64 days and 13 hours. Why is this difference of 1 day and 13 hours observed? Well, as mentioned in *section 2.2,* the production chain in week 5 is quite long. Frankly, too long. Sometimes, a complete batch cannot be finished within this week. Therefore, product A that is not finished yet will have a delay of an entire week, resulting in a throughput time of 10 weeks. This does not happen too often. Therefore, the average total throughput time is only increased by approximately a day and a half.

Lastly, the overall behavior of the model was again showed to the director. The following questions were asked, with his actual response:

Do you think the throughput time is realistic, based on the model's input?
"At this moment we have chosen for a throughput time of every production step every week. In the starting-up phase, it was easy to let every department experience the new product.
Now we have a flow, and everybody understands what he has to do in the process, we can go one step up by industrializing the process further. This means shorter lead times and a higher number of Products A. Would 4 weeks be realistic? I really hope so, but I realize that the target is very sharp and hard to reach."

Do you think the other output numbers describe reality accurate enough? Did you expect these numbers based on the content of the model?
"The numbers are presented by our customer and it represents our market share on which we won the contract."

Do you have any other remarks regarding the model?
"No, I believe that we put enough effort into creating the model as it is today to have a clear output."

All in all, based on all arguments above, I believe that the current base-model describes reality accurate enough in its overall behavior.

Experimentation validation
Experimentation validation will be done in *chapter 6.*

Solution validation
Solution validation will not be done since it needs to compare the solution model to the implemented solution in the real world. Since implementation is not part of this thesis, this will not be done.

5.3 Summary and conclusions for chapter 5

By making a conceptual model, all inputs, outputs, and contents of the simulation model have been determined, based upon the outlined problem context. The content is based is upon several assumptions and simplifications regarding reality. The capacity used in the model does differ from the capacity analysis done in chapter 2 because of less real working hours. Reasons for this are the locking of certain machines, variability, and no consideration of efficiency issues. The paper-model can now be translated into a computer model.

The conceptual model has been programmed in a discrete event simulation type, in a program called Tecnomatix Plant Simulation. It is believed that the model describes reality accurately enough since it has been verified and validated with numerous approaches. For this, also the opinion of the director of COMPANY A has been used.

Chapter 6: Experiments with the simulation model

In this chapter, multiple experiments will be run within the simulation model. In order to do this, an experimental set-up needs to be determined in order to acquire accurate experimental results. If these are determined, experiments can be run. This will be done on the planning approach, the influence of variability, transporting to THE OUTSOURCING COMPANY, the influence of extra machines, and the transport to the customer. The results of all experiments will also be analyzed within this chapter. Eventually, the best results will be combined to determine what is needed to reduce the throughput time to four weeks. If there are any doubts about outcomes, data accuracy or data analysis, do not hesitate to contact me (the author of this thesis) to acquire raw data or the simulation models.

6.1 Obtaining accurate experimental results

In this section, the experimental set-up will be determined by determining the warm-up length, the run-length, and the number of replications.

Determining the simulation model type

The simulation output of a model is stochastic. The simulation model does not have an endpoint since the production will continue. Not forever, but probably for a long period. A good approximation could be the lifetime of an airplane, which is about 30 years. To conclude, I classify the simulation output as non-terminating. The output of the simulation model is steady-state output since the output of the model, for example, average throughput time or average total WIP, displays steady-state behavior when plotted in a graph, except for the start (see: *appendix E.1*). This is the initialization bias. This because there is no WIP in the system yet, which is unrealistic since there will be WIP in the production.

Dealing with the initialization bias

In order to cope with the inaccurate data present in the initialization bias, it has been determined to use a warm-up length. Initial conditions can be set based on real-world data. Since this is not present, it is not possible to use this. Another approach is setting initial conditions by determining these after the warm-up period. In this case, the warm-up period will still have to be determined. Since the run-time of the simulation model is not that long, removing the warm-up length is no problem. Moreover, using initial conditions acquires extra coding.

For the warm-up period, the average daily total WIP has been used as KPI. Data from five replications of the base model were used. The model was run for 1277 days. This average total WIP was plotted per day. This graph can be found in section *appendix E.1.* By inspecting the graph (so-called time-series inspection), it seems that the system is in a steady-state somewhere around day 100. Though with such an inspection you can quickly make a reading error. Therefore, as extra argument, the marginal standard error rule (MSER) will be used in order to calculate the warm-up period, as an addition to the graphical method.

Using the data from the five replications (just a random number) and the total average WIP per day, a warm-up period could be chosen using the MSER-heuristic. The eventual warm-up period should be 98 days according to the heuristic, with a minimum MSER-value of approximately 0,00148. Since the value is below 638 days, the conclusion should not be rejected.

Actually, the warm-up period should be determined for every KPI and experiment. Since this takes quite some time, the warm-up period is only determined on basis of the base model and one KPI. To conclude, the warm-up period should be overestimated to give a margin of safety and checked regularly just to be sure. Eventually, it was chosen to set the warm-up period on 100 days since this is a nice round number that overestimates the initial warm-up period. Based on an average weekly throughput from five replications (16,78) this is equal to approximately ((100/7)*16,78=239,7862) 240 products A. So, in the table that stores all values of every product A, the first 240 products A can be ignored.

The run length

The run length of the simulation should be much longer than the warm-up period. Rules of thumb can be used for this. However, in order to have an argument for the run length, the cumulative mean of the internal throughput time is plotted in a graph. This was done for 5 replications, with a run-length of 7300 days. The warm-up period of 100 days was removed from this dataset. The eventual graph is displayed in *appendix E.2.* Two graphs are displayed, a zoomed-in version in which the axes are more clearly displayed and a zoomed-out version in which the graph is more clearly displayed. Just like in Robinson's method for the run-length (2014, p. 191) the point where the graph becomes flat will be chosen. This seems to be the point around day-number 4993. To be sure, a run-length of 5000 days is chosen.

The number of replications

For the number of replications, it was chosen to use the confidence interval method. Multiple KPI's were used for this method for example average WIP, average internal throughput time, total throughput time. The value for the allowed relative error (d) was chosen to be 0,05. Unfortunately, the method did not provide sufficient results for all KPI's. According to this method, two replications should be used. Since this contrasts with most rules of thumb (like the rule of thumb of Law and McComas, 1991), it was chosen to not use this. It has been decided to use 10 replications. This seems to be more than enough since the run length is also quite long. In addition, it is more than most rules of thumb.

To conclude this section, the following experimental set-up has been chosen:

Table 12: The experimental set-up for all experiments.

Warm-up length	100 days/240 products A
Run length	5000 days
Number of replications	10

6.2 The planning approach experiments

Since the experimental set-up is set, the experiments can be run. This will first be done for the different planning and control approaches. The runtime of one experiment in the base model, with the experimental set-up as described above, is approximately 2 minutes and 33 seconds.

The base model

In order to determine the performance of the other planning approaches, first, the values of main KPI's of the base model will be given and analyzed in table 13. This output can be directly acquired from the simulation model output. Though, in order to do paired-t tests, you first need to analyze simulation output. To get an idea of simulation output, screenshots have been provided in *appendix E.3.* Eventually, the following combined table has been created:

Table 13: Values of main KPI's for the base model.

	Average internal TT (DD:HH:MM:SS)	Average total TT (DD:HH:MM:SS)	Average daily WIP (pc.)	Total output (pc.)	Average weekly output (pc.)
Mean	44:03:46:57	65:02:21:55	167,39	12703,60	18,00
Standard deviation	00:04:59:39	00:05:02:43	0,54	3,34	0,01
Confidence interval min (95%)	44:00:12:35	64:22:45:21	167,01	12701,21	17,99
Confidence interval max (95%)	44:07:21:18	65:05:58:27	167,78	12705,99	18,00

Where the internal throughput time is the total throughput time minus outsourcing (2 weeks) and waiting for the delivery to the customer. The confidence interval is based on a confidence level of 95%. The average weekly output can be assumed as 18 pieces. This weekly output consists of 6 AC-type products A and 12 B-type products A. You would expect these numbers since you also push 18 products A per week through the process. As expected from the planning method (outlined in *chapter 2*) the average total throughput time is close to 9 weeks. Though, it is somewhat higher since some batches do not finish the long production chain in week 5 on time, resulting in a throughput time of 10 weeks. The internal throughput time is shorter since the two weeks of outsourcing are not included. Moreover, the waiting time for delivery is also not included in the internal throughput time. The WIP is also close to the value you would expect, namely weekly demand times the throughput time (Little's Law).

The other planning approaches: MRP, ConWIP and bottleneck control

The three planning approaches have been modeled within the simulation model. How this is done, will be outlined in this section. First, for all models, the weekly schedule from the base model has been deleted since this results in high waiting times. This is where the assumption that products A are processed immediately or have priority is important. The current base model is based on the fact that this does not happen, therefore the long intervals of a week are implemented. However, these intervals are deleted in the other approaches, leading to massive improvements. All other values are equal in all models. The basic logic of the planning approaches is also displayed in a flow chart in *appendix D.2.* Again, the actual logic in the model is a bit more complex. The flow chart is provided to give an idea of how the programming methods work.

Second, the MRP-model has not been modeled with an MRP-table. The MRP model just delivers 18 products A every week (6 AC-type and 12 B-type). As shown, this results in eventually 18 products A of output (6 AC-type and 12 B-type). As mentioned in *chapter 4*, the MRP model is actually an MPS table. Making a table would only result in more coding complexity, with a similar outcome since this is exactly what you try to attain with MRP. This can be classified as a push system in which 18 products A are pushed through the system every week. Since a sufficient capacity is assumed, no additional capacity analysis is needed.

Third, the ConWIP model has been programmed by setting AC-card limits and B-card limits. For the first week, the WIP-limits will be ordered. After this, every week the number of products A that will be delivered are also ordered, such that the WIP always remains constant and equal to the WIP-limits. This is done by maintaining a counter for each product A type that is finished. In reality, this cannot be done like this since you do not exactly know what will be finished at the time you place a certain order for products A (see *chapter 4)*. Though, it is assumed that it is possible to estimate this. It is, in this case, better to overestimate this order quantity a little bit and just put products A that perhaps should not be ordered aside for a while. The warm-up period is important in the ConWIP-model since in the first few weeks the throughput time of products A will be relatively long because so many products A come in at the same time, resulting in long queues.

Lastly, bottleneck control has been programmed based on multiple bottlenecks, in order to compare the results. Based on the simulation model, it turns out that the deburring department is not that constrained. So, deburring will not be considered. At first, again, the WIP-limits will be ordered. After this, every week the number of products A that are finished at the bottleneck are also ordered, such that the WIP always remains constant and equal to the set WIP-limits up until the bottleneck. This is done by maintaining a counter for each product A type that is finished at the bottleneck. The potential bottlenecks are THE OUTSOURCING COMPANY1 (referring to the first time outsourcing), THE OUTSOURCING COMPANY2 (referring to the second time outsourcing), the Machine 1 (turning and milling), and the Machine 2 (grinding - see *section 2.6*).

In order to compare the model to MRP, ConWIP, and bottleneck control, the right values for ConWIP cards and bottleneck control cards should be analyzed.

Determining the number of CONWIP cards

The ConWIP cards will be set for both AC-type and B-type products A. The number of AC-type cards and B-type cards determine the output of the system. Therefore, a configuration of cards will be chosen such that a similar output as in the base model and in the MRP-model (6 AC-type of products A and 12 B-type of products A) will be attained. If this output is equal, the performance of the systems can be compared. Moreover, the output ratio should always remain 1:3, otherwise the ConWIP model will automatically be better by simply scheduling more AC-type products A since the throughput time of an AC-type is automatically lower.

For ConWIP, 9 experiments have been run with different AC cards and B cards. The results of these experiments are shown in *appendix F.1.* Based on these results, 35 AC-type cards and 73 B-type cards attain a similar output as the base model and the MRP-model. Even though 36 AC-type cards together with 72 B-type cards attain an output closer to 18, the individual outputs of the AC-type and B-type deviate more.

Determining the bottleneck and bottleneck cards

For bottleneck control, not only the number of bottleneck cards should be determined, but also the department that performs the best under bottleneck control. Recall that possible departments are the Machine 1 machine, Machine 2 machine, THE OUTSOURCING COMPANY1 (referring to the first time outsourcing to THE OUTSOURCING COMPANY), and THE OUTSOURCING COMPANY2 (referring to the second time outsourcing). Again, the values should be set such that the weekly output is close to 6 AC-types and 12 B-types.

In order to save time, the following will be done. For each potential bottleneck, experiments will be run in order to determine the number of cards. Instead of ten replications, only three replications are used, just to save time. If for each bottleneck the right number of cards are chosen, the systems can be compared on their performance. The best performing system should be chosen. For this system, the number of cards will be determined once again, but now based on 10 replications. Eventually, the best system will remain with the right number of cards.

In *appendix F.2* the results of the three replications are shown. The values where the output is close to 6 AC-types and 12 B-types of output are chosen as values for the AC and B cards. With all card-values set, the bottleneck control systems are compared. For this, a confidence interval of the difference in the average total throughput time (in seconds) was created, with the paired-t approach, as explained in *section 3.2* and displayed in table 14. A confidence level of 95% was used. Actually, the paired-t approach is in literature usually used to compare observations that are correlated. However, my teacher's personal opinion (Dr. Ir. M.R.K. Mes) is that the outcome of the paired-t approach can always be used, regardless of independence. Of course, the determined experimental set-up is used. The results and conclusions are displayed in the following table. Recall that if the confidence interval is completely smaller than zero, the scenario in the row is significantly smaller than the scenario in the column. Similarly, if the confidence interval is completely bigger than zero, the scenario in the column is significantly bigger than the scenario in the row. If zero is included in the interval, no significant difference can be observed. The confidence intervals will be in seconds since only the best scenario will be determined. The relative difference is, for now, less important.

Table 14: Paired-T approach for bottleneck control (sec).

		Machine 1	**THE OUTSOURCING COMPANY1**	**THE OUTSOURCING COMPANY2**
Machine 2	*Paired-T test result*	(-205031, -63663)	(-22231, -3341)	(-19784, -15228)
	Statist. conclusion	*Machine 2 < Machine 1*	*Machine 2 < THE OUTSOURCING COMPANY 1*	*Machine 2 < THE OUTSOURCING COMPANY2*
Machine 1	*Paired-T test result*	--- ---	(55520, 187603)	(46192, 187491)
	Statist. conclusion		*Machine 1 > THE OUTSOURCING COMPANY 1*	*Machine 1 > THE OUTSOURCING COMPANY 2*
THE OUTSOURCING COMPANY1	*Paired-T test result*	--- ---	--- ---	(-15377, 5937)
	Statist. conclusion			*No difference*

So, if bottleneck control is used, the machine 2 should be the bottleneck within the model. It outperforms all other bottleneck control approaches since it can be concluded, with a used level of significance of 95%, that the total throughput time of bottleneck control on the machine 2 is lower than bottleneck control on the Machine 1, THE OUTSOURCING COMPANY1 or THE OUTSOURCING COMPANY2. Similarly, it can be concluded (95% significance level) that bottleneck control on the Machine 1 outperforms bottleneck control on outsourcing. It can also be concluded that putting bottleneck control on THE OUTSOURCING COMPANY1 or THE OUTSOURCING COMPANY2 does not make a significant difference. Since the Machine 2 was the best performing bottleneck control approach, the nine experiments of the card configuration were rerun with 10 replications, as shown in *appendix F.2,* resulting in the same configuration of 22 AC-type cards and 46 B-type cards.

This is somewhat a surprise, because why is a production step that on average approximately takes 2 hours and 19 minutes the bottleneck? First, this has to do with the fact that the Machine 2 cannot pause its activity, leaving less available time on a given day. Second, in the model, sufficient capacity is assumed for every department. If capacity was more constrained, like in reality, perhaps a different bottleneck would be more effective. For example, it is unlikely that THE OUTSOURCING COMPANY can handle every batch-size that is sent to them. In addition, the Machine 1 has 24-hour shifts. The Machine 1 can do a lot of work while the other departments are not producing, such that it is also not a bottleneck. Lastly, recall that the Machine 2 is within the long chain in week 5 in which the batch size is sometimes problematic to complete within a week. By improving this, more products A can go into the THE OUTSOURCING COMPANY truck for the second time sooner, improving total throughput time.

Comparing the four planning approaches

Eventually, all four models (the base model, the MRP-model, the ConWIP model, and the bottleneck control model) have been run. The results are summarized in the following table:

Table 15: Results of KPI's for the models of the four planning approaches.

	Average internal WIP (pc.)	Total output (pc.)	Internal throughput time (DD:HH:MM:SS)	Total throughput time (DD:HH:MM:SS)
Base model	167,4	12703,6	44:03:46:57	65:02:21:54
ConWIP model	108,0	12759,5	22:06:50:45	41:22:31:37
MRP-model	107,0	12764,7	21:23:07:28	41:14:41:39
Bottleneck control model	107,4	12803,5	21:23:20:47	41:14:09:58

As shown in the table, the throughput times and WIP levels are much lower while a similar output is acquired. For all models, the average weekly output was close to 6 AC-types and 12 B-types, as shown in table 16:

Table 16: Output numbers for the models of the four planning approaches.

	Avg. Weekly output B (pc.)	Avg. Weekly output AC (pc.)	Avg. total weekly output (pc.)	Confidence interval (sign. 95%)
Base model	6,00	12,00	18,00	(17,99, 18,00)
ConWIP model	6,01	12,01	18,02	(17,99, 18,06)
MRP-model	6,00	12,00	18,00	(18,00, 18,00)
Bottleneck control model	5,98	12,09	18,07	(18,03, 18,11)

The output for bottleneck control is slightly higher but based on these numbers, the systems can be compared. The confidence intervals (confidence level 95%) are displayed in figure 4, for the ConWIP, MRP and bottleneck control model:

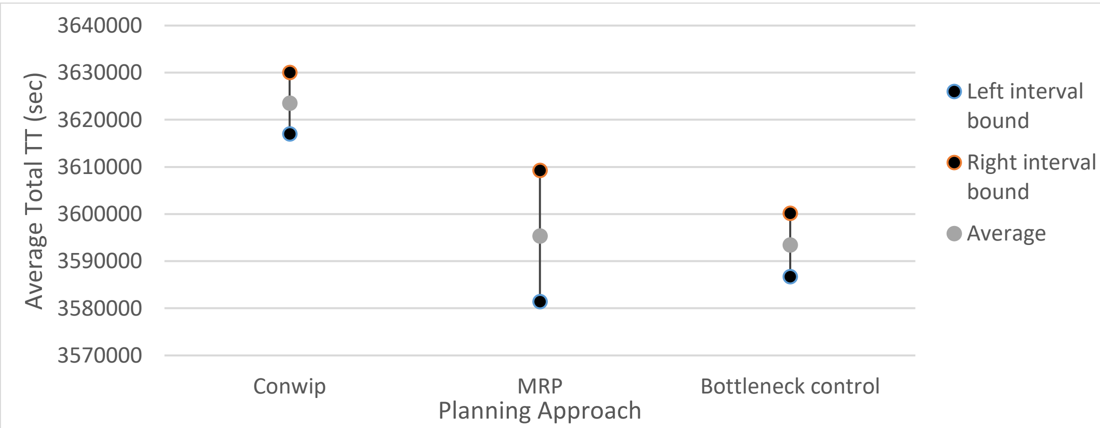

Figure 4: Confidence intervals for the average total throughput time, for the planning approach experiments.

This figure will be recurring for all other experimental levels. Therefore, it will be shortly explained in this section. The right interval bound (orange) displays the maximum of the confidence interval, whereas the left interval bound (blue) displays the minimum of the confidence interval. The average (grey) displays the average of the observations from the simulation model. With a confidence level of 95%, it can be stated that the average of the total throughput time is within this interval. The confidence level refers to the amount of confidence with which can be stated that the average is within this interval. So, preferably, the confidence interval (and its average) needs to lay as low as possible in this graph. The confidence interval of the total throughput time of the ConWIP lays higher than the confidence interval of the MRP and bottleneck control approaches. The average of the MRP-approach and bottleneck control approach are close together. Though, the confidence interval of the MRP-approach is larger than the others. As an addition to this comparison, comparing the systems was done with a confidence interval of the difference in the average total throughput time (in seconds), with the paired-t approach. The confidence level is again equal to 95%.

Table 17: Paired-T approach for comparing the planning approaches on average total throughput time (sec).

		MRP model	**ConWIP model**	**Bottleneck control model**
Base model	*Paired-T test result*	(2022395, 2036035)	(1990863, 2011172)	(2020896, 2041337)
	Statist. conclusion	*Base model > MRP*	*Base model > ConWIP*	*Base model > Bttlnck ctrl.*
MRP model	*Paired-T test result*	--	(-38534, -17862)	(-7377, 11180)
	Statist. conclusion	--	*MRP < ConWIP*	*No sign. difference*
ConWIP model	*Paired-T test result*	--	--	(27661, 32537)
	Statist. conclusion	--	--	*ConWIP > Bttlnck ctrl.*

Based on the confidence intervals of the difference in the average total throughput time, it can be concluded that the throughput time in the base model (sign. 95%) is much longer than in all other approaches. Any other approach will at least improve the total throughput time with approximately 23 days and one hour (minimum of the confidence interval of ConWIP) and perhaps even with 23 days and 15 hours (maximum of the confidence interval of Bottleneck control), with a significant level of 95%. Moreover, it can be concluded (sign. 95%) that total throughput time in the MRP model and the bottleneck control model is shorter than the total throughput time in the ConWIP model. Lastly, there is no significant difference (sign. 95%) that the total throughput time in the MRP-model is longer than in the bottleneck control model. The same conclusions can be drawn (95% sign.) regarding average internal throughput time:

Table 18: Paired-T approach for comparing the planning approaches on average internal throughput time (sec).

		MRP	**ConWIP model**	**Bottleneck control model**
Base model	*Paired-T test result*	(1911014, 1924123)	(1879740, 1899804)	(1906014, 1927525)
	Statist. conclusion	*Base model > MRP*	*Base model > ConWIP*	*Base model > Bttlnck ctrl.*
MRP model	*Paired-T test result*	--	(-37427, -18166)	(-10206, 8608)
	Statist. conclusion	--	*MRP < ConWIP*	*No difference*
ConWIP model	*Paired-T test result*	--	--	(24766, 29230)
	Statist. conclusion	--	--	*ConWIP > Bttlnck ctrl.*

The results of the two best approaches will be summarized. These are displayed in table 19 for the MRP-model:

Table 19: Confidence interval for average internal and total throughput time in the MRP-model.

	Internal TT	Total TT
Mean (DD:HH:MM:SS)	21:23:07:28	41:14:41:39
95% Confidence interval min	21:19:30:29	41:10:49:28
95% Confidence interval max	22:02:44:29	41:18:33:51

And the bottleneck control model in table 20:

Table 20: Confidence interval for average internal and total throughput time in the bottleneck control model.

	Internal TT	Total TT
Mean (DD:HH:MM:SS)	22:06:50:45	41:22:31:37
95% Confidence interval min	22:05:10:04	41:20:43:15
95% Confidence interval max	22:08:31:26	42:00:19:59

Based on the paired-t approach (95%), the following table can be made regarding the total average throughput time. In addition, the means of the WIP and WIP values (€5000*WIP) will be compared, on request of the project supervisor. The comparison of the WIP is not based on a statistical test (a confidence interval).

Table 21: Comparing the planning approaches based on time gains, WIP, and WIP value

Planning approach	Approximate time gain in average total throughput time regarding the base model	Difference in mean WIP	Difference in mean WIP value
Base model	0	0	0
MRP model	23 days and 10 hours to 23 days and 14 hours.	59,4	€297000
ConWIP model	23 days and 1 hour to 23 days and 7 hours.	60,4	€302000
Bottleneck control model	23 days and 9 hours to 23 days and 15 hours.	60	€300000

As shown in table 21, different planning approaches result in much lower average total throughput times, mean WIP levels, and WIP values.

Analysis of the results for planning and control

Multiple conclusions are drawn based on the experiments above. First, the current planning algorithm is outperformed by all the other planning and control approaches. This is mainly because the current planning and control approach results in a long waiting time because of the week-to-week scheduling. This waiting time increases the throughput time significantly. Therefore, consequent stations stay idle while they could already be processing other products A. As discussed in *section 2.2* this is implemented because it brings certainty. In reality, the departments also work on other products. This is not taken into consideration in the simulation model. Giving them a longer time period in which they can make the products. This gives more flexibility and certainty in the lead time (9 weeks). However, this is not even completely the case since the average throughput time is longer than 9 weeks (see confidence interval), so multiple products A take longer to produce. This is because of the long production-chain in week 5. In addition, the base model still needs the same capacity as the other planning models. So also regarding capacity, no gains can be acquired by using this planning.

Second, MRP outperforms ConWIP control. This is unexpected since normally a ConWIP system should have lower throughput times for a similar output (Hopp & Spearman, 2008, p. 370). Why is this not the case? Multiple reasons can be identified:

1. Waiting time. In order to analyze the waiting times in the ConWIP system and the MRP system, the two models were run for a second time, with average waiting time in front of the Machine 1, Machine 2, deburring department, and THE OUTSOURCING COMPANY as KPI's. This is shown in *appendix F.3*. The difference between the waiting times is approximately 8 hours, similar to the differences in internal throughput time. Although this should be significantly statistically proven, it shows that the waiting time is probably the main reason for the longer throughput time.
2. Literature usually assumes that orders can be processed immediately and delivered immediately. If a product A is finished, it should leave the system and a new product A should enter the system. This is not the case in this system. For example, when products A are finished, they have to wait for delivery of finished products A and arrival of new products A. This results in fluctuating order quantities, increasing variability in the model.

Reason 1 is actually a consequence of reason 2, and that is why both reasons are in my opinion the main reason that ConWIP is not working as it should be. As shown by Slack, Brandon-Jones, and Johnston, variability reduces the efficiency of the process and increases waiting time (2013, p. 117-118). Because products have to wait for delivery, a different number of products A are ordered every week, increasing variability and thus waiting time.

3. Furthermore, in the model sufficient capacity is assumed. If a certain capacity was more constrained than it currently is in the model, ConWIP would quickly become more efficient than push-systems. By setting a WIP limit, large queues will not build up in front of departments, whereas a push-system just pushes products on, no matter what state the system is in (Hopp & Spearman, 2008, p. 372). Following this, the model did not take into consideration failures, maintenance and other reasons a machine might not be working. In such a case, the WIP in a push system would automatically build up significantly since it just pushes on products into the system, and thus throughput times. ConWIP would have observed this failure, and stop the input of new products, preventing queues to build up.

Reason 2 can be solved by making another rack on which castings and finished products A can be stored. In this way, finished products A can be stored and fictively "leave the system", while a new product A "enters the system". However, in reality, this would still mean that product As are in the system and the actual WIP is not constant. Moreover, the question arises if there is enough room for this and if the customer wants to store this extra WIP (since they own product As). The effect of this system would be interesting for further research but will be beyond the scope of this thesis.

Lastly, bottleneck control performs similarly as the MRP-model. Why is this the case? Well first, the entire system is behaving like an MRP system, except that there is one trigger that controls the WIP up until the Machine 2. So, the systems should act similarly beyond the bottleneck. In addition, as shown in *appendix F.3*, the average waiting time is also quite similar to the MRP model, and thus much shorter as that in the ConWIP system. Thus, the question arises what the advantages are of bottleneck control if it does not outperform MRP. Bottleneck control is relatively new for COMPANY A and harder to implement than an MRP system (*see section 4.4*). Though, just like with ConWIP, if capacity was probably more constrained, bottleneck control would quickly outperform the MRP-model.

Bottleneck control did outperform ConWIP. As mentioned by Lödding (2013, p. 347), if a clear bottleneck is present, bottleneck control performs better than ConWIP. This is also shown in this simulation model. Even though the bottleneck is not clear if definitions from literature are used, in the model a clear bottleneck is present. Bottleneck control on the Machine 2 outperforms bottleneck control on all other departments. Furthermore, while it is not tested, it is believed that the variability in the order quantity of bottleneck control model is much lower since the WIP-limits are lower than in a ConWIP model. The WIP limits are much lower because the chain length of the production process up until the Machine 2 is shorter than the chain length of the entire system. This makes sure that the waiting times are also lower than in the ConWIP model because variability is lower. In addition, as explained in the literature study, ConWIP does not work as good if the production chain is quite long (Thürer, Stevenson, & Protzman, 2016).

Side note

The planning and control approaches have not been compared on their utilization levels, whereas this was actually one of the KPI's in chapter 4, together with throughput time/output, applicability, and adaptability. Applicability and adaptability are not considered since this cannot be made measurable within a simulation model. Though, utilization is.

As mentioned, in this thesis, a certain capacity is assumed. Therefore, the capacities are not changed that much when different planning approaches are used. This would be the case if the capacities are more constrained, as mentioned in literature. Moreover, not everything can be compared during experimentation. It has been chosen to only compare throughput time and consequent WIP levels since this was the main goals of this thesis.

6.3 Other planning and control experiments and the costs analysis

Next to the planning approach, additional experiments will be run within this section. All experiments are somehow related to the key concepts of planning and control. The experiments are about variability, transport to outsourcing, adding machines, and transporting to the customer. The possible time gains will be compared to their costs and decrease in WIP and WIP value.

The upcoming experiments will be done in both the base model and the MRP-model. The MRP model will also be used because of several reasons:

1. As will be outlined in the *conclusion*, it will be recommended to COMPANY A to use an MRP-model.
2. The base model sometimes has strange results because of the week-to-week scheduling. As will be *outlined*, the transport-day of the customer does not influence the base model. In addition, some time gains are a lot smaller because it is influenced by the week-to-week scheduling. If this scheduling is removed, and products just go on (like in the MRP-model) consequences are much larger, resulting in a bigger reduction in throughput time.
3. Eventually, all best results will be combined into one model to determine what is needed to reduce the throughput time to four weeks. This will not be possible with the base model because it is made to have a throughput of 9 weeks or more. Furthermore, since MRP (together with bottleneck control) is the best-performing planning and control approach, the best results should also be analyzed in this model in order to combine them. Bottleneck control is not used since it is believed that it will also disturb some values because of the WIP limits that are set within the model.

All in all, it is believed that the consequences of different interventions are more clearly observed when the MRP-model is used instead of any other planning approach model.

The influence of delivery variability

On request of COMPANY A, the influence of different delivery numbers and intervals will be experimented. In the base model, it is assumed that the delivery day is fixed (Monday). Moreover, it is also assumed that the delivery numbers are always the same (6 AC-types and 12 B-types). Though, in reality, this is not the case. Customer X delivers different numbers quite arbitrarily to COMPANY A, resulting in a lot of variability which influences the operations heavily. In this section, this variability will be investigated.

Scenario 1 was modeled by allowing every day to be a potential delivery day. Furthermore, the intervals between these delivery days are either 3 or 11 days. The simulation model selects a random number of days and sets this as a new interval such that the average interval length remains a week, but the variance that is present is also modeled. In this way, the situations can be compared with all other values equal.

Scenario 2 was modeled by setting a fixed delivery day (Monday), just like in the base model. Though, the numbers that will be delivered are not fixed (18) but different. For the AC-type, this number fluctuates randomly between 4 and 8, whereas for type B, this number fluctuates between 8 and 16. Again, it was made sure that the average remains equal such that the situations can be compared with all other values equal.

Scenario 3 was modeled by combining scenario 1 and 2 into one model. These experiments resulted in the following confidence intervals (95%) for the average total throughput time (sec):

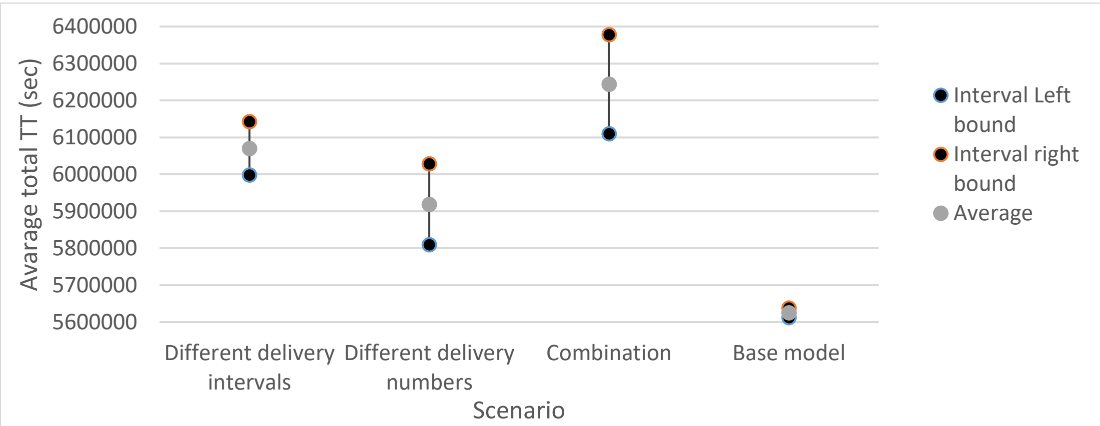

Figure 5: Confidence intervals for the average total throughput time, for the variability experiments (base model only).

The confidence intervals are partially overlapping. Though, the average of the combined model lays higher than the other scenarios, whereas the average of the different intervals is higher than the average of the different numbers. The average of the base model is much lower. This confidence interval does also not overlap with any other confidence intervals. So, the base models looks like the best-performing model.
The following confidence intervals (95%) for the average WIP level (pc.) have been constructed:

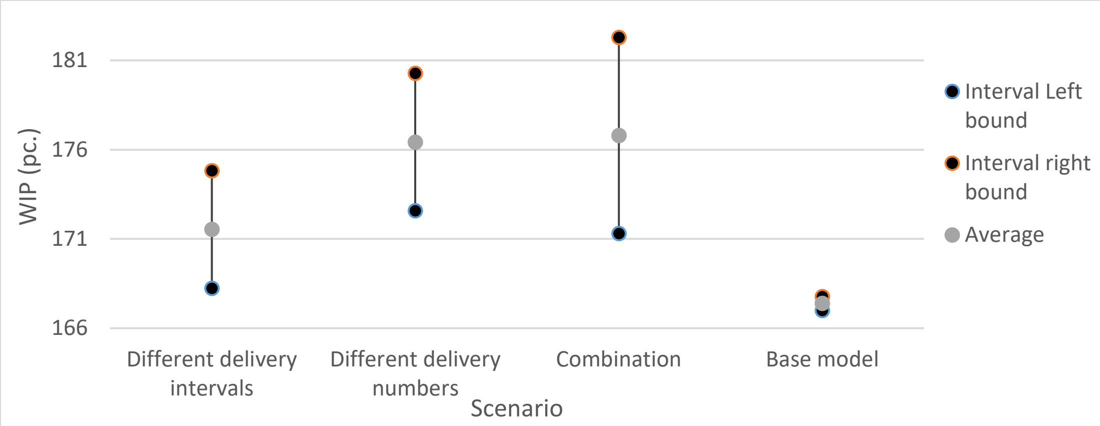

Figure 6: Confidence intervals for the average total WIP, for the variability experiments (base model only).

In this graph, the WIP of the combination model and the model with only different delivery numbers seem to be similar. The confidence interval of the combination model is slightly larger. The average of the confidence interval of the different delivery intervals seem to lay lower. Though, the base model is, again, lower and smaller than all other scenarios. So, it seems that it is again the best-performing model. To better compare the scenarios, a paired-T approach (confidence level 95%) was used in order to say something about the difference between the scenarios. This was done in *appendix F.4*. In addition, on request of the project supervisor, also the difference in WIP and WIP value is added. This is, however, not based on a statistical test, but simply on the difference between the two means.

Table 22: Comparing variability based on time gains, WIP, and WIP value (base model).

	Approximate extra time regarding base model	**Difference in mean WIP regarding the base model**	**Difference in mean WIP value regarding the base model**
Different delivery intervals	4 days and 8 hours to 5 days and 23 hours.	4,14	€20716
Different delivery numbers	2 days and 5 hours to 4 days and 14 hours.	9,03	€45174
Combination	5 days and 16 hours to 8 days and 16 hours.	9,4	€47046

The table shows considerable time gains in total throughput time. Other interesting results are:

Table 23: Waiting times in the base model and the models with variability (base model).

	Avg. Waiting for Machine 2 (DD:HH:MM:SS)	**Avg. Waiting for Machine 1 (DD:HH:MM:SS)**	**Avg. Weekly output (pc.)**
Different delivery intervals	04:13:08:10	09:12:46:21	17,08
Different delivery numbers	05:16:57:36	07:04:58:09	18,03
Combination	05:21:01:57	10:02:34:07	17,12
Base model	02:20:05:40	06:21:12:57	18

The goal of this table is to show the increase in waiting times while lower or similar outputs are attained. For the MRP model, only the combination (both delivering different numbers and in different intervals) was compared. This resulted in the same conclusion with similar numbers.

On request of the project supervisor, one extra experiment is run. In this experiment, the interval varies between 6, 7 or 8 days, and the number of delivered products A vary between 5, 6, or 7 AC types, and 11, 12, or 13 B types products A. This would, based on the assumptions, perhaps be more realistic in the future. In this way, not only the two extremes are compared (no variability vs. a lot of variability), but also something in between. The average total throughput time gain regarding the base model would then be (based on paired-t approach, sign. level 95%) and the difference between mean WIP and WIP value:

Table 24: The influence of little variability on the base model.

	Extra throughput time regarding base model	WIP gain regarding base model	WIP value gain regarding base model
Model with little variability	2 days and 4 hours to 2 days and 18 hours.	3,35	€167746

However, regarding the model with a lot of variability, time gains can be observed. The average total throughput time saving regarding the model with more variability would then be (based on paired-t approach, sign. level 95%) and the difference between mean WIP and WIP value:

Table 25: Savings by reducing variability.

	Throughput time saving	WIP saving	WIP value saving
Model with little variability	3 days and 3 hours to 6 days and 7 hours	6,06	€30300

Analyzing the results

The assumption in the base model, in which the delivery numbers and delivery intervals are fixed, heavily influences the results total average throughput time and WIP levels. As expected and underlined in literature several times, variance heavily influences waiting times and thus the average total throughput times. In all scenarios, the average total throughput time was longer and the WIP-levels were larger while attaining a lower or similar output. This output is lower since more parts are in the WIP. Moreover, the variance of this WIP is much larger together with the variance in the total throughput time (Little's Law). Interestingly, the increase in WIP in the combination model is not much larger than the WIP in the model where only the delivery numbers are varying while the throughput time is much larger. The variability in WIP in the combination model is much larger though, as displayed by the confidence interval. Perhaps, this has some influence on this result. Lastly, the MRP-model shows a similar increase in its average total throughput time. This is because the variability affects the same things as in the base model, which do not depend on the used planning approach.

Based on these results, COMPANY A would heavily improve its efficiency if a fixed delivery day together with fixed numbers will be negotiated with customer X. This was also underlined by the director. This thesis provided extra prove in these negotiations. Perhaps, this variability cannot be completely removed. Though, it shows that reducing variability already decreases the total throughput time significantly. As shown by the differences in WIP value, this can also be beneficial for the customer since less of their products A will be in the WIP. In this way, the customer would have less capital tied up in stock. Furthermore, it can also be statistically proven that negotiating fixed numbers is more effective than negotiating fixed intervals.

To conclude this section, I want to mention that I believe that in reality, the effects would perhaps be even more severe. In reality, much more randomness is present than is assumed in the model. Think about machine break downs, illness of employees, production errors. These are only a few examples, but I can think of many more examples. All this randomness does create even more variability (even though the added randomness is less than the sum of the two). Since all machines are running on high utilization, waiting times would increase significantly, as shown by Slack, Brandon-Jones, and Johnston (2013, p. 119).

Transport to the outsourcing company THE OUTSOURCING COMPANY

In the base models, the delivery day, the acquiring day, and transport to THE OUTSOURCING COMPANY is set on Monday. With delivery and acquiring day, the day on which the truck from customer X brings new products A and acquires finished products A is meant. Moreover, the truck to THE OUTSOURCING COMPANY is only leaving once. In this section, there will be investigated what the influence of a different transport day to THE OUTSOURCING COMPANY will do. Lastly, it will be investigated what the influence of driving one time, two times and three times to THE OUTSOURCING COMPANY are. This will be done both in the base model and in the MRP-model. In the base model, this does actually change week-to-week planning since transport is not necessarily done at the start of the week as assumed in the planning, but also on other days.

By describing these experiments, it shows that interaction effects play a big role. The number of acquiring and delivery days can be 5 days. Moreover, the number of THE OUTSOURCING COMPANY-transport days can also be 5 days. This already results in 5x5=25 experiments. Doing it for two models already results in 25x2=50 experiments. Moreover, by experimenting with also two or three transport days to THE OUTSOURCING COMPANY, this will result in another 6 experiments (outlined later), resulting in another 5x6=30 experiments, and with two models, in 60 experiments. So many experiments cannot be conducted in the specified time for this thesis. Mainly because of these interaction effects, the delivery and acquiring day is set on Monday in order to test the optimal transport to THE OUTSOURCING COMPANY day, as assumed in the base model. This still gives an indication of possible time gains by transporting more often.

By experimenting with multiple transport days, multiple combinations are possible. So not only Monday and Wednesday but for example also Tuesday and Friday. These combinations are interesting since they result in significant different results. As mentioned, the delivery/acquiring day is set on Monday. To again reduce the number of experiments, only combinations of days separated by one day are considered. For example, no combinations of Monday and Tuesday or Wednesday and Thursday are considered, but only of for example Monday and Wednesday and Wednesday and Friday. This is also because I believe that driving two days in a row does not have much effect. Lastly, the processing time from outsourcing remains a week. So, for example with the combination of driving on Friday and Tuesday, products A that leave on a Tuesday also come back on Tuesday a week after, and products A that leave on a Friday also come back on a Friday a week after. So it's not that products A that leave on Tuesday come back on Friday. This timeframe is considered too short in order to process the entire batch of products A. This was communicated with the director of COMPANY A.

The best transport day to THE OUTSOURCING COMPANY

Different transport days to THE OUTSOURCING COMPANY were experimented within the base model. The results can be summarized in the following table (DD:HH:MM:SS):

Table 26: Results of KPI's for different transport days (base model).

	Avg. InternalTT	Avg. TotalTT	Waiting for THE OUTSOURCING COMPANY
Monday	44:03:46:57	65:02:21:54	04:08:42:12
Tuesday	43:05:44:09	64:04:33:19	04:04:51:56
Wednesday	42:11:13:45	63:09:59:03	04:04:16:04
Thursday	42:06:58:31	63:06:03:29	04:01:21:42
Friday	40:22:11:57	61:20:42:02	02:12:47:09

With the confidence intervals (95%) of the average total throughput time summarized in the following figure:

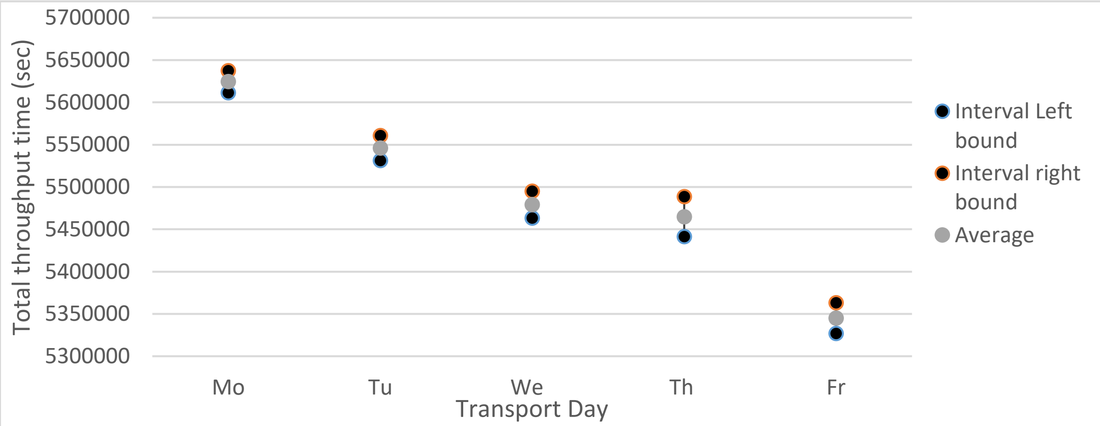

Figure 7: Confidence intervals for the average total throughput time, for different transport days (base model).

As can be observed in the figure and table, further on in the week, the average and the confidence intervals are lower. The reason for this will be outlined later. The confidence intervals of Wednesday and Thursday are partially overlapping. In addition, a paired-T approach was conducted with a confidence level of 95%. This paired-T approach can be found in *appendix F.5.* This confidence interval showed that the transport day on Friday acquires a lower total throughput time than any other transport day.

Within the MRP-model, the following results were acquired (DD:HH:MM:SS):

Table 27: Results of KPI's for different transport days (MRP-model).

	Avg. InternalTT	Avg. TotalTT	Waiting for THE OUTSOURCING COMPANY
Monday	21:23:07:28	41:14:41:39	04:20:17:19
Tuesday	21:02:27:50	40:05:49:17	04:06:11:18
Wednesday	19:16:35:32	37:19:11:58	03:12:12:18
Thursday	19:14:07:48	36:13:00:51	03:04:49:02
Friday	20:13:29:17	37:10:48:30	03:00:45:53

With the confidence intervals (95%) of the average total throughput time summarized in the following figure:

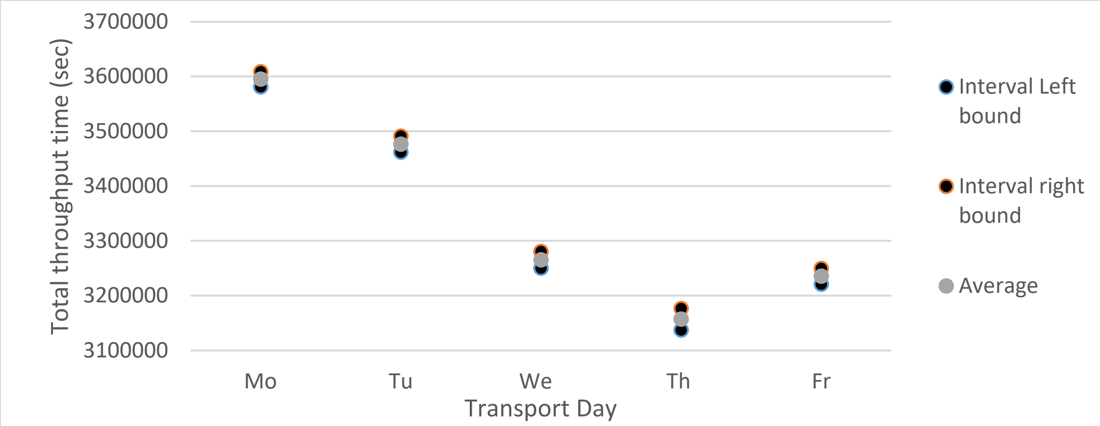

Figure 8: Confidence intervals for the average total throughput time, for different transport days (MRP-model).

In this figure and table, the average and the confidence interval of driving on Thursday lays the lowest, whereas Friday and Wednesday seem to lay on a similar level. In addition, a paired-T approach was conducted with a confidence level of 95%. This paired-T approach can be found in *Appendix F.5.* This confidence interval showed that the transport day on Thursday acquires a lower total throughput time than any other transport day.

Transporting multiple times and the combination of days

In the week planning, the following combinations have been experimented. The results can be summarized in the following table (DD:HH:MM:SS):

Table 28: Results of KPI's for combinations of transport days (base model).

	Avg. InternalTT	**Avg. TotalTT**	**Waiting for THE OUTSOURCING COMPANY**
Mo-Th	44:03:46:57	65:02:21:54	04:08:42:12
Mo-We	40:00:52:09	60:23:55:36	02:20:18:43
Tu-Th	39:02:42:11	60:01:32:12	02:16:26:38
Tu-Fr	37:05:05:10	58:04:19:55	01:11:59:13
We-Fr	36:08:10:13	57:07:19:35	01:12:59:36
Mo-We-Fr	36:07:53:42	57:06:49:09	01:06:19:12

With the confidence intervals (95%) of the average total throughput time summarized in the following figure:

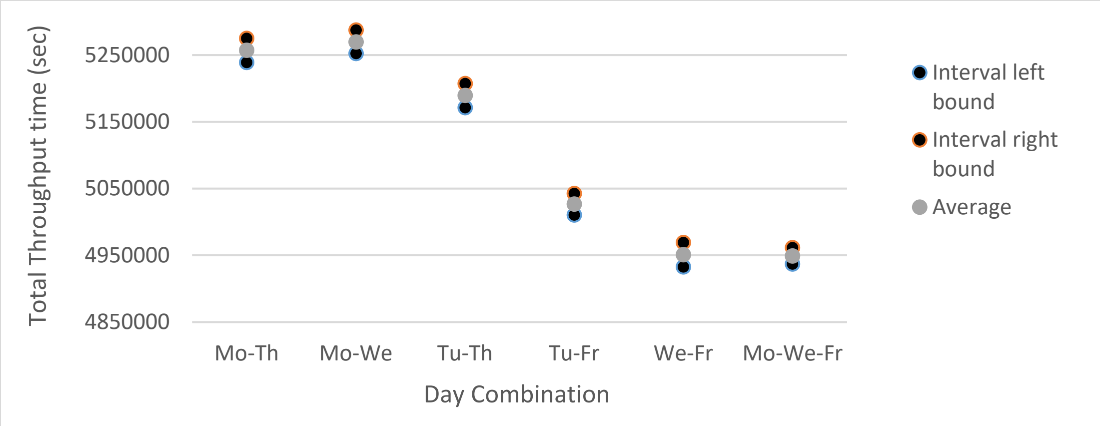

Figure 9: Confidence intervals for the average total throughput time, for combinations of transport days (base model).

As displayed in the table and figure, multiple combinations give different outcomes. When driving twice, the confidence interval of Wednesday and Friday lays the lowest. Driving three times does not seem to do much since that confidence interval is on a similar level. As an addition, a paired-T approach was conducted with a confidence level of 95%. This paired-T approach can be found in *appendix F.6.* This showed that driving two times, on Wednesday and Friday outperformed all other combinations. Moreover, driving three times also outperformed all other combinations. However, between driving two times on Wednesday and Friday, or three times on Monday, Wednesday and Friday, no significant difference was observed.

Within the MRP-model, the following results were acquired (DD:HH:MM:SS):

Table 29: Results of KPI's for combinations of transport days (MRP-model).

	Avg. InternalTT	**Avg. TotalTT**	**Waiting for THE OUTSOURCING COMPANY**
Mo-Th	15:14:46:03	33:11:01:24	02:04:47:18
Mo-We	15:19:13:50	34:23:03:07	02:10:52:51
Tu-Th	15:09:15:48	34:02:22:19	02:01:54:04
Tu-Fr	15:13:02:48	33:00:57:08	01:20:10:29
We-Fr	15:09:52:26	33:01:16:50	01:18:02:17
Mo-We-Fr	13:17:49:53	31:09:38:24	01:10:05:30

With the confidence intervals (95%) of the average total throughput time summarized in the following figure:

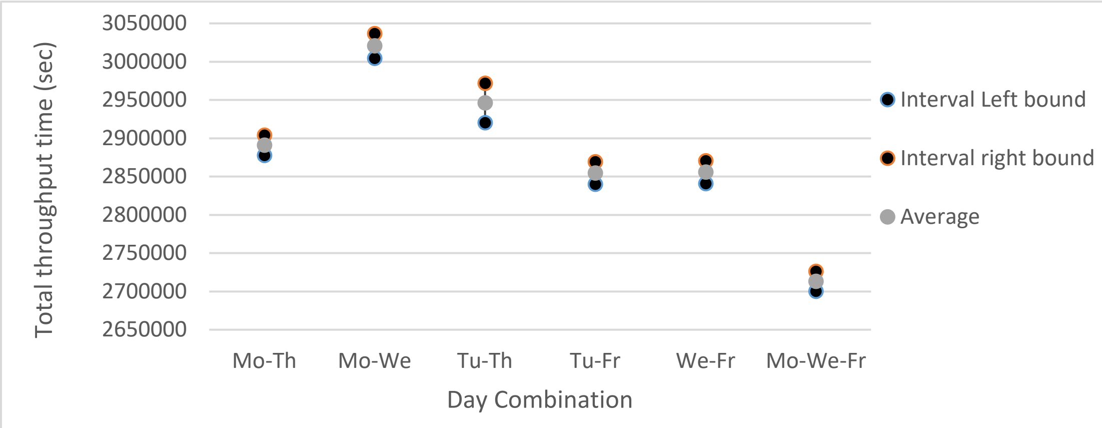

Figure 10: Confidence intervals for the average total throughput time, for combinations of transport days (MRP-model).

Again, as shown in the table and figure, multiple combinations give different outcomes. Some confidence intervals are overlapping. The combinations Tuesday-Friday and Wednesday-Friday seem to lay on the lowest level when driving twice. In the MRP-model, it can be observed that driving twice does make a difference since the confidence interval lays lower than the others. In addition, a paired-T approach was conducted with a confidence level of 95%. This paired-T approach can be found in *appendix F.6* This showed that driving two times, on Wednesday and Friday or Tuesday and Friday outperforms all other combinations. Between these two combinations, no significant difference can be observed. Moreover, driving three times does outperform all other combinations.

Conclusions regarding the transport-day

In the base model, the best transport-day is on Friday, if transport is done once. When transport is done twice, the best combination is on Wednesday and Friday. Transporting three times (Mo-We-Fr) does not outperform this combination.

Using the base model, transporting three times does not make much difference since every Monday product As move on to the next 'production chain'. Therefore, too little products A finished the production chain in the time that the next truck arrives. For a similar reason, the best transport day (Friday) sounds reasonable. In this way, most products A can be produced and send to THE OUTSOURCING COMPANY because all products A that are ready, are sent to THE OUTSOURCING COMPANY. Or in other words, the truck is loaded with more products A. This is because products produced in the time Monday to Friday, are now also loaded in the truck, while they were initially scheduled a week later. The same reasoning can be drawn for the combination Wednesday-Friday.

Regarding costs, the following table can be made. For this, the transport costs as defined in *section 2.4* are assumed. In this section, the transport costs for one trip were [censored]resulting in yearly transport costs of [censored], assuming no holidays, days off, etc. The differences with the Monday is based on the paired-T approach (95%) for the average total throughput time and the difference between the mean WIP and WIP value.

Table 30: Comparing the transport days based on time gains, WIP, and WIP value for the base model.

Transport	Approximate time saving regarding transporting once on Monday	Yearly costs (rounded)	Difference in mean WIP regarding base model (pc.)	Difference in mean WIP value regarding base model
Monday	0	€21241,-	0	0
Friday	3 days and 2 hours to 3 days and 6 hours	€21241,-	8,34	€41676,-
Wednesday and Friday	7 days and 16 hours to 7 days and 22 hours.	€42482,-	20,4	€100209,-
Monday, Wednesday and Friday	Similar to Wednesday and Friday.	€63723,-	Similar to Wednesday and Friday.	Similar to Wednesday and Friday.

Or regarding Friday (the optimal day):

Table 31: Comparing the transport days based on time gains, WIP, and WIP value for the base model, regarding the best transport day.

Transport	Approximate time saving regarding transporting once on Friday	Yearly costs (rounded)	Difference in mean WIP regarding Friday (pc.)	Difference in mean WIP value regarding Friday (pc.)
Friday	0	€21241,-	0	0
Wednesday and Friday	4 days and 9 hours to 4 days and 17 hours.	€42482,-	11,71	€58533,-

Within the MRP-model, the best transport-day is on Thursday, if transport is done once. When transport is done twice, the best combination is on Tuesday and Friday or Wednesday and Friday. Transporting three times (Mo-We-Fr) does outperform these combinations. Why these exact days are better, is not that clear to me. Probably the same reasoning as before can be used. The truck is probably loaded the most when Thursday is chosen as transport day. Another reason could be that the truck back to customer X is loaded the most when Thursday is chosen. Somewhere, there is a trade-off between these two. The same reasoning can be used for the other transport combinations.

Regarding costs, the following table can be made (costs as defined in *section 2.4).* The difference with the Monday is based on the paired-T approach (95%) and the difference between the mean WIP.

Table 32: Comparing the transport days based on time gains, WIP, and WIP value for the MRP-model.

Transport	**Approximate time saving regarding transporting once on Monday**	**Yearly costs (rounded)**	**Difference in mean WIP with regarding base MRP model (pc.)**	**Difference in mean WIP value regarding base MRP model**
Monday	0	€21241,-	0	0
Thursday	4 days and 21 hours to 5 days and 6 hours.	€21241,-	13,04	€65181,-
Tuesday and Friday	8 days and 11 hours to 8 days and 15 hours.	€42482,-	22,04	€110200,-
Wednesday and Friday	8 days and 9 hours to 8 days and 18 hours.	€42482,-	22,00	€110016,-
Monday, Wednesday and Friday	10 days and 3 hours to 10 days and 6 hours.	€63723,-	26,25	€131259,-

Or regarding Thursday (the optimal day):

Table 33: Comparing the transport days based on time gains, WIP, and WIP value for the MRP-model, regarding the best transport day.

Transport	**Approximate time saving regarding transporting once Thursday**	**Yearly costs (rounded)**	**Difference in mean WIP regarding Thursday (pc.)**	**Difference in mean WIP value regarding Thursday (pc.)**
Thursday	0	€21241,-	0	0
Tuesday and Friday	3 days and 7 hours to 3 days and 17 hours.	€42482,-	9,00	€45020,-
Wednesday and Friday	3 days and 7 hours to 3 days and 16 hours.	€42482,-	8,97	€44835,-
Monday, Wednesday and Friday	5 days to 5 days and 7 hours.	€63723,-	13,22	€66078,-

The tables show that considering the transport day is important for reducing the throughput time. This can already reduce throughput time significantly without increasing any costs. In addition, transporting more often will also reduce the throughput time significantly, but with a cost. Even though the cost increase, the WIP and with that the WIP value decrease. Based on these numbers, the management of COMPANY A should make an assessment if this is worth it. The optimal day and combination of days depends on the delivery and acquiring day of the customer. All these combinations are not tested, though aligning these is important since it can significantly reduce waiting times.

The influence of an extra machine

By experimenting with an extra machine, it is not a matter of simply adding an extra machine. In the base model, the shifts of the machines are adapted such that an extra machine is not needed. Though, if an extra machine is added, the shifts might not need to be this long. Therefore, multiple scenarios will be compared, again for both the base and the MRP-model.

Adding an extra Machine 1 for the base model

For adding an extra Machine 1, multiple scenarios will be compared, both in the base model and in the MRP-model.

- S.1. The base model
- S.2. The base model with an extra Machine 1 (no changes to shifts)
- S.3. The base model with an extra Machine 1, working 24 hours, 5 days per week.
- S.4. The base model with an extra Machine 1, working 24 hours, 3 days per week.

Why these scenarios? Scenario 2 is added to check the influence of an extra Machine 1. Scenario 3 is added to have a normal Machine 1 shift, without the Saturday. Scenario 4 is added to check the effect if the minimal number of working hours is used. Though, the shift in scenario 4 could be only 16 hours for the last day (the third day). However, the difference between working 16 hours and 24 hours is not interesting since the machine can run 8 hours unmanned on a 24-hour shift. This cannot be done on 16-hour shifts since set-up times are too long for that (also see chapter 2). Working shorter than 3 days per week is not possible since the system would, in that case, overload.

Adding an extra Machine 1 for the base model

The results for experimenting within the base model are displayed in table 34:

Table 34: Results of KPI's for the models of the four different scenarios for adding an extra Machine 1 (base model).

	Avg. Internal TT	Total Avg. TT	Average total WIP	Machine 1 Occupation	Avg. Waiting for Machine 1
S1	44:03:46:56	65:02:21:55	167,3941	0,78	06:21:12:56
S2	44:03:48:59	65:02:21:17	167,3918	0,40	05:06:28:59
S3	44:03:48:59	65:02:21:17	167,3918	0,48	05:06:28:59
S4	46:18:25:56	67:17:38:25	174,1758	0,81	06:11:28:09

The average weekly output and average total output was also assigned as an experimental factor. The total output was similar for scenario 1, 2, and 3. The total average output was only one product A lower in scenario 1 and seven to eight products A lower for scenario 4. Therefore it can be assumed that all scenarios acquire a similar output, making them comparable.

This resulted in the following confidence intervals (95%) for the average total throughput time:

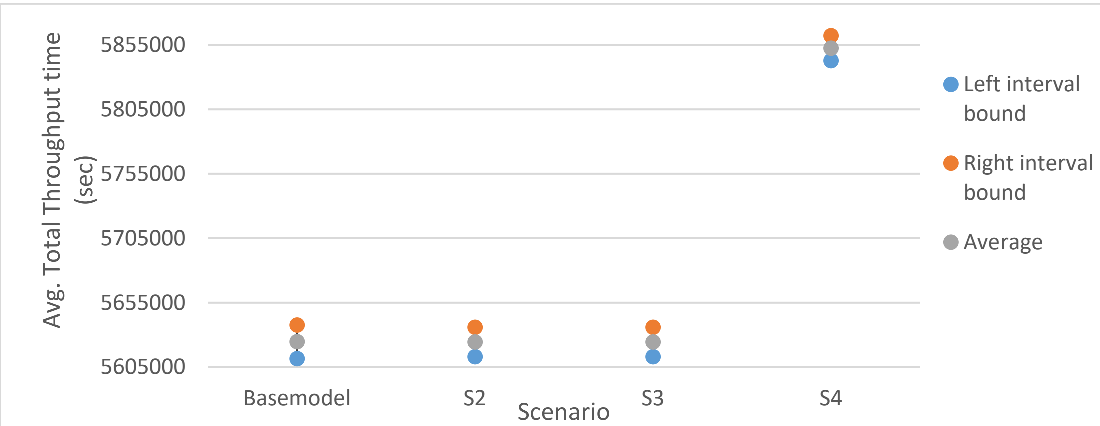

Figure 11: Confidence intervals for the average total throughput time for the models of the four different scenarios for adding an extra Machine 1 (base model).

Based on the table and graph, no difference is observed between the base model, scenario 2, and scenario 3, while in scenario 4 the total throughput time is much larger. This is underlined by the paired-T approach (95% sign.), which can be found in *appendix F.7.*

Analysis of the results of adding an extra Machine 1 machine for the base model

Some interesting results can be observed by adding an extra Machine 1 machine. For scenario 1, 2 and 3, no difference is observed. This is because one Machine 1 machine could already handle all 18 products A in one week. Adding an extra Machine 1 does not change this. The limiting of weekly working hours in scenario 3 was also not enough to change this. In scenario 4, working hours are limited even more to save costs. Because of this, an increase in the occupation can be observed. A result of this is, that not all products A are finished at the end of Wednesday, such that they do not make the week planning, resulting in a longer average total throughput time, and thus, a larger WIP. Furthermore, adding an extra Machine 1 reduces the waiting time. The waiting time is lower since now two Machine 1s are present. However, this waiting time is now behind the Machine 1 since the parts must wait for the next week to start (based on the planning of the base model). In addition, the occupations differ because of the different number of Machine 1 machines and changes in shifts.

Even though no decrease in throughput time is observed, adding an extra Machine 1 machine made it possible to limit the working shifts on the Machine 1. Perhaps this is cheaper than working in the shift assumed in the base model. To check this, a cost-analysis will be done.

Recall that the following costs are assumed in this thesis (*section 2.4*):

Table 35: Assumed costs (based on section 2.4).

	Costs
Full-time employee machine operator p/h	
Full-time employee overtime (17%) p/h	
Machine 1 machine p/y	
Machine 2 machine p/y	

It is assumed that the overtime costs on Saturday night are equal to normal overtime costs (17%). In reality, this is probably not true. Recall that a Machine 1 is unmanned for 8 hours on a 24-hour shift (also see chapter 2).
This results in the following comparison for the scenarios, by simply assuming 52 weeks in a year.

Table 36: Total machine and employee cost for adding an extra Machine 1.

	S1	**S2**	**S3**	**S4**
Number of Machine 1 machines	1	2	2	2
Number of normal manned hours per week	40	80	80	48
Number of overtime manned hours per week	40	80	80	48
Saturday hours per week	16	32	0	0
Machine 1 costs (y)				
Normal FTE costs (y)				
Overtime FTE costs (y)				
Saturday Costs (y)				
Total (y)	**€ 369.481,60**	**€ 738.963,20**	**€ 661.088,00**	**€ 516.652,80**

Two Machine 1 machines cannot be operated by one operator. Therefore, another operator is needed for an extra machine. Based on this table, it can be concluded that working in 24-hour shifts and on Saturday, is always cheaper (per year) than buying an extra Machine 1. This is mainly because you still need this extra employee for this extra Machine 1. It is not possible to limit the working hours enough such that a second Machine 1 is cheaper. In addition, in the base model, no time gains can be acquired by adding an extra Machine 1 because of the week-to-week planning.

Adding an extra Machine 1 for the MRP-model

The results for the MRP model are:

Table 37: Results of KPI's for the models of the four different scenarios for adding an extra Machine 1 (MRP-model).

	Internal Avg TT	Total Avg TT	Average Daily Total WIP	Machine 1 Occupation	Avg. Waiting for Machine 1
S1	21:23:07:28	41:14:41:39	107	0,78	02:14:08:29
S2	21:21:45:26	41:13:30:56	106,88	0,41	00:15:43:44
S3	21:21:02:36	41:12:43:12	106,79	0,49	00:15:43:52
S4	22:12:02:54	42:01:39:19	108,18	0,82	01:22:17:37

All scenarios, again, had similar output, making them comparable. The following confidence intervals (95%) for the average total throughput time were constructed:

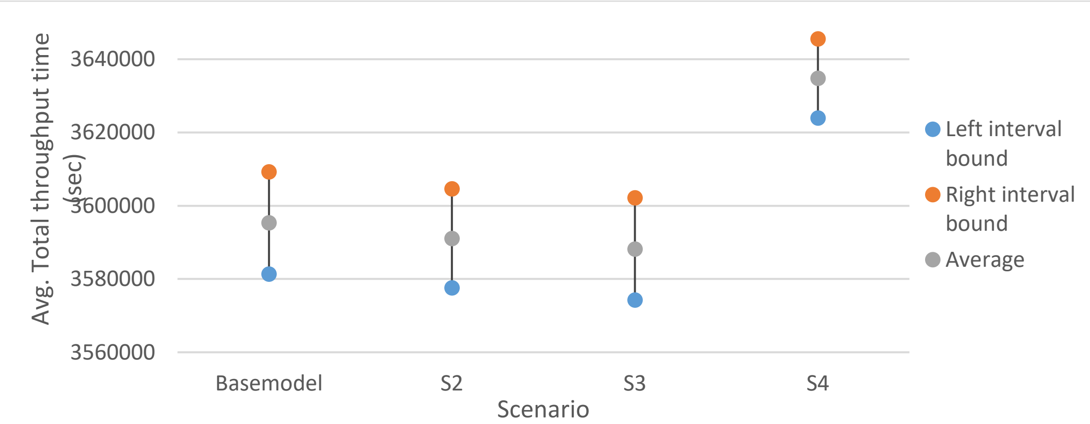

Figure 12: Confidence intervals for the average total throughput time for the models of the four different scenarios for adding an extra Machine 1 (MRP-model).

The graph and table have a similar pattern as the graph in the base model. The first three scenarios are on a similar level, whereas scenario 4 is much higher. A paired-T approach was done in *appendix F.7* in order to check if this difference was a significant difference between the results (95%). Again, the first three scenarios do not have a significant difference in average total throughput time. The first three scenarios outperform scenario 4.

Analysis of the results of adding an extra Machine 1 machine for the MRP-model

Again some interesting results can be observed. First, no significant difference between the base model, scenario 2 and scenario 3 can be observed, which is strange. You would expect scenario 2 and 3 to perform much better since the utilization of the Machine 1 is relatively low. Moreover, waiting time in front of the Machine 1 is significantly reduced. I do not completely know why no difference is observed, but I could think of two reasons:

1. Probably all products A are finished up until the transport to THE OUTSOURCING COMPANY, not matter if one or two Machine 1 machines are used. Therefore, the second Machine 1 does not make the process faster since products need to wait for the transport to THE OUTSOURCING COMPANY on Monday. So, it does not matter if the products are finished earlier or not, as long as the products are finished before the next Monday.
2. Because the Machine 1 department is much faster with two machines, the queue simply builds up a department after the Machine 1, for example at the deburring department. One factor that enhances this, is that the Machine 1 department works during the night while the deburring department is only working in normal hours. So, any time the deburring starts its shift, it will observe a queue, made during the night.

Scenario 2 and scenario 3 perform similar since the working hours in scenario 3 are not decreased that much regarding scenario 2. The occupation only increases a little bit, but not enough to perform worse. Scenario 4 is performing significantly worse than the other scenarios. In this situation, the working hours are reduced that much, such that it affected the performance of the model. This is because the occupation is relatively high for both Machine 1 machines in this scenario. In this case, some products A are probably not finished before the next Monday, resulting in longer total throughput time.

With regard to costs, the costs for the scenarios in the MRP-model are the same as in the base model, which are displayed in *table 34*. Again, no significant improvement in total throughput time can be observed by adding an extra Machine 1, nor in costs or average total throughput time. So, also for the MRP-model, adding an extra Machine 1 is not interesting.

Adding an extra Machine 2

For adding an extra Machine 2 machine, the following scenarios have been compared:

- S.1. The base model (for the MRP comparison, the base MRP-model).
- S.2. The base model with an extra Machine 2 (no changes to shifts).
- S.3. The base model with an extra Machine 2, working normal office hours.
- S.4. The base model with an extra Machine 2, working only 8 hours, 3 days per week.

Why these scenarios? Scenario 2 is added to check the influence of an extra Machine 2. Scenario 3 is added to have a normal working shift, just like the other departments. Scenario 4 is added to check the effect if the minimal number of working hours is used (using intervals of 4 hours). So, if in scenario 4 the shift would be 4 hours shorter, the system would have an occupation higher than 85%, something that was not allowed (assumption).

The results for the base model

The results of adding an extra Machine 2 to the base model are:

Table 38: Results of KPI's for the models of the four different scenarios for adding an extra Machine 2 (base model).

	Internal Avg TT	Total Avg TT	Average Daily Total WIP (pc.)	Avg. Waiting for Machine 2 (sec)	Avg. Machine 2 occupation
S1	44:03:46:56	65:02:21:55	167,39	245139,9	0,84
S2	42:00:41:03	63:00:00:58	162,00	45573,15	0,42
S3	42:00:41:03	63:00:00:58	162,00	45573,15	0,50
S4	44:00:24:51	64:23:28:51	167,10	174838,9	0,84

Again, with similar outputs such that the scenarios can be compared. The following confidence intervals (95%) have been constructed for the total average throughput time:

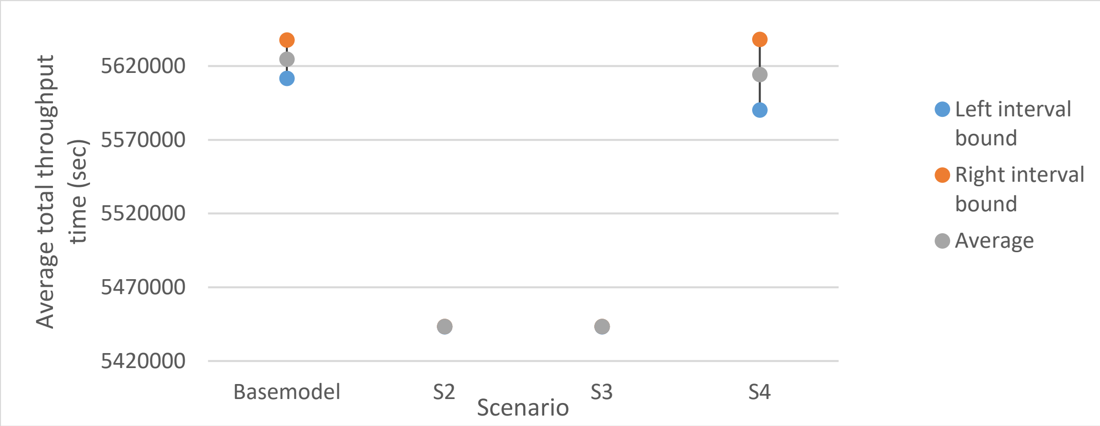

Figure 13: Confidence intervals for the average total throughput time for the models of the four different scenarios for adding an extra Machine 2 (base model).

In the graph (and corresponding numbers in the table), the base model and scenario 4 seem to lay on a similar level, whereas scenario 2 and 3 are also on a similar level, much lower. Moreover, the confidence interval of scenario 2 and 3 seem to be much smaller than the other scenarios. A paired-T approach was done in order to check if a significant different was present (95%). This can be found in *appendix F.7*. Scenario 2 and scenario 3 outperform scenario 1 and 2. Between the two scenarios, no difference can be observed. Between scenario 1 and scenario 4, no significant difference can be observed.

Analysis of the results of adding an extra Machine 2 machine to the base model

In contrast to adding an extra Machine 1, adding a Machine 2 machine does change the performance of the base model. As mentioned, in the base model, the chain in week 5 is quite long. So long that sometimes not all activities can be performed within one week. By adding an extra Machine 2 machine and scheduling enough production hours on these Machines 2, this problem is probably solved, reducing the total throughput time to approximately 63 days, just as the planning intends to do. The total average throughput time is slightly higher since in some replications the 63 days were still not attained. That is also why the confidence intervals for scenario 2 and 3 are so small. By limiting the number of hours on the Machine 2, as done in scenario 4, it can be observed again that some activities will not be finished for every Product A in week 5, resulting in again a higher average total throughput time. Apparently, the capacity in scenario 3 is not limited that much, such that it does not change anything regarding the total throughput time, in comparison to scenario 2. Only the occupation in scenario 3 is slightly higher.

In order to make a costs analysis, the same costs as in the previous section will be used. One big advantage of using an extra Machine 2 over an extra Machine 1 is that two Machines 2 can be operated by one operator, instead of two. This was acknowledged by the current Machine 2 operator. A restriction for this is, that the same Machine 2 should be bought, with the same programs and set-up. Otherwise, it becomes more difficult (also acknowledged by the operator). For the four scenarios, the following costs have been constructed, by simply assuming 52 weeks in a year.

Table 39: Total costs for the models of the four different scenarios for adding an extra Machine 2.

	S1	S2	S3	S4
Number of Machines 2	1	2	2	2
Number of normal hours per week	40	40	40	24
Number of overtime hours per week	0	0	0	0
Saturday hours per week	8	8	0	0
Machine 2 costs (y)				
Normal FTE costs (y)				
Overtime FTE costs (y)				
Saturday Costs (y)				
Total (y)	**€ 137.668,80**	**€ 172.668,80**	**€ 153.200,00**	**€ 119.920,00**

Mainly because one operator can operate two Machines 2, the costs are much lower by buying another Machine 2 in comparison to an extra Machine 1. The costs of adding an extra Machine 2 increase when the same working shift or an office working shift is used. Though, when the working shift is shortened to only three days, the model performs like the base model (paired-t test, sign. 95%), with lower costs. So, adding an extra Machine 2 is an interesting option.

To compare the scenarios, the yield/costs for the scenarios are:

Table 40: Comparing the four scenarios for adding an extra Machine 2, based on time gains, costs, WIP, and WIP value.

	Approximate time saving regarding the base model	**Extra/reduction in yearly costs (rounded)**	**Difference in mean WIP regarding the base model (pc.)**	**Difference in mean WIP value regarding the base model**
S2	1 day and 23 hours to 2 days and 6 hours.	€ 35.000	5,39	€26962,-
S3	1 day and 23 hours to 2 days and 6 hours.	€ 15.531	5,39	€26962,-
S4	0	- € 17.749	0,31	€1575,-

The results for the MRP-model

The results of adding an extra Machine 2 to the MRP-model are:

Table 41: Results of KPI's for the models of the four different scenarios for adding an extra Machine 2 (MRP-model).

	Internal Avg TT	**Total Avg TT**	**Average Daily Total WIP (pc.)**	**Avg. Waiting for Machine 2 (sec)**	**Avg. Machine 2 occupation**
S1	21:23:7:28	41:14:41:39	107,00	250230,6	0,84
S2	19:10:1:54	39:01:07:19	100,41	47215,53	0,42
S3	19:10:1:54	39:01:07:19	100,41	47215,53	0,50
S4	21:3:33:43	40:16:50:37	104,66	158283,9	0,84

Again, with similar outputs such that the scenarios can be compared. The following confidence intervals (95%) have been constructed for the total average throughput time:

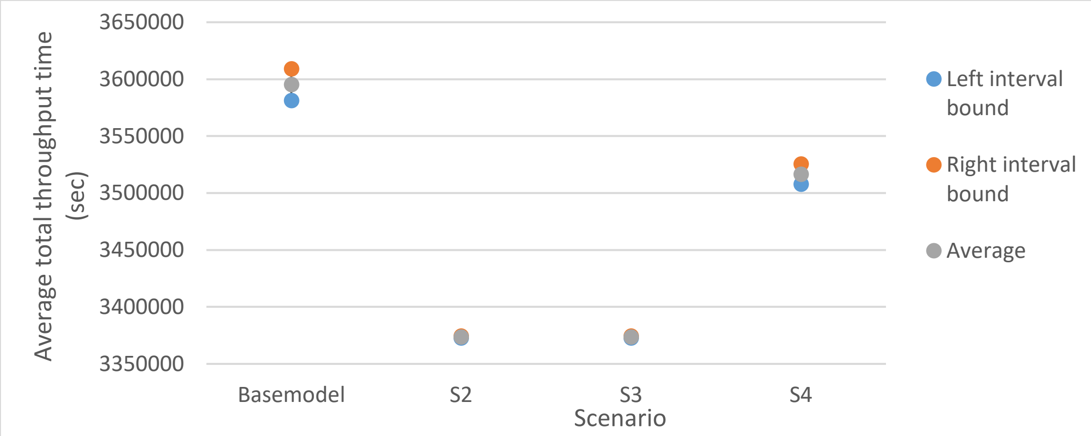

Figure 14: Confidence intervals for the average total throughput time for the models of the four different scenarios for adding an extra Machine 2 (MRP-model).

The confidence interval of the base model seems to lay higher than the other scenarios. Again, scenario 2 and 3 seem to perform similar, with, again, a small confidence interval. Scenario 4 lays higher than scenario 2 and 3, but a bit lower than the base model. A paired-T approach was done in order to check if this difference was significant (95%). This can be found in *appendix F.7.* Again, scenario 2 and scenario 3 outperformed all other scenarios. Between the two, no difference can be observed. Scenario 4 outperforms scenario 1.

Analysis of the results of adding an extra Machine 2 machine to the MRP-model

Regarding adding an extra Machine 2 to the MRP-model, similar conclusions can be drawn as in adding a machine 2 to the base model. Scenario 2 and 3 outperform the other scenarios. Between the two, again no differences can be observed regarding average total throughput time. The decrease in shift hours in scenario 3 is not so big such that waiting time in front of the machine 2 increases regarding scenario 2. The decrease in shift hours is big enough in the fourth scenario, such that the total throughput time increases again. Scenario 4 is still significantly lower than the base model though. Regarding costs, the following conclusion can be drawn:

Table 42: Comparing the four scenarios for adding an extra Machine 2 based on time gains, costs, WIP, and WIP value.

Scenario	Approximate time saving regarding the MRP-model	Extra/reduction in yearly costs (rounded)	Difference in mean WIP regarding the base MRP model (pc.)	Difference in mean WIP value regarding the base MRP model
S2	2 days and 10 hours to 2 days and 18 hours.	€ 35.000	6,59	€32941,-
S3	2 days and 10 hours to 2 days and 18 hours.	€ 15.531	6,59	€32941,-
S4	18 hours and 20 minutes to 1 day, 1 hour and 22 minutes.	- € 17.749	2,34	€11709,-

The time gains in the MRP-model are much larger since it is not affected by the week-to-week planning. In addition, scenario 4 is acquiring time gains while also saving costs in the MRP-model. So, adding a Machine 2 machine is again an interesting option.

Transport to customer X

Waiting for delivery to the customer is also a factor that influences the throughput time. For example, if products A are transported to the customer on for example Monday, and product A is finished on Tuesday, it has to wait for another 6 days before it will be transported. Therefore the delivery day and the frequency might also be an interesting factor to experiment with.

Choosing a different delivery and acquiring day does not influence the base model. A different delivery and acquiring day would only mean that the entire production schedule does not start on, for example, Monday, but on a Tuesday, resulting in similar results. It would be interesting to see what the effect would be of delivering and acquiring products A twice per week. Though, to change the base model as such, such that this can be experimented, would take a lot of modeling time. Regarding the time of this thesis, this will not be done since the results would, in my opinion, not be that valuable for the base model. This opinion is based on the following example:

For example, the new and finished products A are delivered and acquired on Monday and Thursday. Delivering twice would mean that 9 products A start on Monday and are acquired on Monday 9 weeks later. The same goes for Thursday. This is because this is simply how the planning is made. The only effect this has, is that the batch sizes are smaller. Therefore, spreading product As more over the week such that products A are produced not only at the start of the week but also at the end of the week. In this way, queues would probably be lower in longer chains (for example the chain in week 5) such that perhaps less waiting time is observed. Though, the departments still have to do the same amount of work, so queues at bottlenecks would probably still be as long. Lastly, delivering twice would, if the planning was strictly followed, also need transporting to THE OUTSOURCING COMPANY twice. If not, delivering and acquiring is also influenced by the chosen THE OUTSOURCING COMPANY date, adding even more complexity.

To conclude, the delivery and acquiring days and intervals will not be experimented for the base model. Though, to see the influence of transporting on a different day than Monday and of transporting more often, it will be done for the MRP-model. In this model, the issues mentioned above do not play a role since the planning is not 'fixed'. The transport day to THE OUTSOURCING COMPANY is set on Monday for similar reasons as outlined above (interaction effects), just like in the base model.

The optimal delivery and acquiring day in the MRP-model

Regarding the optimal transport day, the following results were acquired.

Table 43: Results of KPI's for a different delivery and acquiring day (MRP-model).

	Average Internal throughput time	Total average throughput time	Total average WIP (pc.)	Avg. Waiting for Delivery
Mo	21:23:07:28	41:14:41:39	107,00	05:15:34:11
Tu	22:06:27:35	38:12:19:05	99,04	02:05:51:30
We	22:08:29:38	37:14:53:11	96,74	01:06:23:32
Th	23:14:38:38	39:17:56:06	102,21	02:03:17:28
Fr	23:17:03:12	40:20:42:55	105,09	03:03:39:43

With the following corresponding confidence intervals (95%) of the total average throughput time:

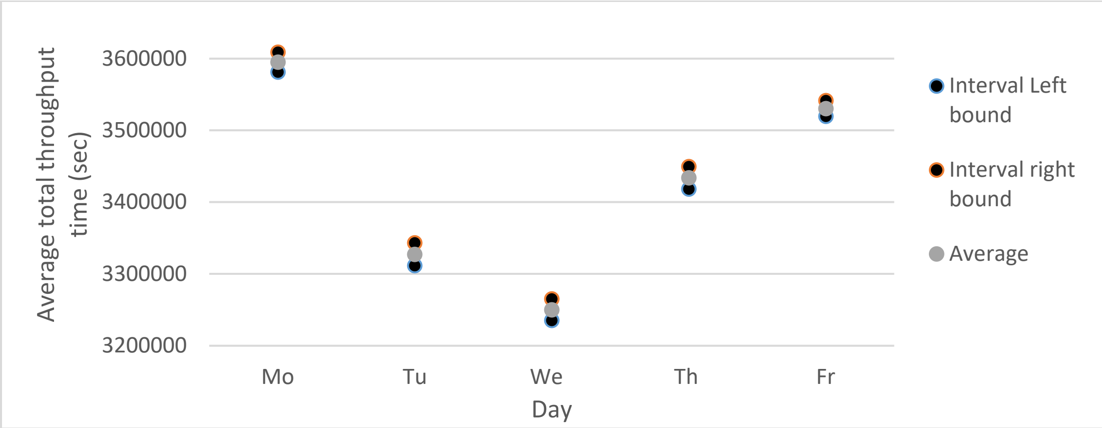

Figure 15: Confidence intervals of the average total throughput time for a different delivery and acquiring day (MRP-model).

The different days change the throughput time. The confidence interval of Wednesday lays lower than all other days. Moreover, no confidence interval seems to be overlapping. This shows that choosing a different day does change outcomes. As an addition, a paired-T approach was conducted with a confidence level of 95%. This paired-T approach can be found in *appendix F.8*. Based on this, Monday is significantly larger as all the other days. Moreover, Wednesday outperforms all other delivery and acquiring days. Tuesday outperforms Thursday and Friday, while Thursday outperforms Friday.

Multiple transport days and the best combination

Regarding the optimal combination, if driving two customer X is done two or three times, the following results can be acquired:

Table 44: Results of KPI's for a combination of different delivery and acquiring days (MRP-model).

	Internal avg. TT (s)	Total avg. TT (s)	Total average WIP (pc.)	Average waiting for delivery (s)
Mo - We	19:14:26:50	34:16:35:52	89	01:02:09:00
Mo - Th	19:16:24:51	35:14:37:14	92	01:22:12:22
Tu - Th	20:06:12:39	35:00:53:55	90	00:18:41:15
Tu - Fr	20:08:09:30	35:10:11:11	91	01:02:01:41
We - Fr	20:12:01:47	35:16:19:56	92	01:04:18:08
Mo - We - Fr	19:20:05:56	34:21:00:08	90	01:00:54:11

With the corresponding confidence intervals (95%) regarding the total average throughput time:

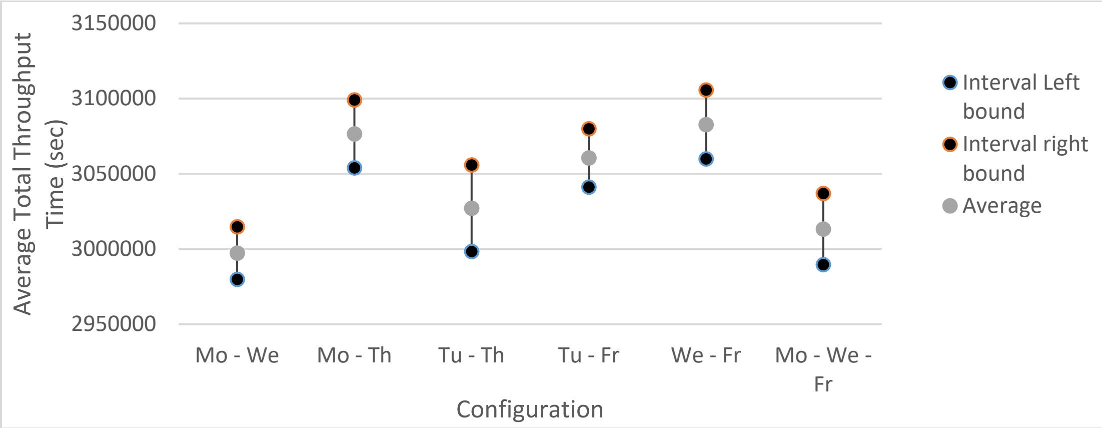

Figure 16: Confidence intervals of the average total throughput time for a combination of different delivery and acquiring days (MRP-model).

In contrast to different delivery days, confidence intervals of combinations of days are overlapping. This is because the averages in the tables are relatively close to each other. The average of the combination Monday-Wednesday seem to lay the lowest. Though, based on the graph it is difficult to say which combination performs the best. Therefore, a paired-T approach was conducted with a confidence level of 95%. This paired-T approach can be found in *appendix F.8.* With this paired-T approach, Monday and Wednesday have also been compared to driving more often to customer X. Driving two times always outperformed driving one time. Moreover, driving Monday and Wednesday outperformed all other combinations of transport days, including driving three times. The conclusions for the other configurations can be found in the appendix.

Analysis of the results

Regarding the standard MRP-model, the best day to acquire new products A and send finished products A is on Wednesday. It is interesting to see that the internal throughput time on Monday is lower than on Wednesday. An explanation for this could be that waiting on THE OUTSOURCING COMPANY is lower in the model (included in internal throughput time) but waiting on the customer is longer, resulting in a longer total throughput time.

When transporting is done twice, the best configuration is on Monday and Wednesday. Another interesting configuration is Tuesday and Thursday since it has the lowest waiting on delivery time. Though, with the configuration Monday – Wednesday, average waiting for THE OUTSOURCING COMPANY time is probably lower. This configuration even outperforms driving three times. An explanation for this might be the introduced set-up times. If the batches become smaller, departments finish the smaller batches faster, leaving the department idle. Later, a new batch comes in, and the department needs to be set-up again. In a larger batch, the department only needs set-up once for the entire batch. This disadvantage does not outweigh the difference between driving one or two times but does outweigh the difference between driving two or three times.

Regarding the saving in throughput time, the following conclusions can be drawn based on the paired-T approach (95%). Unfortunately, no costs are known for this transport. It is unclear who will pay what since transporting more often is also interesting for the customer because it acquires product As faster.

Table 45: Comparing the different delivery and acquiring days on time gains, WIP, and WIP value.

Configuration	Approximate time saving regarding delivering and acquiring once on Monday.	Difference in mean WIP regarding the base MRP model (pc.)	Difference in mean WIP value regarding the base MRP model
Monday	0	0	0
Wednesday	3 days and 21 hours to 4 days and 2 hours.	10,26	€51308,-
Monday and Wednesday	6 days and 19 hours to 7 days and 1 hour.	17,80	€88983,-

And the approximate time saving regarding delivering and acquiring once, on Wednesday compared to driving twice on Monday and Wednesday is 2 days and 20 hours to 3 days and 1 hour (paired-T approach – 95%). This corresponds to a difference in mean WIP of approximately 7,54 pc. and a difference in mean WIP value of €37676,-. This experiment shows again that the outsourcing day to THE OUTSOURCING COMPANY and delivery and acquiring day of the customer should be well-aligned.

6.4 Determining the required capacity

This section will return to the main question of this thesis, namely the action problem presented by the company:

How can the throughput time of product A be minimized from 9 weeks to a maximum of 4 weeks?

This section will combine the best results from the experiments to determine the capacity and things that are needed to reduce throughput time to a maximum of 4 weeks. This will be done in a simulation model, in which the results are combined. With these combined results, the model will be run. Consequently, it will be investigated if the average throughput time is under 4 weeks. If this is true, all the things will be outlined that are needed to produce under 4 weeks. This includes the number of full-time employees (FTE's), by tracking their occupation and calculating the minimal number of needed FTE's. FTE's are based on 40 hours per week.

This is also done because, during this thesis, a sufficient capacity was assumed by calculating the needed capacities. In addition, in the simulation model, some departments were modeled separately because their occupations are not that high, while they are one department in reality. By combining them in this section, the needed capacity can still be determined. So, this solves these two assumptions that were made when modeling was initiated.

Determining what is needed to reduce throughput time to four weeks

In order to experiment, the inputs of the model in which the throughput time is under four week should be determined. First, the throughput time can never be under 4 weeks by using the current planning. The current planning is built to create a throughput time of 9 weeks. Therefore, the MRP-model is the starting planning for the model. In addition, an extra Machine 2 is added with a normal office shift. As shown in the last section, this saves time and money. It was chosen to give the Machine 2 an office shift, instead of the three-day shift, in order to compare it to the other departments, that also have a normal office shift. No extra Machine 1 will be added since this was not interesting (see previous section). Therefore, the Machine 1 will need the same shift as in the base model.

Unfortunately, this is not enough to produce the required amount (18 per week) in four weeks on average. An effective way to increase the throughput time is increasing transport from one to two times per week. Another way would be by adding more personnel or machines. However, I think so many staff and machines should be added to decrease the total throughput time to four weeks, that it would become unrealistic and too costly. By adding more personnel or machines only gains of a few hours are acquired while transporting is gaining days in total throughput time. Since transporting more often to THE OUTSOURCING COMPANY was more effective than transporting more often to the customer, this was added to the model. As observed in the experiments, the optimal combination with the delivery day of the customer on Monday, was Wednesday and Friday. So, this configuration was added. This led to the following results:

Table 46: Results of the combined model (1).

	Average (DD:HH:MM:SS)	**Confidence (95%) interval left bound**	**Confidence (95%) interval right bound**
Internal throughput time	13:06:08:39	13:06:01:49	13:06:15:29
Internal throughput time incl. THE OUTSOURCING COMPANY	27:06:08:39	27:06:01:49	27:06:15:29
Total throughput time	30:14:41:30	30:14:26:42	30:14:56:18
Internal WIP	78,72	78,70	78,75
WIP value	€ 393.606	€ 393.477	€ 393.735

The same experimental set-up as before was used. I am showing these results since the confidence interval of the internal throughput time incl. THE OUTSOURCING COMPANY is already under 4 weeks, while the total throughput time is not. Recall that the total throughput time also includes the time when the customer has product As in the truck. So, depending on what COMPANY A wants to achieve, this could already be enough to produce the required amount.

However, if COMPANY A also wants to have the total throughput time under four weeks, more is needed. As shown, for this, driving two times to the customer should be added. As mentioned in the previous chapter, the optimal combination of driving two times to THE OUTSOURCING COMPANY and driving to times to the customer was not tested. This would, because of interaction effects, result in too many experiments. In order to acquire a good combination, the transport to THE OUTSOURCING COMPANY was set on Wednesday and Friday. By consequently testing combinations of transporting to the customer, a combination of both transporting configurations were chosen. This testing was done with one replication (run length 5000 days). It turned out that the best combination was driving to the customer on Monday and Thursday if the transport day to THE OUTSOURCING COMPANY is set on Wednesday and Friday. It is not certain if this is the optimal combination. Though, I believe it is quite a good combination. The results of the corresponding model are:

	Average (DD:HH:MM:SS)	Confidence (95%) interval left bound	Confidence (95%) interval right bound
Internal throughput time	10:18:30:10	10:18:23:27	10:18:36:52
Internal throughput time incl. THE OUTSOURCING COMPANY	24:18:30:10	24:18:23:27	24:18:36:52
Total throughput time	25:21:10:49	25:21:02:37	25:21:19:02
Internal WIP	66,55	66,54	66,57
WIP value	€ 332.771	€ 332.697	€ 332.845

Table 47: Results of the combined model (2).

As shown, the confidence interval is completely under four weeks. So, the goal is achieved.

Capacity and cost analysis for reducing throughput to four weeks

Since it is known what is needed to produce under four weeks, this can now be outlined. First, the minimal number of FTE's will be given. The capacities in both models (with and without driving twice to the customer) is equal, and thus the occupations are also equal. This is not completely true. The average occupations differ with numbers as big to the power minus five. Therefore, these differences are neglected. The average occupations from the replications can be found in *appendix F.9.* These occupations have been combined per skill-group. This is not actually the case since, for example, cleaning is currently not doing the inserts. Though, I believe they can do this in the future. The colors display the occupations from the appendix that are added together in one department. Note that the occupation of the Machine 2 is so low since two Machines 2 are present, operated by one operator. In reality, it is perhaps unlikely that the operator can work twice as hard by adding an extra Machine 2, resulting in probably a higher occupation.

Table 48: Outlined needed FTE's with the attached costs.

Department	Occupation	Portion FTE's	Real FTE's	FTE's costs (y)
Expedition	0,49	0,49	1	
Quality control	0,24	0,24	1	
Benchworking and part marking	1,80	1,80	2	
Cleaning, control room, assembly of inserts, and cleanliness test	0,79	0,79	1	
Office	0,24	0,24	1	
Assembly	0,37	0,37	1	
Sandblasting	0,51	0,51	1	
Machine 2	0,37	0,37	1	
	Total	4,82	9	[censored]

By assuming a utilization 100% for the employees, the portion FTE's is equal to the occupation. The 'real FTE's' can be determined by rounding this number up. Though, these FTE's do not have to be busy with product As all the time. To conclude, in total 9 FTE's will be needed in order to do 4,82 portion of FTE work. Note that 100% utilization is not true because of holidays, illness, etc. In addition, the machines have failures, breakdowns, and maintenance. Therefore, the 4,82 FTE work is actually higher. The costs are based on the costs assumed in *chapter 2.*

Note that the Machine 1 machine operator is not added in this analysis since the Machine 1 has a totally different shift. Because of this, the Machine 1 has the following costs, based on the number of working hours.

Table 49: Needed shift for the Machine 1 machine and the attached costs.

	Normal hours	Overtime hours	Utilization	FTE's costs (y)
Machine 1	40	56	0,78	[censored]

It is uncertain how many employees are needed to run these shifts. At least two will be needed to do the work during the week. However, more operators are needed to also do 16-hour shift on Saturday, or else the two other employees need to work 8 hours of overtime every week. In my opinion, three employees, running 32 hours per week would be the best option. In this way, the Saturday hours can be equally divided by the operators during the year. In addition, if an operator needs to work on Saturday, he/she can have spare time during the week. Another interesting option could be that 3 operators work 40 hours per week in order to have normal shifts. This makes it probably easier to acquire new employees since there is currently a lot of demand for turning and milling operators, that probably preferably want to work 40 hours per week. The time that these employees will have left, can be used for other customers.

Next to employee costs, the following yearly costs for the machines will be made:

Table 50: Yearly machine costs.

Machine 1 (y)	
Two Machines 2 (y)	
Measuring machine (y)	
Sandblasting machine (y)	

And for transport to THE OUTSOURCING COMPANY (twice), the yearly costs will be €42482,-.
Next to employee, transport, and machine costs, the following other costs are assumed by COMPANY A:

Table 51: Other yearly costs.

Building, 440 m2 (y)	
Usage building (electricity, hearting etc.) (y)	
Machine maintenance (y)	
Machine interest (y)	
Tool wearage (y)	
Packaging (y)	
THE OUTSOURCING COMPANY outsourcing (y)	

Resulting in the following total costs to produce products A under 4 weeks:

Table 52: Total yearly costs for producing under four weeks.

Total	**Costs**
Portion employee costs	
Machine costs	
Transport costs	
Other	
Total	**€ 1.028.623,24**

Note that in these costs, the "portion" employee costs are used. In addition, no extra transport costs for driving twice to the customer are used since it is uncertain who will pay these costs. Thus, this cost analysis should be seen as a minimum. As mentioned, probably more hours are needed because employees and machines cannot achieve 100% utilization. Furthermore, because in the model employees immediately start their production when a product A arrives, even more hours are needed. This can be done by giving product As a priority in any case. Though, even then, in reality, the employees will probably first finish their work on a certain order, before processing product A.

Summarizing results

- In order to acquire an average throughput time of four weeks, the planning should be changed to an MRP-based planning. In addition, an extra Machine 2 machine should be added together with driving to the outsourcing company twice per week. The internal throughput time incl. outsourcing is, in that case, already under four weeks. Though, if the total throughput time also needs to be under four weeks, also transporting to the customer should be done twice.
- Based on skills, in total 9 FTE's are needed to do 4,82 FTE of work, together with a Machine 1 machine shift of 24 hours, 6 days per week (of which 8 hours per day are automated) in order to have a throughput time of below four weeks. This Machine 1-shift could be done with 2 to 3 employees.
- Regarding costs, the total costs are approximately €1.028.623,-. This number should be seen as a minimum because of a 100% utilization assumption, together with the priority for products A assumption.

6.5 Summary table for all experiments

Regarding the base model, the results can be summarized in the following table. The scenario describes the experiment level. The throughput time reduction is calculated statistically, that is why "significant" is added. The WIP and WIP value reduction are not calculated statistically, but are just the difference between the mean values. The costs row describes the costs of the intervention. If a result is colored red, it means that no reduction but only an increase of that concerned KPI is observed.

Table 53: Summarized results for interventions to the base model.

Scenario	Sign. throughput time reduction	WIP reduction	WIP value reduction	Extra costs
Planning approach				
MRP model	23 days and 10 hours to 23 days and 14 hours.	59,4	€297000	n.a.
ConWIP model	23 days and 1 hour to 23 days and 7 hours.	60,4	€302000	n.a.
Bottleneck control	23 days and 9 hours to 23 days and 15 hours.	60	€300000	n.a.
Delivery variability				
Different intervals	4 days and 8 hours to 5 days and 23 hours.	4,14	€20716	n.a.
Different delivery numbers	2 days and 5 hours to 4 days and 14 hours.	9,03	€45174	n.a.
Combination	5 days and 16 hours to 8 days and 16 hours.	9,4	€47046	n.a.
Little variability	2 days and 4 hours to 2 days and 18 hours.	3,35	€167746	n.a.
Transport to THE OUTSOURCING COMPANY				
Different day	3 days and 2 hours to 3 days and 6 hours	8,34	€41676	€21241
Two days	7 days and 16 hours to 7 days and 22 hours.	20,4	€100209	€42482
Three days	7 days and 16 hours to 7 days and 22 hours.	20,4	€100209	€63723
Adding a Machine 1 machine				
Adding an extra Machine 1	0	0	0	€369481
Adding an extra Machine 1, while limiting the shift	2 days and 13 hours to 2 days and 18 hours.	1,18	€5900	€147141

Adding a Machine 2 machine				
Adding an extra Machine 2	1 day and 23 hours to 2 days and 6 hours.	5,39	€26962,-	€35000
Adding an extra Machine 2, while limiting the shift	0	0,31	€1575,-	- €17749

Based on the table, within the base model, it can be observed that the biggest time gain can be acquired by changing the planning. Another big time gain can be acquired by driving more often to the outsourcing company. Though, this comes with a cost. Total costs can be reduced by adding an extra Machine 2 and limiting shift-hours. This will not influence the throughput time significantly. Another "costless" way of reducing the throughput time significantly is negotiating a fixed delivery interval and number.

Though, some experiments have also been done within the MRP-model. This is mainly because the base model gives some disturbing values because of the week-to-week planning. The results of this model are summarized in the following table:

Table 54: Summarized results for interventions to the MRP-model.

Scenario	Sign. throughput time reduction	WIP reduction	WIP value reduction	Extra costs
Transport to THE OUTSOURCING COMPANY				
Different day	4 days and 21 hours to 5 days and 6 hours.	13,04	€65181	€21241
Two days (Tu-Fr)	8 days and 11 hours to 8 days and 15 hours.	22,04	€110200	€42482
Two days (We-Fr)	8 days and 9 hours to 8 days and 18 hours.	22,00	€110016	€42482
Three days	10 days and 3 hours to 10 days and 6 hours.	26,25	€131259	€63723
Adding a Machine 1 machine				
Adding an extra Machine 1	0	0	0	€369481
Adding an extra Machine 1, while limiting the shift	9 hours to 13 hours.	1,18	€5900	€147141
Adding a Machine 2 machine				

Adding an extra Machine 2	2 days and 10 hours to 2 days and 18 hours.	6,59	€32941,-	€35000
Adding an extra Machine 2, while limiting the shift	18 hours and 20 minutes to 1 day, 1 hour and 22 minutes.	2,34	€11709,-	- €17749
Delivery to customer X				
Different day	3 days and 21 hours to 4 days and 2 hours.	10,26	€51308,-	Unknown
Two days	6 days and 19 hours to 7 days and 1 hour.	17,80	€88983,-	Unknown

Based on the table, it can be observed that driving two times to THE OUTSOURCING COMPANY is the most effective way to reduce the throughput time. Though, it (again) comes with a cost. Another interesting option is adding an extra Machine 2 machine since it saves costs while also reducing throughput time.

The experiments in both the base model and MRP-model show that most gains can be acquired regarding transport. Improving things internally does help, but the time gains are relatively small regarding transport. This is mainly because products will have to wait for the truck later on in the process. Usually, costs are also much higher for improving things internally since it usually involves extra personnel or machines.

Eventually, the best results have been combined into one model. In order to acquire an average throughput time of four weeks, the planning should be changed to an MRP-based planning. In addition, an extra Machine 2 machine should be added together with driving to the outsourcing company twice per week. The internal throughput time incl. outsourcing is, in that case, already under four weeks. Though, if the total throughput time also needs to be under four weeks, also transporting to the customer should be done twice.

Chapter 7: Conclusions, recommendations, and discussion

Conclusions are drawn at the end of every chapter. These conclusions can be linked to the main research question. Though, in this chapter, only key-answers to the main research question will be summarized:

*How should a **production planning approach** be **applied at COMPANY A** such that the **relevant characteristics** and **restrictions** of the **production** are satisfied to reduce throughput time?*

Based on these key-conclusions, recommendations will be given. The chapter will conclude by giving options for further research, analyzing shortcomings in this research, and outlining the contribution to practice.

In this thesis, multiple planning and control approaches were investigated and assessed on their applicability to COMPANY A. By gathering data of the production of product A, a simulation model was created. Within this simulation model, the planning and control approaches could be compared. In addition, other planning and control related subjects were tested in this simulation model.

7.1 Conclusions

It was difficult to determine a clear planning for product A at COMPANY A. Though, the intended planning includes a lot of waiting time, resulting in a throughput time of 9 weeks. Potential bottlenecks that substantially contribute to a higher throughput time are the turning and milling machine, grinding machine, and outsourcing to THE OUTSOURCING COMPANY that takes a week. According to literature, and assessing this literature, ConWIP, MRP and bottleneck control seem to be suitable planning and control approaches to apply to COMPANY A. This is mainly because their implementation is relatively easy compared to other approaches.
The following conclusions can be drawn based on the simulation model:

- Bottleneck control on the grinding machine is the best-performing bottleneck control approach.
- MRP, ConWIP and bottleneck control outperform the current planning approach, mainly because the long waiting times are deleted. Deleting these waiting times can improve the throughput time with at least 23 days while the same capacity is needed.
- MRP and bottleneck control outperform the base model and ConWIP control. MRP and bottleneck control almost perform similarly.
- Decreasing or eliminating delivery variability significantly reduces total throughput time by approximately 2 to 3 days (little variability) and perhaps 3 to 6 days (a lot of variability). Furthermore, negotiating a fixed number is more effective than negotiating a fixed interval.
- Choosing a different transport-day to the outsourcing company THE OUTSOURCING COMPANY can significantly reduce throughput time. Regarding the assumed transport day in the base model, the throughput time can be reduced by approximately 3 days (in the base model) or 5 days (in an MRP-model) by just choosing a different transport-day.
- Driving twice to the outsourcing company THE OUTSOURCING COMPANY can significantly reduce throughput time by approximately 8 days in the base model and 8 to 9 days in an MRP-model. One factor that massively influences the right transport day to THE OUTSOURCING COMPANY, is the day on which new products A are delivered and finished products A are acquired by customer X.
- Adding an extra turning and milling machine would not reduce total throughput time, while increasing costs. The shift hours cannot be limited enough in order to save more costs such that a second turning and milling machine is lucrative.

- Adding an extra grinding machine would reduce total throughput time, while it can also save costs. The shift hours can be limited enough in order to save more costs such that a second grinding machine is lucrative. This is mainly because one operator can operate two grinding machines if these machines are the same.
- A different day for the delivery of new products A and acquiring of finished products A by customer X can improve total throughput time by approximately 4 days (based on the MRP-model). Furthermore, driving twice to customer X can significantly reduce the throughput time by approximately 7 days (based on the MRP-model).
- The experiments show that improving things internally is less effective than improving things regarding transport. This is because most efficiency gains also end up in longer waiting times for the truck later on in the process.
- A throughput time excluding the delivery to the customer of less than four weeks can be acquired by using an MRP planning and control approach, buying an extra grinding machine, and driving twice to the outsourcing company THE OUTSOURCING COMPANY. A throughput time including the delivery to the customer of less than four weeks can be acquired by doing the same but also driving two times to the customer.
- In order to produce the required number of products A within four weeks, at least 9 FTE's are needed to eventually do at least 4,82 FTE work, excluding the turning and milling machine. This machine needs a 24-hour shift, 6 days per week (of which 8 hours per day are automated). This could be done with 2 to 3 operators.

7.2 Recommendations

- Use MRP or bottleneck control (on the grinding machine) as a planning and control approach. This can save approximately 23 to 24 days in total throughput time. MRP would be more interesting if sufficient capacity is present since it is a familiar approach for COMPANY A. In addition, it is simpler to explain than bottleneck control. What makes it even more easy, is the fact that the MRP-table of product A is relatively small. Though, I would also recommend using an extra capacity analysis system to check if the scheduled numbers in the MRP are still suitable. For this, the excel sheet created by COMPANY A, that was also used in this thesis, can be used. Bottleneck control would be more interesting if capacity is more constrained than assumed in this thesis. Though, it is more difficult to implement since it is relatively new for COMPANY A.
- Try to negotiate a fixed delivery interval with fixed delivery numbers since it reduces variability and thus waiting times. This can save approximately 5 to 9 days of throughput time. If this is not possible, try to reduce variability since it reduces throughput time significantly with 2 to 3 days in total throughput time.
- Reconsider the transport-day to THE OUTSOURCING COMPANY. Considerable time gains of days can be acquired by setting the right transport-day. For example, changing the day to Friday can lead to a throughput time saving of 3 days (base-model). Transporting to THE OUTSOURCING COMPANY twice can improve the throughput time even more but comes with a yearly cost of approximately €42.480,-. For example, driving on both Wednesday and Friday can reduce total throughput time with approximately 8 days (base model). Determining the right day on which new products A are delivered and finished products A are acquired by customer X can also considerably reduce the throughput time with approximately 4 days (MRP-model). In addition, driving two times to customer X reduces the throughput time even further with approximately 7 days (MRP-model), but probably also comes with a cost. Driving three times to customer X is not interesting since the increase in set-up times will compensate for the decrease in waiting times. Thus, trying to find the right

alignment between the transport day to THE OUTSOURCING COMPANY and the delivery and acquiring day is important since it can massively influence the total throughput time.

- Do not buy an extra turning and milling machine since it is more expensive (approximately €147.140,- per year) than running longer shifts in order to cope with the specified demand. In addition, no throughput time gains are acquired when adding an extra turning and milling machine.
- Add an extra grinding machine since it is cheaper (approximately €17.750,- per year) than running longer shifts in order to cope with the specified demand. In addition, within the MRP-model, it even leads to a total throughput time saving of 18 to 25 hours.
- Review the current calculated process times. The calculated times within the ERP-system that are currently used differ (approximately 206 minutes) from the process times assumed in this thesis.
- Re-introduce clocking of the process times by outlining how each operator should start his/her clocking operation. Where this was done right, it gave valuable data which could be analyzed.

7.3 Further research and shortcomings in this research

During this thesis, some limitations were observed which were not done because of time limits. Though, some issues are interesting for further research:

The production layout of product A and perhaps other products

As mentioned in the first chapter of this thesis, there is a lot of movement present in the production of product A. This is because products A needs to travel to a central rack in the middle of the hall. In addition, the different departments are located all over the hall. It might be interesting to think about a new layout, where product As move more smoothly through the production. Though, with this, also the other projects for other customers need to be considered because improving the efficiency of one project also influences the efficiency of the others. This thesis could become quite complex considering the number of projects, machines, and space-constraints within the production hall.

Investigating the valuable operating time of employees and machines and their importance

In this thesis, breakdowns, maintenance, and other inefficiencies of machines are not considered. In addition, also employees can be ill or go on holiday. This will influence the results of this thesis since less valuable operating time is available. In addition, more variance will be present in the system, again influencing the waiting times (Slack, Brandon-Jones, & Johnston, 2013, p. 117). No data is present about this yet. It might be interesting to acquire data about failures of machines and employee illness. Regarding machines, even some maintenance schedules could be constructed. Lastly, the influence of these failures could be included in the current simulation model, such that the model represents reality more accurately. This would perhaps lead to different conclusions, especially regarding the planning approach since, for example, the MRP is not so suitable for unexpected events.

Make pull-control work within this environment

Closely related to this thesis, another thesis could change the research question a little bit by investigating how pull-control can work within the environment of COMPANY A. Since pull-control is quite promising according to literature, small variations could perhaps make sure that pull-control is performing better than push-control. In this thesis, no variations to the basic push and pull methods were tested. Though, as discussed in *chapter 6*, little variations will probably already improve the methods massively. In addition, bottleneck control, that was one of the best-performing methods in this thesis, also has several variations to the basic methods. It is also interesting to test these. Lastly, by also considering breakdowns, failures, etc. push-control becomes more interesting. Eventually, the best performing pull-method should be compared to a push-method in the same environment, preferably with also considering inefficiencies. I strongly believe that considering the aforementioned things, pull-control can and will outperform push-control.

Implement product A planning in the ERP and implementation itself
As mentioned in *chapter 1*, the current production of product A is not part of the ERP. Implementing this could be a nice additional thesis for people with an IT-background. This is interesting since product A is quite different from the other products that COMPANY A works with. By thinking of how this could be implemented in the upcoming new ERP-system, interesting results could be obtained. Implementing the planning in the ERP would improve visibility of the process, but also data reliability. In addition, occupations of departments can be considered since the other products are also part of the ERP-system.
Moreover, this thesis does also not outline a complete guide on how to implement MRP or other planning and control approach. It does only test potential results. This guide would be useful for COMPANY A in order to get a feeling of how planning and control approaches would work for their production.

In addition, this research also made some assumptions and simplifications. For example, the entire simulation model is built upon several assumptions and simplifications (see *chapter 6).* Usually, these are given any time results are presented. Though, the biggest assumptions and simplifications are:

1. The capacity assumption. During this thesis, sufficient capacity is assumed and calculated since the current system cannot cope with the demand that is assumed in this thesis yet. Therefore, the real world would probably be different, leading to a strange situation where departments are not that constrained. Usually, in a production process, a clear constrained department is present. This made pull planning approaches famous.
2. The turning and milling machine is somewhat too efficient in this thesis. In this thesis, it is assumed that the total process time of the turning and milling machine is equal to the process times. It is assumed that all set-up for a certain product A will be done during the program of another product A (except for the first one). In reality, not enough pallets are present to do this yet. The fact that there are enough pallets is a restriction to acquire the throughput times that are assumed in this thesis.
3. In the simulation model, it is assumed that departments immediately process a product A when it arrives. Though, in reality, production steps also work on other products. It is unlikely that they will stop their process on this (batch of) product(s) in order to immediately process product A. This influences the throughput time.
4. As mentioned above, efficiency issues (machines, breakdowns, employee illness) are not considered in this thesis.
5. In this thesis, multiple interaction effects are not considered in order to save experimenting time.
6. To validate the simulation model more accurately, a comparison to real-world data would be interesting. Unfortunately, the current system is not similar to the desired situation in the simulation model. Therefore, these things cannot be properly compared yet.
7. When assessing the planning approaches in literature, no scoring templates were provided. A scoring template would enhance the argument for the choice of a certain planning approach.
8. A warm-up period should actually be determined for every KPI and experiment. In this thesis, this is only done once and used for every KPI and experiment.

7.4 Contribution to practice of this thesis

The main goal of this bachelor thesis was improving the situation regarding throughput time for COMPANY A. By testing different scenarios regarding planning, transport, and capacities, in a simulation model, the situation can be improved. This thesis has provided insight into possible interventions. By not only considering the time gains, but also the attached costs, and decrease in WIP and WIP value, a more thorough consideration of interventions can be done by the management of COMPANY A. By also considering the required full-time employees, I hope to give COMPANY A an insight into what is needed to acquire the required goal. Lastly, by doing a thorough data gathering and data analysis step in chapter 2, I think even more insights into the production of product As are given. The conclusions in chapter 2 that are not dependent on possible assumptions and simplifications are, therefore, directly usable.

This bachelor thesis contributes to the body of knowledge by outlining another review of different planning approaches and their applicability to the make-to-order environment. By reviewing the effect of different planning approaches regarding throughput time, the performance of the different approaches can be assessed. The simulation study provides extra evidence for the choice of different approaches. Practitioners that also want to implement a certain planning and control approach can use this analysis and compare them to their situation.

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Appendix A: Problem identification and planning for this thesis

In this appendix, the problem list will be displayed, together with the planning for this thesis in order to solve the research question. There will be shortly reflected on the difference between the intended and realized planning.

A.1 The problem list

The first step is basically acquiring all problems within the company. These problems have been identified over a long period of time. It initiated by interviewing the director. Later, multiple interviews with the planner were conducted. Furthermore, the project supervisor was also interviewed. In addition, multiple floor workers have been interviewed in order to identify certain bottlenecks within the process. These were the floor workers that work with product A every day. Moreover, looking around the production process also helped. Lastly, several documents were quickly scanned. All in all, the following relevant problems have been identified.

1. The total throughput time should be decreased from 9 weeks to 4 weeks. This is the wish of the customer and the initial action problem.
2. According to the director, there is too much WIP in the production hall.
3. Consequently, the WIP value is too high, however, this is more a problem of the customer since they remain the owner of product As.
4. The inventory takes in quite some space throughout the process. This is also a consequence of the fact that there is too much WIP.
5. Because there is only one central rack in the production hall, all products must move to this central rack instead of smoothly flowing to the next department.
6. Total outsourcing time in the current situation is three weeks.
7. The product must wait for 14 days after grinding because of tears in the material. The tears in the material (and thus the waiting) is getting fixed.
8. There are many problems with the product, especially in the process after adding the ring to product A. These steps are relatively new to COMPANY A. This is getting solved by the quality manager.
9. Measuring misses a clear structure in the planning, according to the employees there.
10. Measuring has chronically to much work (not only for product A), according to the employees there.
11. Product A interferes with normal work regarding bench working, according to the employees there.
12. The project supervisor sometimes intervenes with the planning process, resulting in an irregular flow.
13. Products need to go through many redundant steps. For example, measuring must be done multiple times because of quality issues.
14. Many drawings are given away, which results in a lot of paper waste.
15. There are a lot of products on hold and thus delayed because of the many deviations and waivers.
16. There is no clear overview of all places where every product A is located.
17. The planning of product A is not part of the integrated planning program called plan the Campagne. It is an excel sheet for the time being. This is more useful in the current situation.
18. Products come in and are not directly taken into production. This is because of delays and because it was forgotten.
19. There is much scrap because of deviations.
20. There is no clear planning algorithm. Every production step now basically gets one day to finish every step.

A.2 Thesis planning

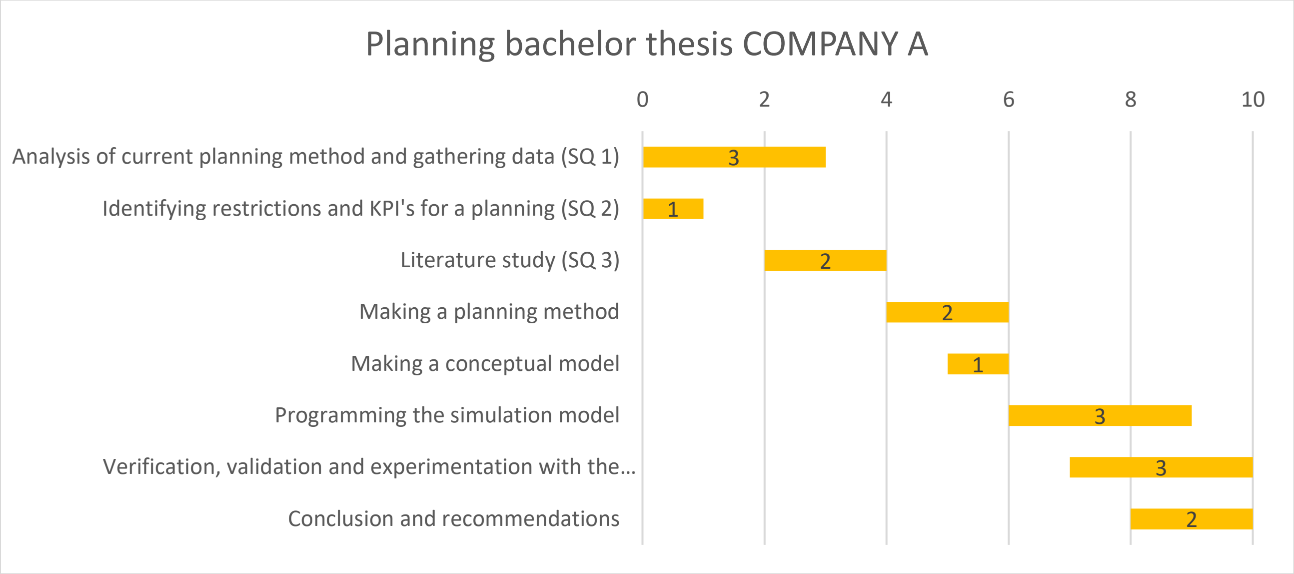


Figure 17: Gantt Chart of the intended planning at the start of this thesis.

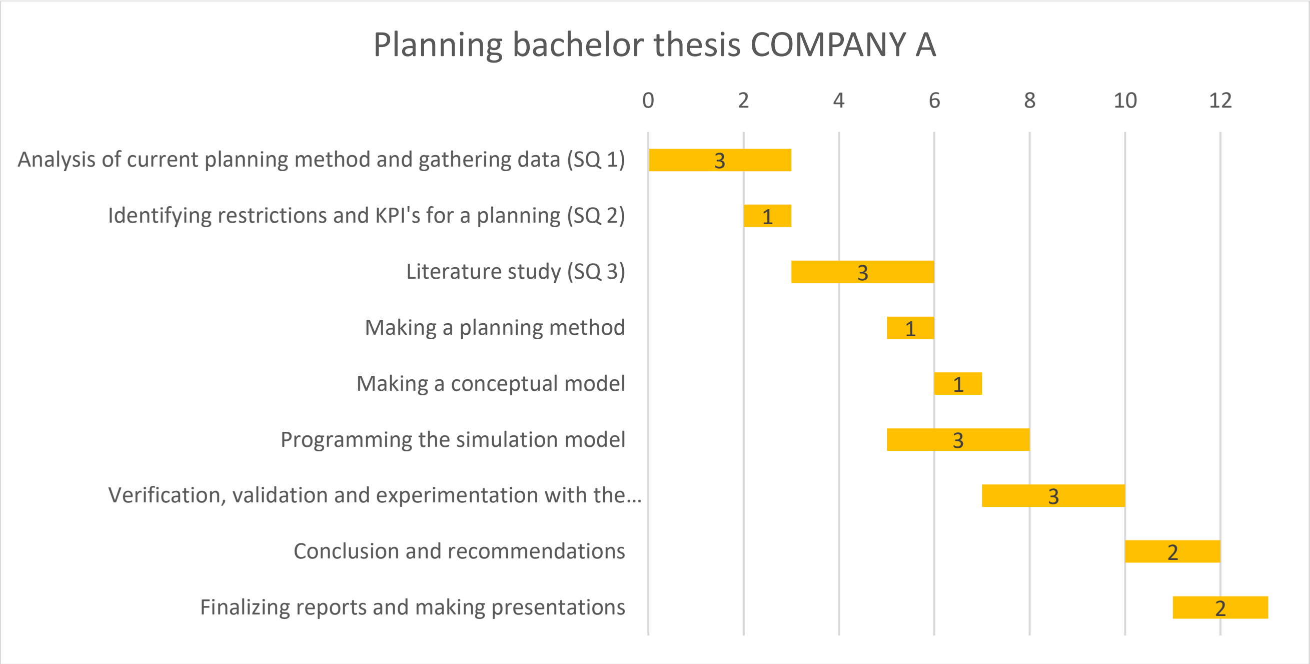


Figure 18: Gantt Chart of the realized planning at the end of this thesis.

Table 55: Intended planning and real planning in numbers.

	Intended planning			*Real planning*		
Activity	**Start week**	**End week**	**Duration**	**Start week**	**End week**	**Duration**
Analysis of current planning method and gathering data (SQ 1)	0	3	3	0	3	3
Identifying restrictions and KPI's for a planning (SQ 2)	0	1	1	2	3	1
Literature study (SQ 3)	2	4	2	3	6	3
Making a planning method	4	6	2	5	6	1
Making a conceptual model	5	6	1	6	7	1
Programming the simulation model	6	9	3	5	8	3
Verification, validation and experimentation with the simulation model	7	10	3	7	10	3
Conclusion and recommendations	8	10	2	10	12	2
Finalizing reports and making presentations	--	--	--	11	13	2

A short reflection on the realized and intended planning

As shown, the realized planning is three weeks longer than the intended planning. The first reason for this is that I already started my thesis two/three weeks in advance (some days were still dedicated to finalizing the project proposal). Though, the intended end-date (July 5) was the same. During these weeks, the data-gathering phase was finalized. I hoped to be in front of my schedule by doing this, though other steps took longer than expected. Especially the literature study and programming the simulation model took longer than expected. Moreover, it was initially thought that multiple steps could be conducted parallel, whereas this was quite difficult in hindsight. Furthermore, reporting was done during the execution of each phase. Though, finalizing a report is quite a lot of work that was initially not scheduled. Lastly, making and preparing presentations was originally also not scheduled, while this also took approximately a week to a week and a half.

It could be concluded that I failed to do the thesis within 10 weeks. Though, if I had not started my thesis two/three weeks in advance, I would have probably made a less elaborate thesis to acquire the intended end-date. For example, the final cost analysis or capacity analysis could be skipped. Though, it should also not be forgotten that the period included a lot of days off (Easter, Whit Monday, Ascension Day, etc.).

Appendix B: The production of product A

B.1 Production map

[censored]

[redacted]

Figure 17: Product A production process map.

B.2 Production processes table

Based on the production route, the following production steps have been outlined. The following attributes are included in the table.

- 'Pos' basically means the order in which the operations should be conducted. So, 10-20-30, etc. Some steps do not have this number yet since they are not included in the ERP-system. Moreover, sometimes the order is not right. Sandblasting (190) is after visual inspection (200). This is because sandblasting is currently done before visual inspection since it is outsourced. However, if COMPANY A is going to do the outsourcing for themselves it will be done after the visual inspection. The cleanliness test (205) is also after cleaning (210). The cleanliness test is not conducted if the product is not cleaned first. However, if the product is not clean, it needs to be cleaned again.
- The code describes the operation code that needs to be conducted. Therefore, some codes are recurring. So, these steps are similar, though, not always completely the same.
- The operation describes the operation that will be conducted in that particular production step.
- The instruction describes the work-instruction code. This is a detailed document written by a quality manager. In these instructions, step-for-step approaches of each production step are outlined. For some steps, these are not present yet.
- The location is the location within the production hall.
- The output describes the output of the operation and thus the input for the next step.

Table 55: Production process table outlining each step in the production.

Pos.	Code	Operation	Instruction	Location	Output
n.a.	n.a.	**Reception of products** 1. Grouping products per purchase batch on pallets and placement in the customer X-rack. 2. Switch broken or weak boxes. 3. Label the product for identification.	-	Expedition	1. Pallets have a label. 2. Pallets are placed in the intended rack. Preferably at the top. 3. The purchasing orders and shipping notes of customer Y are delivered to the business office.

n.a.	n.a.	**Order intake** 1. Making a production-order. 2. Making a purchasing-order. 3. Making a COMPANY A production-order. 4. Printing the order documents. 5. Planning is known.	-	Business office	1. Determine delivery date with planning: check if customer X's delivery date is doable. 2. Making orders in ERP (PdC) 3. Orders are ready and brought to technical work preparation where it gets checked.
10	10	**Documentation/instructions** 1. Check if the serial number on the route is the same as the serial number on the production order of customer Y.	-	Business office	1. Contents of the document are checked on correctness and completeness. 2. Orders are brought to part marking.
20	582	**Part Marking** 1. Marking aluminum label according to 'fabricage aanvullend document' (FAD).	[censored]	Part Marking	1. Alu label placed in order. 2. Order + label are delivered to the expedition.
30	591	**Material inspection** 1. Getting pallet from customer X rack. 2. Get the product out of the box. 3. Add aluminum label. 4. Put product and box in plastic pallet with edges. 5. Add the production card. 6. Put pallet back in customer X rack.	-	Expedition	1. Every product with its empty box is placed in a plastic pallet with an edge. 2. Orders are in this pallet. 3. Production card is attached. 4. Product is in the customer X rack.

50	599	**Inspection** 1. Inspection of casting according to [censored] 2. Gluing measuring pin. 3. Removing scratches and etches if present (in reference A and C). 4. Weighing.	[censored]	Quality control	1. Casting is inspected according to [censored]. 2. Measuring pin is glued (in ref C.) 3. CMM measuring report is saved. 4. Weight is known and attached to the route. 5. Product is back in rack.
60	535	**Turning and milling on MACHINE 1** 1. Producing product according to [censored]. 2. Measuring product. (Operation 1 – Measuring – Operation 2 – Measuring).	[censored]	Machine 1 machine	1. Product is completely turned and milled. 2. Product is washed. 3. Product is measured (CMM). 4. Measurements by hand have been conducted. Results are reported and added to the production map. 5. Gluing pin is removed. 6. Product is back in customer X rack. *For type AC this step is a bit longer than for type 1B.*
70	580	**Secondary Operations** Product is completely deburred ([censored]).	[censored]	Bench working	1. Product is completely deburred. 2. Product is back in customer X rack.
80	582	**Part Marking** Marking ([censored])	[censored]	Bench working	1. Product has a mark. 2. Product is back in customer X rack.
90	593	**Cleaning** Cleaning ([censored])	[censored]	Washing machine (behind Machine 1)	1. Product is cleaned and dried. 2. Product is back in customer X rack.

100	599	**Inspection** 1. The output of measuring is inspected ([censored]). 2. Inspection of marking. 3. Inspection on deburring 4. Control of the document. 5. Control of damages, scratches, wounds, dents or irregularities. 6. Reporting data.	[censored]	Quality control	1. Product A is inspected according to [censored]. 2. CMM measuring reports are saved. 3. Weight is written on the route. 4. Product is back in customer X rack.
110	687	**Outsourcing THE OUTSOURCING COMPANY (tear inspection)** 1. Making the product ready for shipping. 2. Keeping production maps. 3. Empty plastic pallet back in the customer X rack. 4. FPI (S2) (outsourced at THE OUTSOURCING COMPANY) 5. Receival of parts THE OUTSOURCING COMPANY + CoC THE OUTSOURCING COMPANY.	[censored]	Expedition	1. Product delivered to THE OUTSOURCING COMPANY for outsourcing. 2. Production orders are temporarily saved. 3. FPI is conducted by THE OUTSOURCING COMPANY. 4. Product is returned incl. certificate of conformity (CoC). 5. Product is put back into the plastic pallet with production map, follow sheet, label. CoC is placed in the assigned bin. 6. Product is placed in customer X rack.
120	597	**Visual inspection** Visual inspection according to [censored].	[censored]	Control room	1. Product is visually inspected. 2. Product is placed in customer X rack. *Finished "dash six"*

130	585	**Assembly** 1. Shrinking ring according to [censored]. 2. Cleaning product and greasing with anti-corrosion. 3. Writing down the serial number of the ring.	[censored]	[censored]	1. The ring is shrunk onto product A. 2. The ring is greased with Anti-corrosion. 3. Serial number is written down on the route. 4. Depth of the ring is measured and written down on route. 5. Product is placed in customer X rack.
140	505	**Grinding** 1. Grinding [censored]. 2. Drying after grinding. Greasing ring with Anti-corrosion. 3. Measuring and writing down the grinding diameter. 4. Measure on CMM (periodically in strained condition).	[censored]	Machine 2	1. Grinding ring according to [censored]. 2. Greased ring with Anti-corrosion. 3. The diameter of the ring is measured by hand and written down on route. 4. Product is placed back in customer X rack.
150	580	**Secondary Operations** 1. Complete deburring ([censored]) 2. Greasing ring with Anti-corrosion. 3. Use excess pressure	[censored]	Bench working	1. Product A is deburred ([censored]). 2. The ring is greased with Anti-corrosion. 3. Product is placed back in customer X rack.
160	593	**Cleaning** 1. Product is cleaned ([censored]). 2. Greasing ring with Anti-corrosion.	[censored]	Control room	1. Product is cleaned and dried. 2. The ring is greased with Anti-corrosion. 3. Product is placed back in customer X rack.

170	599	**Inspection** 1. CMM measuring ([censored]) 2. Greasing the ring with Anti-corrosion 3. Reporting data referring to the serial number. 4. Check for damages, scratches, wounds, dents or irregularities.	[censored]	Quality control	1. Product A is inspected ([censored]). 2. The ring is greased with Anti-corrosion. 3. Measuring reports are saved. 4. Weighing is done and written down on the route. 5. Product is placed back in customer X rack.
180	687	**Outsourcing THE OUTSOURCING COMPANY (tear inspection)** 1. Making the product ready for shipping. 2. Keeping production maps, including follow sheet and label. 3. Empty plastic pallet back in the customer X rack. 4. FPI (S3) (outsourced at THE OUTSOURCING COMPANY) 5. Receival of parts THE OUTSOURCING COMPANY + CoC THE OUTSOURCING COMPANY.	[censored]	Expedition	1. Product delivered to THE OUTSOURCING COMPANY for outsourcing. 2. Production orders are temporarily saved. 3. FPI is conducted by THE OUTSOURCING COMPANY. 4. Product is returned incl. CoC. 5. Product is put back into the plastic pallet with production map, follow sheet, label. CoC is placed in the assigned bin. 6. Product is placed in customer X rack.
200	597	**Visual inspection** 1. Visual inspection ([censored]) 2. Greasing the ring with Anti-corrosion.	[censored]	Control room	1. Product is inspected visually. 2. The ring is greased with Anti-corrosion. 3. Product is placed in customer X rack.

190	Not present yet.	**Sandblasting** 1. Picking the box, putting it on the working bench. 2. Masking the product with tape. Preparing sandblasting. 3. Sandblasting 4. Getting the product out. 5. Cleaning the product. 6. Demasking.	-	Sandblasting bank	1. The parts of the product that need sandblasting are sandblasted. 2. Product is placed in customer X rack. *This step will not be conducted for type AC.* *This is currently outsourced, however, it will be done in-house soon.*
210	593	**Cleaning** 1. Cleaning the product ([censored] 2. Greasing the ring with Anti-corrosion.	[censored]	Control room	1. Product is cleaned and dried. 2. The ring is greased with Anti-corrosion. 3. Product is wrapped up in a clean and new plastic bag. 4. Product is placed in customer X rack.
205	597	**Visual inspection** 1. Conducting a cleanliness test on 1 out of 10 products. 2. Greasing the ring with Anti-corrosion.	-	Visual inspection room	1. Cleanliness test is conducted. 2. Amount of pollution is measured and written down on route. 3. The filter is saved. 4. Product is placed in customer X rack.
220	585	**Assembly** 1. Assembly ([censored]) of inserts. 2. Greasing the ring with Anti-corrosion	[censored]	Visual inspection room and assembly room	1. Inserts are placed. 2. Product is placed in customer X rack. *This step will not be conducted for type AC.*
230	600	**Final inspection** 1. Inspection ([censored]) 2. Check for damages, scratches, wounds, dents or irregularities. 3. Greasing the ring with Anti-corrosion.	[censored]	Control room.	1. Product is inspected for the final time. 2. The ring is greased with Anti-corrosion. 3. Products are additionally wrapped in a clean, new plastic bag. 4. Product is placed in customer X rack.

n.a.	n.a.	**Delivery (administration)** 1. Preparing delivery.	[censored]	Business office	1. Product is delivered from COMPANY A (fictively) in PDC. 2. Product is invoiced from COMPANY A in PDC. 3. Product is booked in PDP in PdC. 4. A list including CoC for delivery to customer X is made in PdC and printed. 5. Delivery is delivered to customer X's ERP. Barcode is scanned. 6. CoC of THE OUTSOURCING COMPANY is printed. 7. All documents are gathered, scanned and archived.
n.a.	n.a.	**Delivery (expedition)** 1. Wrapping making product ready for delivery. 2. Gathering production maps including following sheet and label. 3. Putting the empty plastic pallets back in the customer X rack. 4. Delivery to customer X.	[censored]	Expedition	1. Product is delivered to customer X. 2. Empty plastic pallets are placed in customer X rack. *Finished "dash zero"*

B.3 Production planning diagram

[censored]

Figure 18: The current product A production planning.

Appendix C: Throughput times

In this chapter, the throughput times will be analyzed. First, statistics will be used to analyze the data points from the ERP-system. Afterward, all sources of data will be compared, and a decision will be made. The theory behind these statistics will not be outlined. Since basic statistics are applied, multiple books can be found within literature that outline these approaches.

C.1 Statistics on the ERP-system data

Turning and milling (Machine 1 - 060)

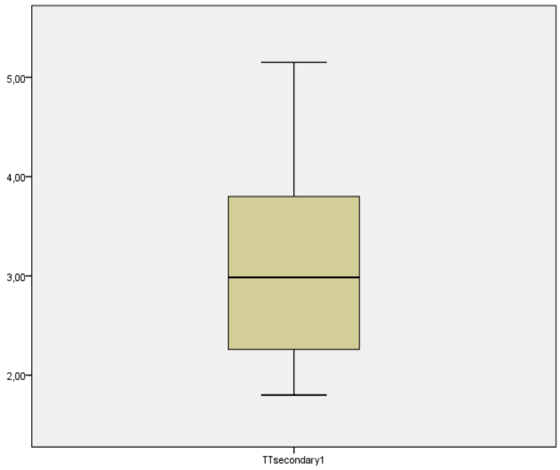
The data of the Machine 1 was seen as unreliable by the planning officer. When extracting data from the ERP system, this was underlined. Seven out of the total 44 points were lower than six hours, while this is the minimum processing time because of the length of the turning and milling programs. Moreover, while switching pallets within the machine and measuring does not take that long. Values much longer than six hours, therefore, seem unlikely. However, the mean of the dataset is already around the ten hours because 21 of the 44 points are larger than 10 hours. The 1,5 x IQR rule only deletes one outlier of 20 hours. So, this data seems of no use for further analysis.

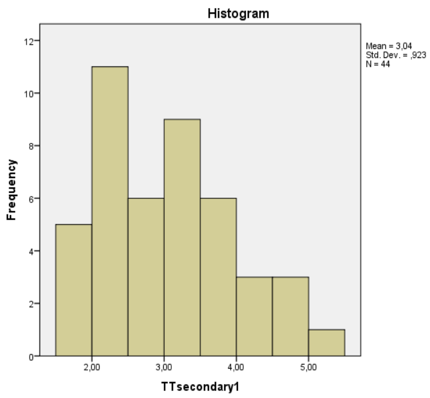
Secondary operations (070)

It was uncertain if the data about the secondary operations was reliable. However, when using descriptive statistics, the mean value that was found was 3,049 hours. This corresponds with the estimate of product A project supervisor and the minimum time mentioned by the employees of the bench working department. In addition, no outliers were identified and all times seemed plausible. No big ‘gaps’ between times were identified. So, it was decided to trust the data set. The corresponding figures were made with SPSS.

Descriptives

			Statistic	Std. Error
TTsecondary1	Mean		3,0439	0,13908
	95% Confidence Interval for Mean	Lower Bound	2,7634	
		Upper Bound	3,3243	
	5% Trimmed Mean		3,0052	
	Median		2,9850	
	Variance		0,851	
	Std. Deviation		0,92257	
	Minimum		1,80	
	Maximum		5,15	
	Range		3,35	
	Interquartile Range		1,59	
	Skewness		0,584	0,357
	Kurtosis		-0,644	0,702



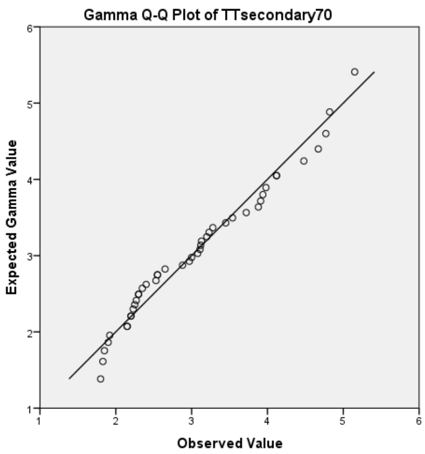


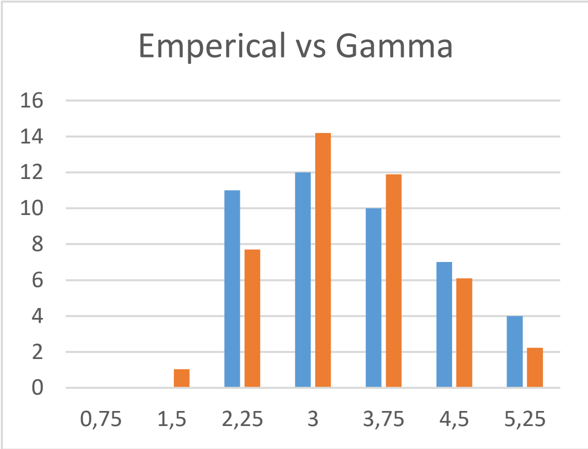
Percentiles

		Percentiles 5	10	25	50	75	90	95
Weighted Average(Definition 1)	TTsecondary1	1,8350	1,9100	2,2550	2,9850	3,8400	4,5750	4,8075
Tukey's Hinges	TTsecondary1			2,2600	2,9850	3,8000		

Figure 21: Figures for the TT from the ERP-system of P70.

Using the 1,5 x IQR rule, no outliers were removed from the dataset. Based on the histogram, it seems that a possible gamma distribution fits the data. This is a familiar distribution for completion of a task, like bench working (Robinson, 2014, p. 345). So a Q-Q plot was made. This Q-Q plot was made with the derived parameters for the gamma distribution (alfa = 10,89, beta = 0,28). This was done by sorting the data ($X_{(1)} \leq X_{(2)} \leq \ldots \leq X_{(n=44)}$). From this data, i-0,5/n=44 was plotted against $F(X_{(i)})$.





bins	Count	pi	Ei	Error
0,75	0	0,000134	0,005907	0,005907
1,5	0	0,023698	1,036813	1,036813
2,25	11	0,198874	7,707721	1,406265
3	12	0,521369	14,18978	0,337929
3,75	10	0,791765	11,89745	0,302611
4,5	7	0,930221	6,092051	0,135319
5,25	4	0,980964	2,232699	1,398914

Figure 22: QQ-plot and a plot of the empirical data against the hypothesized distribution (P70).

The Q-Q plot seems promising. In addition, the empirical data (blue) was plotted against the hypothesized gamma distribution (orange). This was done by plotting the number of observations in the bin interval of the histogram against the expected number of observations with the gamma distribution. This again looks promising. For the number of bins, the rule of thumb SQRT(n=44) was used, resulting in 7 bins.

As final argument, a goodness-of-fit test was conducted. The null hypothesis (H_0) states: there is no significant difference between the expected values if a gamma distribution was used and the observed frequencies. As significance level α = 5% is used. Next, the chi-square test was used to test the goodness-of-fit:

$$X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

Equation 5: chi-square value.

Where O_i is the observed frequency in the 'i^{th}' interval and E_i the expected frequency in the i^{th} interval. The critical value can be derived with α = 5% and degrees of freedom (df) of 43. Robinson (2014) also subtracts the number of estimated parameters. However, it was taught to only subtract one degree of freedom during lectures of Dr. Ir. M.R.K Mes. H_0 is rejected if the calculated chi-square value is equal or greater than the table value. The chi-square value was 4,62 where the critical value 12,59. So, do not reject H_0. So, the difference between the values seems to be due to chance. This does not mean that the null hypothesis is proven! It is just another argument that the gamma distribution seems reasonable.

In addition, the normal distribution was tested with a goodness-of-fit test. However, the chi-square value was higher (15,383) than the value when using the gamma distribution. So, the gamma distribution seems to fit the data better.

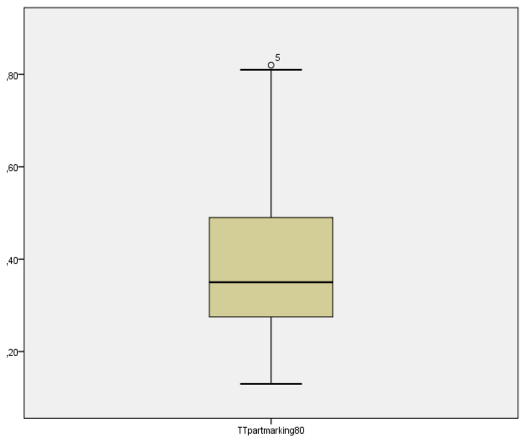
Based on the statistical arguments given, it is assumed that the activity in secondary operations (070) is gamma distributed with α = 10,885 and β = 0,279 (hours).

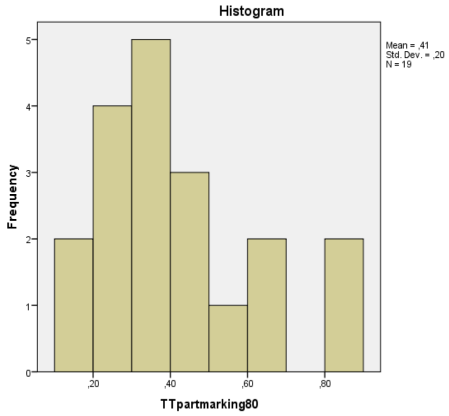
Marking (080)

For marking only 17 data points were present. The calculated mean came down to 24 minutes. This seemed plausible regarding the estimation of product A project supervisor, who estimated 20 minutes. However, the shop-floor worker said that it only took 5-7 minutes. A cause of this difference could be that this estimate was probably not based on also getting the product from the rack and setting everything up. Product A supervisor underlined this. Therefore, it was decided to again trust the data set. The following corresponding figures were made.

Descriptives

			Statistic	Std. Error
TTpartmarking80	Mean		0,4074	0,04581
	95% Confidence Interval for Mean	Lower Bound	0,3111	
		Upper Bound	0,5036	
	5% Trimmed Mean		0,3999	
	Median		0,3500	
	Variance		0,040	
	Std. Deviation		0,19969	
	Minimum		0,13	
	Maximum		0,82	
	Range		0,69	
	Interquartile Range		0,26	
	Skewness		0,837	0,524
	Kurtosis		0,065	1,014



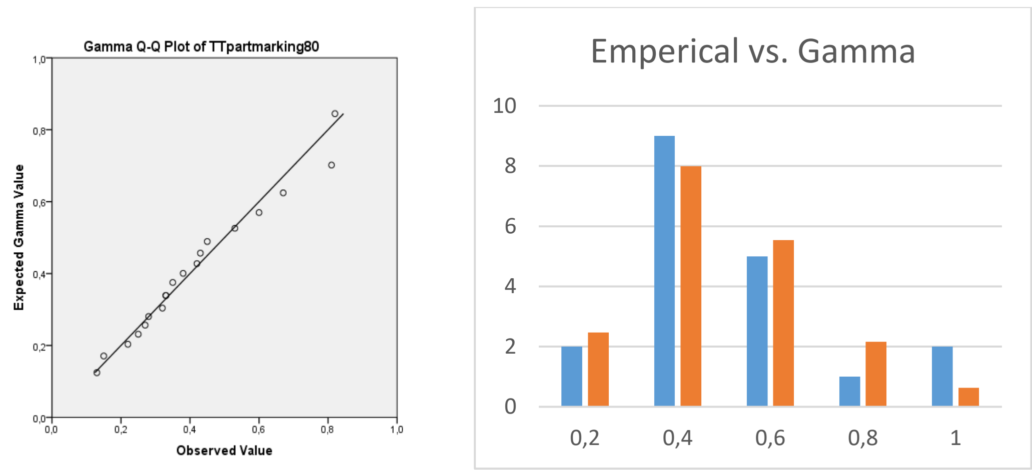


Percentiles

		Percentiles 5	10	25	50	75	90	95
Weighted Average(Definition 1)	TTpartmarking80	0,1300	0,1500	0,2700	0,3500	0,5300	0,8100	
Tukey's Hinges	TTpartmarking80			0,2750	0,3500	0,4900		

Figure 23: Figures for the TT from the ERP-system of P80.

Using the 1,5 x IQR-rule, no outliers were removed. Based on the histogram, it seems that a possible gamma distribution fits the data. This is a familiar distribution for completion of a task, like part marking (Robinson, 2014, p. 345). So a Q-Q plot was made. This Q-Q plot was made with the derived parameters for the gamma distribution (alfa = 4,16, beta = 0,10). This was done by sorting the data ($X_{(1)} \leq X_{(2)} \leq \ldots \leq X_{(n=19)}$). From this data, i-0,5/n=19 was plotted against $F(X_{(i)})$.



bins	Count	pi	Ei	Error
0,2	2	0,130186	2,473542	0,0906564
0,4	9	0,550667	7,98914	0,1279035
0,6	5	0,842087	5,536975	0,0520758
0,8	1	0,95589	2,16226	0,6247394
1	2	0,989358	0,635887	2,9263124

Figure 24: QQ-plot and a plot of the empirical data against the hypothesized distribution (P80).

The Q-Q plot seems promising. In addition, the empirical data (blue) was plotted against the hypothesized gamma distribution (orange). This was done by plotting the number of observations in the bin interval of the histogram against the expected number of observations with the gamma distribution. This again looks promising. For the number of bins, the rule of thumb SQRT(n=19) was used, resulting in 4 bins.

As a final argument, a goodness-of-fit test was conducted. The null hypothesis (H_0) states: there is no significant difference between the expected values if a gamma distribution was used and the observed frequencies. As significance level α = 5% is used. Next, the chi-square test was used to test the goodness-of-fit:

$$X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

Where O_i is the observed frequency in the 'i^{th}' interval and E_i the expected frequency in the i^{th} interval. The critical value can be derived with α = 5% and degrees of freedom (df) of 18. Robinson (2014) also subtracts the number of estimated parameters. However, it was taught to only subtract one degree of freedom during lectures. H_0 is rejected if the calculated chi-square value is equal or greater than the table value. The chi-square value was 3,82 where the critical value 9,48. So, do not reject H_0. So, the difference between the values seems to be due to chance. This does not mean that the null hypothesis is proven! It is just another argument that the gamma distribution seems reasonable.

In addition, the normal distribution was tested with a goodness-of-fit test. However, the chi-square value was higher (6,39) than the value when using the gamma distribution. So, the gamma distribution seems to fit the data better.

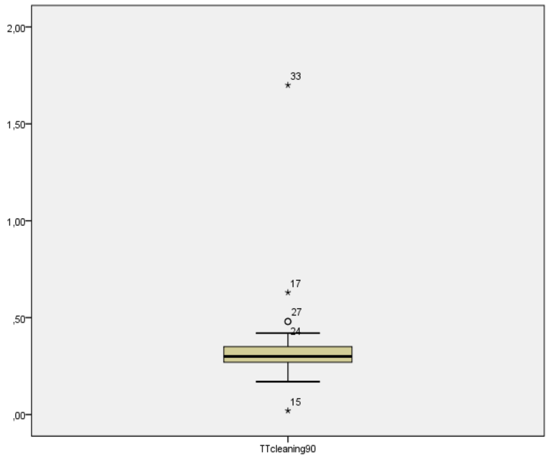
Based on the statistical arguments given, it is assumed that the activity in part marking (080) is gamma distributed with α = 4,16 and β = 0,10 (hours).

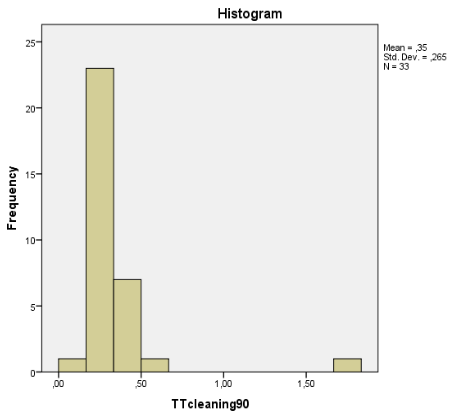
Cleaning (090)

For cleaning 33 data points were present. The calculated mean came down to 21 minutes. This seemed plausible regarding the estimation of product A project supervisor, who estimated 20 minutes. In addition, the calculated time is also 20 minutes. However, the shop-floor worker said that it only took 5-10 minutes. A cause of this difference is unclear. However, it was decided to analyze the dataset. The following figures were made:

Descriptives

			Statistic	Std. Error
TTcleaning90	Mean		0,3467	0,04611
	95% Confidence Interval for Mean	Lower Bound	0,2528	
		Upper Bound	0,4406	
	5% Trimmed Mean		0,3098	
	Median		0,3000	
	Variance		0,070	
	Std. Deviation		0,26485	
	Minimum		0,02	
	Maximum		1,70	
	Range		1,68	
	Interquartile Range		0,10	
	Skewness		4,383	0,409
	Kurtosis		22,566	0,798





Percentiles

		Percentiles 5	10	25	50	75	90	95
Weighted Average(Definition 1)	TTcleaning90	0,1250	0,1820	0,2500	0,3000	0,3500	0,4800	0,9510
Tukey's Hinges	TTcleaning90			0,2700	0,3000	0,3500		

Figure 25: Figures for the TT from the ERP-system of P90.

As shown in the boxplot and the histogram, the data consists of many outliers. By using the 1,5 x IQR-rule 3 data points were removed. Unfortunately, based on the figures no distribution can be identified. Since gamma is really often applicable for activity times (Robinson, 2014, p. 345), it was decided to make a Q-Q plot against a gamma distribution. In addition, if the outliers are removed, some sort of normal distribution seems present. So also a Q-Q plot was made against the normal distribution.

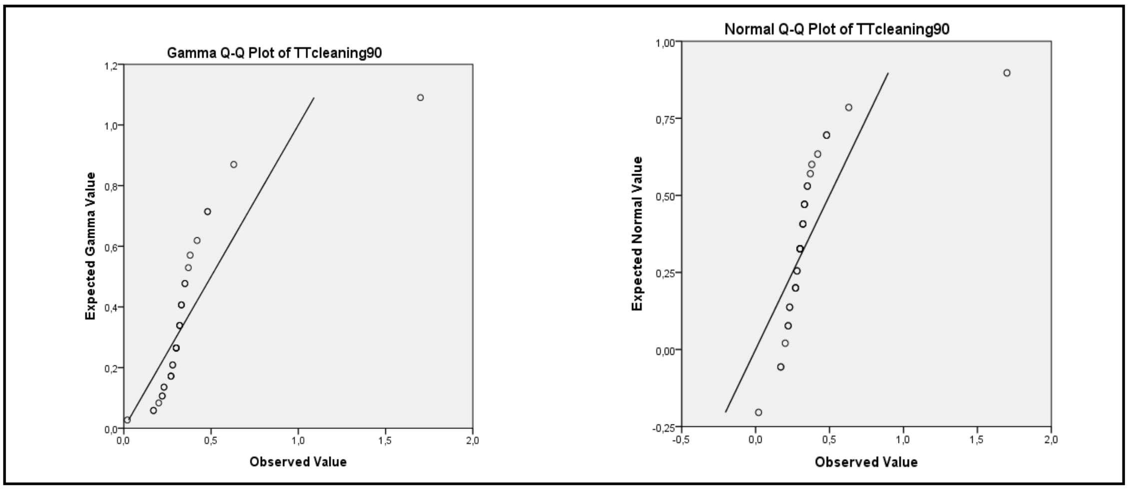


Figure 26: QQ plots for P90.

Neither of the Q-Q plots seem promising. As a final check, a histogram was made without the outliers. Some sort of normal distribution might be present. However, there is a big gap between 0,20 and 0,30.

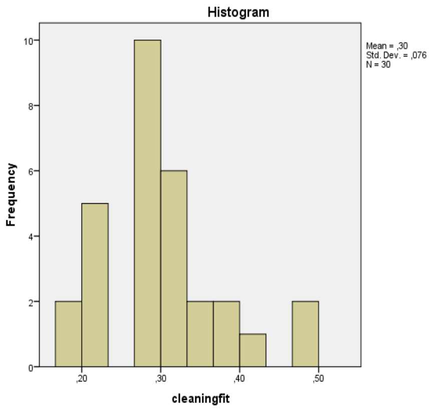


Figure 25: Histogram for the ERP-data from P90 without outliers.

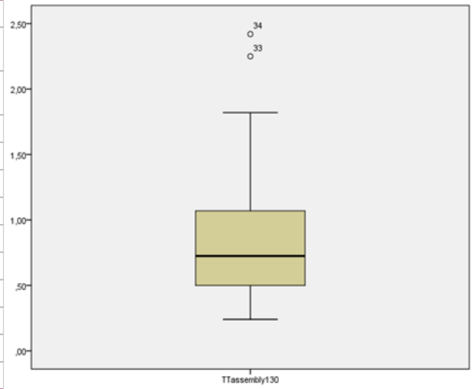
As a final argument, a goodness-of-fit test was conducted for the normal distribution. The chi-square value was 18,1692 where the critical value 11,07 (α=5%). So, reject H_0: there is a significant difference that cannot be due to chance alone. This is proven. A same goodness-of-fit test was conducted for the gamma distribution. The chi-square value was even higher (42,57), so again there was a significant difference that cannot be due to chance alone.

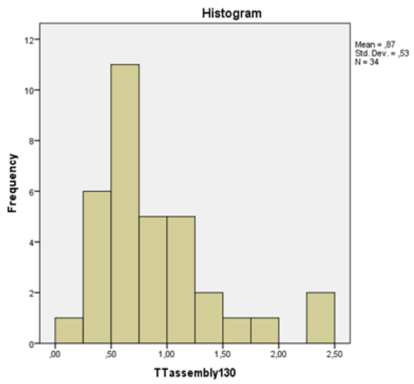
Assembly (130)

The planning officer stated that assembly was reliably clocked. Product A project supervisor underlined this. In addition, the calculated mean from the dataset was 46,9125 minutes whereas the estimate of the mode of the shop floor worker was 45 minutes. The dataset, consisting of 34 points seems therefore reliable and will be used. The corresponding figures were made with SPSS.

Descriptives

			Statistic	Std. Error
TTassembly130	Mean		0,8732	0,09082
	95% Confidence Interval for Mean	Lower Bound	0,6885	
		Upper Bound	1,0580	
	5% Trimmed Mean		0,8223	
	Median		0,7250	
	Variance		0,280	
	Std. Deviation		0,52958	
	Minimum		0,24	
	Maximum		2,42	
	Range		2,18	
	Interquartile Range		0,60	
	Skewness		1,507	0,403
	Kurtosis		1,918	0,788





Percentiles

		Percentiles 5	10	25	50	75	90	95
Weighted Average(Definition 1)	TTassembly130	0,3750	0,4400	0,5000	0,7250	1,1025	1,7750	2,2925
Tukey's Hinges	TTassembly130			0,5000	0,7250	1,0700		
				IQR				

Figure 28: Figures for the TT from the ERP-system of P130.

Using the 1,5 x IQR-rule, two outliers can be removed. Based on the histogram, it seems that a possible gamma distribution fits the data. This is a familiar distribution for completion of a task, like part marking (Robinson, 2014, p. 345). In addition, the normal distribution also seems plausible. So, two Q-Q plots were made. These Q-Q plots were made with the derived parameters for the gamma distribution (alfa = 4,16, beta = 0,10) and the normal distribution (mean = 0,8732, std.^{2} = 0,280). This was done by sorting the data ($X_{(1)} \leq X_{(2)} \leq \ldots \leq X_{(n=34)}$). From this data, i-0,5/n=34 was plotted against $F(X_{(i)})$.

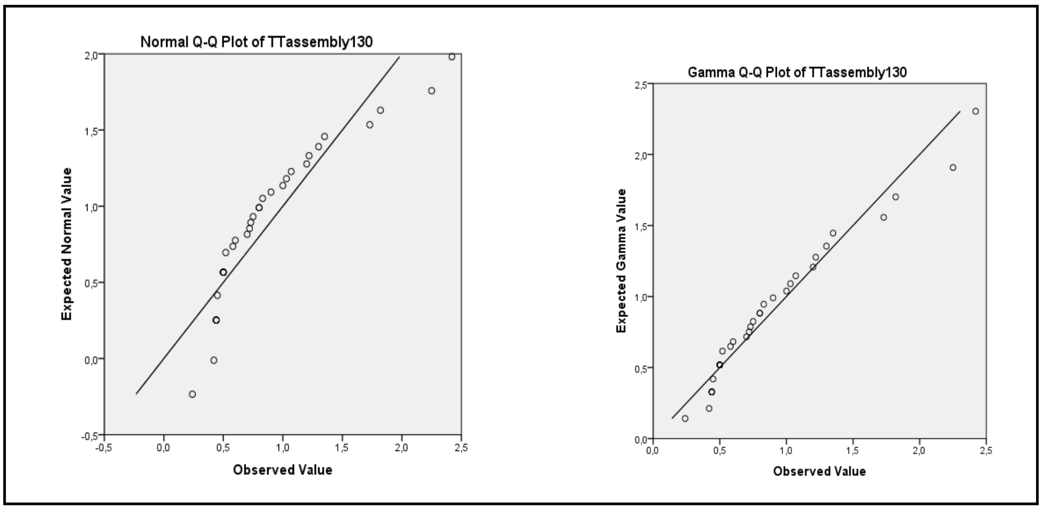
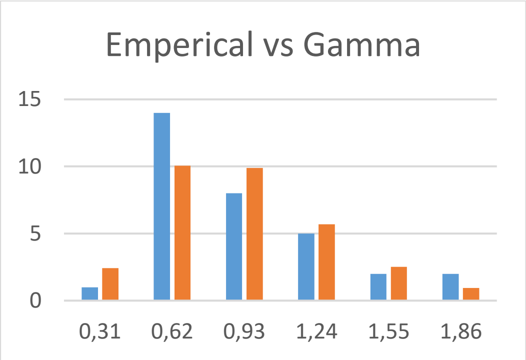


Figure 29: QQ plots for P130.

The Q-Q plot of the gamma distribution seems promising, however, the Q-Q plots of the normal distribution seems less promising. In addition, the empirical data (blue) was plotted against the hypothesized gamma distribution (orange). This was done by plotting the number of observations in the bin interval of the histogram against the expected number of observations with the gamma distribution. This again looks promising. For the number of bins, the rule of thumb SQRT(n=32 because outliers are removed) was used, resulting in 6 bins.



bins	Count	pi	Ei	Error
0,31	1	0,075857	2,427434	0,839391
0,62	14	0,390257	10,06078	1,542373
0,93	8	0,699585	9,898505	0,364128
1,24	5	0,877619	5,697095	0,085296
1,55	2	0,956082	2,510821	0,103925
1,86	2	0,985584	0,944048	1,18112

Figure 30: A plot of the empirical data against the hypothesized distribution (P130).

As final argument, a goodness-of-fit test was conducted. The null hypothesis (H_0) states: there is no significant difference between the expected values if a gamma distribution was used and the observed frequencies. As significance level α = 5% is used. Next, the chi-square test was used to test the goodness-of-fit:

$$X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

Where O_i is the observed frequency in the 'i^{th}' interval and E_i the expected frequency in the i^{th} interval. The critical value can be derived with α = 5% and degrees of freedom (df) of 31 (outliers removed). Robinson (2014) also subtracts the number of estimated parameters. However, it was taught to only subtract one degree of freedom during lectures. H_0 is rejected if the calculated chi-square value is equal or greater than the table value. The chi-square value was 4,12 where the critical value 11,07. So, do not reject H_0. So, the difference between the values seems to be due to chance. This does not mean that the null hypothesis is proven! It is just another argument that the gamma distribution seems reasonable.

In addition, the normal distribution was tested with a goodness-of-fit test. However, the chi-square value was higher (9,74) than the value when using the gamma distribution. So, the gamma distribution seems to fit the data better.

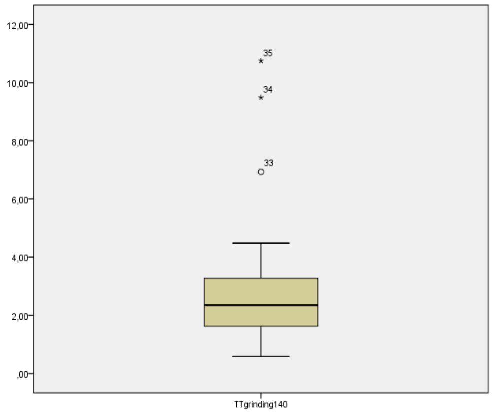
Based on the statistical arguments given, it is assumed that the activity assembly (130) is gamma distributed with α = 4,03 and β = 0,19 (hours).

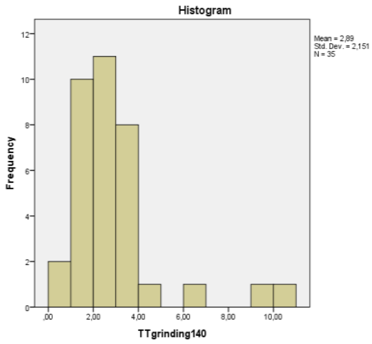
Grinding (140)

The planning officer stated that assembly was reliably clocked. Product A project supervisor underlined this. In addition, the calculated mean from the dataset was 138 minutes whereas the estimate of the mode of the shop floor worker was 90 minutes. However, the estimate of product A project supervisor was 120 minutes. There is a difference between these estimates. However, since the clocking is done consistently and reliable, the dataset consisting of 35 data points will be used. The corresponding figures were made with SPSS.

Descriptives

			Statistic	Std. Error
TTgrinding 140	Mean		2,8877	0,36361
	95% Confidence Interval for Mean	Lower Bound	2,1488	
		Upper Bound	3,6267	
	5% Trimmed Mean		2,6020	
	Median		2,3500	
	Variance		4,628	
	Std. Deviation		2,15117	
	Minimum		0,58	
	Maximum		10,75	
	Range		10,17	
	Interquartile Range		1,68	
	Skewness		2,498	0,398
	Kurtosis		6,674	0,778





Percentiles

		Percentiles						
		5	10	25	50	75	90	95
Weighted Average(Definition 1)	TTgrinding 140	0,8200	1,3300	1,6200	2,3500	3,3000	5,4600	9,7420
Tukey's Hinges	TTgrinding 140			1,6250	2,3500	3,2750		

Figure 31: Figures for the TT from the ERP-system of P140.

Using the 1,5 x IQR-rule, three outliers can be removed. Based on the histogram, it seems that a possible gamma distribution fits the data. This is a familiar distribution for completion of a task, like part marking (Robinson, 2014, p. 345). In addition, the normal distribution also seems plausible. So, two Q-Q plots were made. These Q-Q plots were made with the derived parameters for the gamma distribution (alfa = 1,80, beta = 1,60) and the normal distribution (mean = 2,89, std.^{2} = 4,628). This was done by sorting the data ($X_{(1)} \leq X_{(2)} \leq \ldots \leq X_{(n=35)}$). From this data, i-0,5/n=35 was plotted against $F(X_{(i)})$.

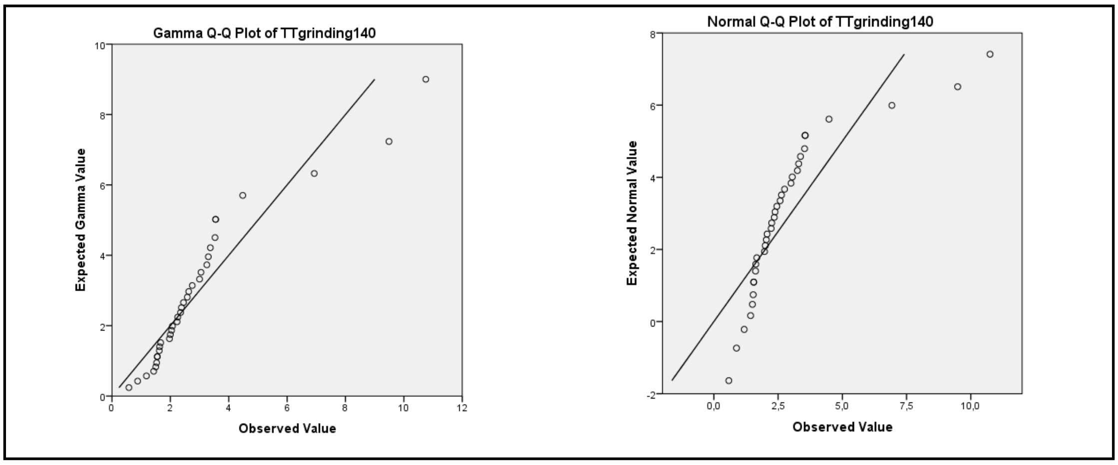
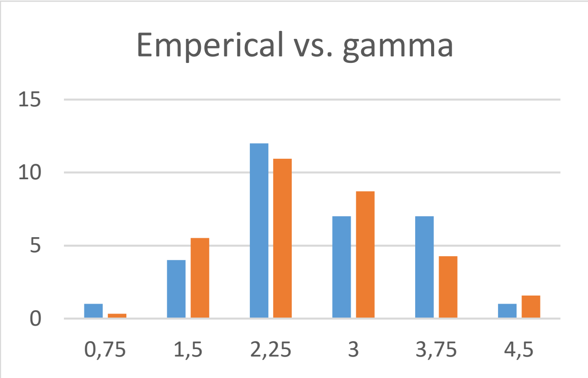
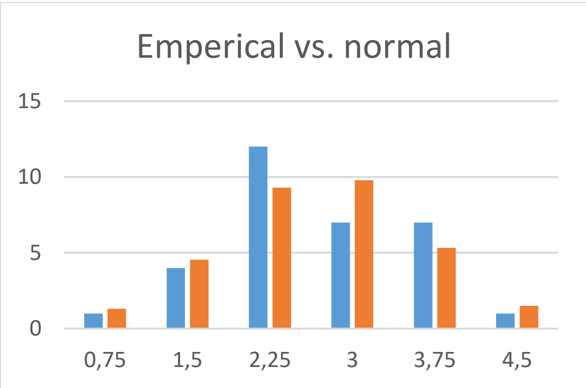


Figure 32: QQ plots of ERP-data from P140.

The Q-Q plot of the gamma distribution seems promising, however, the Q-Q plot of the normal distribution seems less promising. In addition, the empirical data (blue) was plotted against the hypothesized gamma distribution (orange) and the normal distribution (orange). This was done by plotting the number of observations in the bin interval of the histogram against the expected number of observations with the gamma distribution. This again looks promising. For the number of bins, the rule of thumb SQRT(n=32 because outliers are removed) was used, resulting in 6 bins.



bins	Count	pi	Ei	Error
0,75	1	0,010596479	0,339087	1,288180053
1,5	4	0,183079349	5,519452	0,41829042
2,25	12	0,525194166	10,94767	0,101152965
3	7	0,797274842	8,706582	0,334507967
3,75	7	0,931000743	4,279229	1,729890168
4,5	1	0,980091085	1,570891	0,207472387



bins	Countif	pi	Ei	Error
0,75	1	0,040897588	1,308723	0,072826562
1,5	4	0,183179363	4,553017	0,067170314
2,25	12	0,473582885	9,292913	0,78859253
3	7	0,779582015	9,791972	0,796071344
3,75	7	0,9460639	5,32742	0,52511771
4,5	1	0,992754976	1,494114	0,163407209

Figure 33: Plots of the empirical data against the hypothesized distributions (P140).

As final argument, a goodness-of-fit test was conducted. The null hypothesis (H_0) states: there is no significant difference between the expected values if a gamma distribution was used and the observed frequencies. As significance level α = 5% is used. Next, the chi-square test was used to test the goodness-of-fit:

$$X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

Where O_i is the observed frequency in the ‘i^{th}’ interval and E_i the expected frequency in the i^{th} interval. The critical value can be derived with α = 5% and degrees of freedom (df) of 31 (outliers removed). Robinson (2014) also subtracts the number of estimated parameters. However, it was taught to only subtract one degree of freedom during lectures. H_0 is rejected if the calculated chi-square value is equal or greater than the table value. The chi-square value was 4,07 where the critical value was 11,07. So, do not reject H_0. So, the difference between the values seems to be due to chance. This does not mean that the null hypothesis is proven! It is just another argument that the gamma distribution seems reasonable.

In addition, the normal distribution was tested with a goodness-of-fit test. However, the chi-square value was lower (2,41) than the value when using the gamma distribution. So, normal distribution seems to fit the data better.

To be sure, two other Q-Q plots are made with the filtered data (based in the 1,5 x IQR rule).

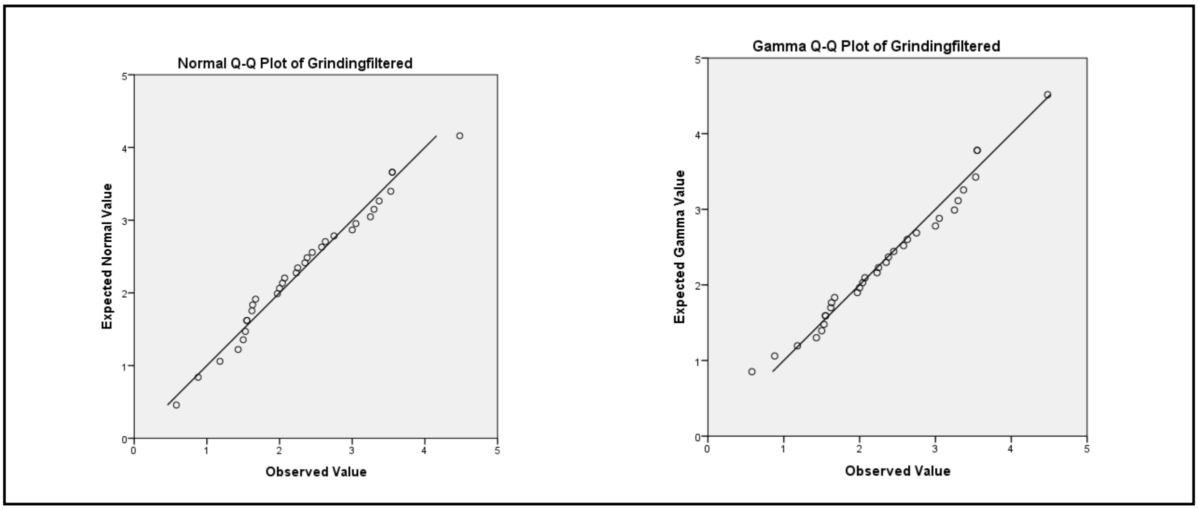


Figure 34: Additional QQ plots for P140.

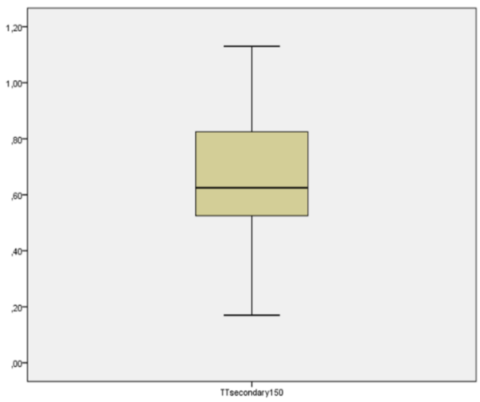
Both distributions seem to be suitable. Maybe the normal distribution seems to be slightly better. However, since the chi-square value is lower for fitting the normal distribution, it is assumed that the activity grinding (140) is gamma distributed with mean 2,31 and variance 0,80 (hours).

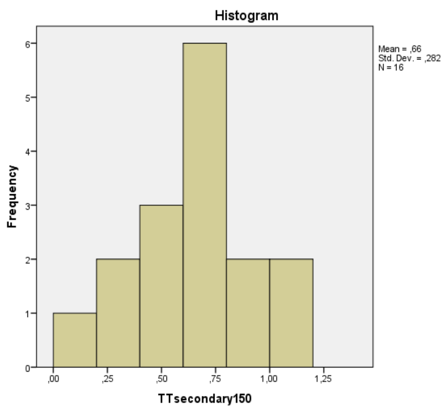
Secondary operations (150)

For secondary operations (150) 16 data points were present. The calculated mean came down to 39,488 minutes. This seems quite high regarding the estimation of product A project supervisor, who estimated 20 minutes. In addition, the calculated time is 25 minutes. In addition, the shop-floor worker also said it usually took 25 minutes. A cause of this difference is unclear. However, it was decided to analyze the dataset. The following figures were made:

Descriptives

			Statistic	Std. Error
TTsecondary150	Mean		0,6581	0,07061
	95% Confidence Interval for Mean	Lower Bound	0,5076	
		Upper Bound	0,8086	
	5% Trimmed Mean		0,6590	
	Median		0,6250	
	Variance		0,080	
	Std. Deviation		0,28245	
	Minimum		0,17	
	Maximum		1,13	
	Range		0,96	
	Interquartile Range		0,33	
	Skewness		0,030	0,564
	Kurtosis		-0,353	1,091





Percentiles

		5	10	25	50	75	90	95
Weighted Average(Definition 1)	TTsecondary150	0,1700	0,2050	0,5225	0,6250	0,8525	1,1230	
Tukey's Hinges	TTsecondary150			0,5250	0,6250	0,8250		

Figure 35: Figures for the TT from the ERP-system of P150.

As shown in the boxplot and the histogram, the data does not have any outliers. Unfortunately, based on the figures no distribution can be identified. Since gamma is really often applicable for activity times (Robinson, 2014, p. 345), it was decided to make a Q-Q plot against a gamma distribution. In addition, some sort of normal distribution seems present. So also a Q-Q plot was made against the normal distribution.

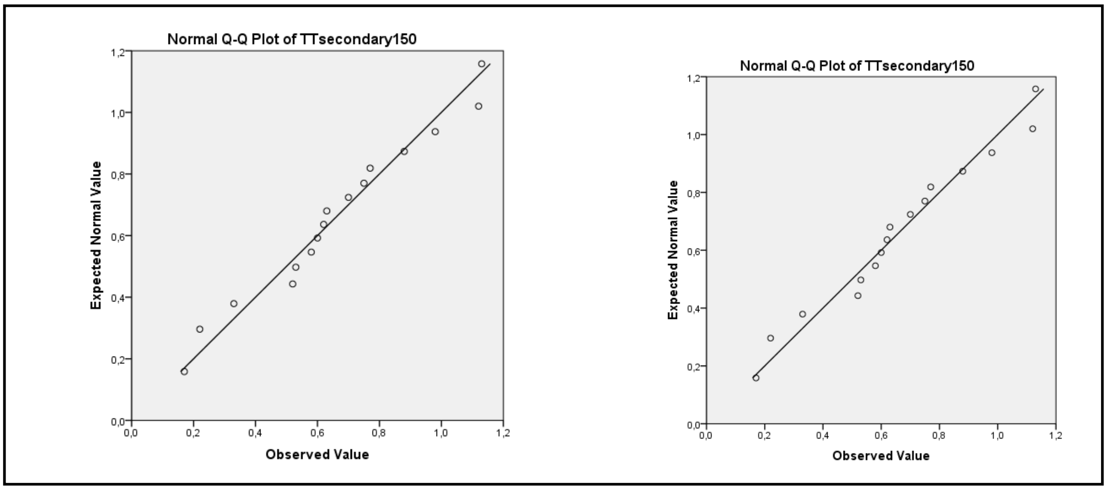


Figure 36: QQ plots for P150.

Both Q-Q plots seem promising. As a final argument, a goodness-of-fit test was conducted for the normal distribution and the gamma distribution. Using the rule of thumb (SQRT(16)) four bins were made.

The null hypothesis (H_0) states: there is no significant difference between the expected values if a gamma distribution was used and the observed frequencies. As significance level α = 5% is used. Next, the chi-square test was used to test the goodness-of-fit:

$$X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

Where O_i is the observed frequency in the 'i^{th}' interval and E_i the expected frequency in the i^{th} interval. The critical value can be derived with α = 5% and degrees of freedom (df) of 15. Robinson (2014) also subtracts the number of estimated parameters. However, it was taught to only subtract one degree of freedom during lectures. H_0 is rejected if the calculated chi-square value is equal or greater than the table value. The chi-square value was 12,99 where the critical value is 7,81. So, reject H_0. So, there is a significant difference that cannot be due to chance alone. This is proven.

In addition, the normal distribution was tested with a goodness-of-fit test. However, the chi-square value was even higher (14,311) than the value when using the gamma distribution. So, the same conclusion can be drawn.

C.2 Throughput time of Machine 1

The throughput time of Machine 1 has been determined a bit different than for the other production steps. Machine 1 has several programs for its operation. By COMPANY A the following program times have been determined for type AC and type B.

Table 56: Throughput times of different programs for the Machine 1 machine (type AC).

Program	Type	Set-up time [min]	Processing time [min]
1AC SU1 P1	Pre-processing	30	85
1AC SU1 P2+P3	Processing	40	190
1AC SU2 P4	Processing	20	130
1AC	**Total**	**90**	**405**

Table 57: Throughput times of different programs for the Machine 1 machine (type B).

Program	Type	Set-up time [min]	Processing time [min]
1B SU1 P1	Pre-processing	30	70
1B SU1 P2+P3	Processing	40	165
1B SU1 P4	Processing	20	115
1B	**Total**	**90**	**350**

As shown, the processing time for the type AC is a bit longer. For determining the throughput time, only the total processing time is assumed. This is because ten pallets are present. These pallets are placed in the machine and the machine can immediately start. Therefore, the machine operator can set-up products on a pallet while a program runs. This is possible since the program does not need any intervention of the operator. However, there need to be sufficient products A in the queue before the Machine 1.

Another thing the Machine 1 operators has to do, is measure the product. This is again a separate program that can be done without intervention of the operator. The measuring program only needs to be started and the operator can continue by setting-up other products A.

It is believed that these things can be done simultaneously since the processing times of the Machine 1 are quite long and set-up times are quite short. Furthermore, measuring only takes 45-60 minutes. There are two restrictions for this: there need to be sufficient pallets and there need to be sufficient products A in the queue. The interview with the machine operator underlines this. He believes this is possible, just like it is done with other machines in the production for other products. In addition, product A project supervisor also calculated this.

The only variation that will be assumed is ± 15% for both processing times. COMPANY A determined this in order to cope with the variation in processing time. The machine sometimes runs a bit smoother than the other times. In my opinion, this variation is quite a lot. However, COMPANY A has analyzed the throughput time of the Machine 1 quite detailed. For me, analyzing it even further would take much time to finish within the 10 weeks of this thesis.

C.3 Sources of throughput time data and the decision

Table 58: Combining sources of data for the throughput times.

#	Operation	Product A supervisor (min)	Calculated times (min)	ERP Average (min)	Reliability of ERP data (planning officer)	Shop floor worker estimate (min)	My opinion	Eventual Decision
	Reception of products	6	-	-	n.a.	-	n.a.	Uniform 5-7.
	Order intake	15	-	-	n.a.	10	n.a.	Uniform 10-15.
10	**Documentation/instructions**	5	6	-	n.a.		n.a.	
20	**Part marking**	10	20	-	n.a.	5 if many. 10 if one.	Uniform 5-10.	Uniform 5-10.
30	**Sawing/material inspection**	15	27	-	n.a.	20	Uniform 15-25.	Uniform 15-25.
50	**Inspection**	30 (FTE-sheet) 20	20	-	n.a.	15-20	Uniform 15-20.	Uniform 15-20.
60	**Turning/milling**	360	225	11,0868	Unreliable	310	Constant throughput time.	Uniform B 360 ± 15% Uniform AC 405 ± 15% (sheet "palletlooptijden")
70	**Secondary Operations**	120 (FTE-sheet) 180	60	182,63	Uncertain	Min: 180 Mode: 210 Max: 240	Gamma distribution with alfa 10,885 and beta 0,279 (hours) or triangular with 180, 210 and 240 (min).	Gamma distribution.
80	**Marking**	20	-	24	Uncertain	5-7	Gamma distribution with alfa 4,16 and beta 0,10 (hours).	Gamma distribution.
90	**Cleaning**	20	20	21	Uncertain	2-3 minutes for washing	n.a.	Uniform 5-10.

						plus 5 for cooling		
100	**Inspection**	60 (However, what if something is wrong?)	20	-	n.a.	5-10	n.a.	Uniform 5-10.
110	**THE OUTSOURCING COMPANY**	5-7 minutes 1 week outsourcing	-	-	n.a.	-	n.a.	Uniform 10-14 (loading and receiving)
120	**Visual inspection**	15	20	-	n.a.	10 but if something is wrong 25-30.	n.a.	Uniform 15-20.
130	**Assembly**	20	80	46,9125	Reliable	Min: 30 Mode: 45 Max: 60	Gamma distribution with alfa 4,03 and beta 0,19 (hours).	Gamma distribution.
140	**Grinding**	120	60	138	Reliable	Min: 85 Mode: 90 Max: 100	Normal with mean 2,31 and st. dev 0,90 (hours). Or triangular with 85, 90, 100 (min).	Normal distribution with limits (2 * std) to prevent extreme values
150	**Secondary Operations**	20	25	39,488	Uncertain	Min: 20 Mode: 25 Max: 30	Triangular distribution with 20, 25 and 30.	Triangular distribution with 20, 25 and 30.
160	**Cleaning**	10	20	-	n.a.	15	15 ± 5	Uniform 10-20.
170	**Inspection**	10	50	-	n.a.	10	n.a.	Uniform 5-10.
180	**THE OUTSOURCING COMPANY**	5-7 minutes 1 week outsourcing	-	-	n.a.	-	n.a.	Uniform 10-14 (loading and receiving)
200	**Visual inspection**	15	20	-	n.a.	10 but if something	n.a.	Uniform 15-20.

						is wrong 25-30.		
190	**Sandblasting**	60-90	-	-	n.a.	-	n.a.	Uniform 60-90.
210	**Cleaning**	20	255	-	n.a.	15	15 ± 5	Uniform 10-20. (same as 160)
205	**Visual inspection**	12 (per product, so you do 1 product for 120 minutes)	-	-	n.a.	Min: 90 Mode: 120 Max: 140/150 (if error).	Triangular with 90, 120, and 140 (1 out of 10 products).	Triangular with 90, 120, and 140 for 1 out of 10 products.
220	**Assembly**	20	75	-	n.a.	5	n.a.	Uniform 8-12
230	**Final inspection**	15	6	-	n.a.	10 but if something is wrong 25-30.	n.a.	Uniform 10-20.
	Delivery (administration)	30	-	-	n.a.	21	Uniform 15-25.	Uniform 15-25.
	Delivery (expedition)	15	-	-	n.a.	--	n.a.	Uniform 10-20.

Arguments for decisions

Table 59: Chosen throughput times for each department.

#	Operation	Decision	Argument
	Reception of products	Uniform 5-7.	Based on only one estimate of 6 minutes.
	Order intake	Uniform 10-15.	10 minutes for intake, 2,5 for putting it in the system. Estimate based on 18 orders.
10	**Documentation/instructions**		
20	**Part marking**	Uniform 5-10.	5 if many products and 10 if just one (because of set-up times).
30	**Sawing/material inspection**	Uniform 15-25.	Around 20 minutes for everything.
50	**Inspection**	Uniform 15-20.	Based on estimate shop floor worker.
60	**Turning/milling**	Uniform B 360 ± 15% Uniform AC 405 ± 15%	Based on programming time of machine. Based on how the machine runs ± 15 % (smooth or not). This is an earlier estimate of COMPANY A.
70	**Secondary Operations**	Gamma distribution.	Based on reliability of ERP-data and statistics.
80	**Marking**	Gamma distribution.	Based on reliability of ERP-data and statistics.
90	**Cleaning**	Uniform 5-10.	Based on estimate shop floor worker.
100	**Inspection**	Uniform 5-10.	Based on estimate shop floor worker and no errors.
110	**THE OUTSOURCING COMPANY**	Uniform 10-20.	Based on estimate product A project supervisor of 15 minutes.
120	**Visual inspection**	Uniform 15-20.	Based on shop floor worker.
130	**Assembly**	Gamma distribution.	Based on reliability of ERP-data and statistics.
140	**Grinding**	Normal distribution with limits.	Based on reliability of ERP-data and statistics.
150	**Secondary Operations**	Triangular distribution with 20, 25 and 30.	Based on estimate of shop floor workers.
160	**Cleaning**	Uniform 10-20.	Based on all estimates.
170	**Inspection**	Uniform 5-10.	Based on estimate shop floor worker and no errors.
180	**THE OUTSOURCING COMPANY**	Uniform 10-20.	Based on estimate product A project supervisor of 15 minutes.
200	**Visual inspection**	Uniform 15-20.	Based on shop floor worker.
190	**Sandblasting**	Uniform 60-90.	Based on estimate product A project supervisor of 60-90 minutes.
210	**Cleaning**	Uniform 10-20. (same as 160)	Based on all estimates.
205	**Visual inspection**	Triangular with 90, 120, and 140 for 1 out of 10 products.	Based on estimate quality manager.
220	**Assembly**	Uniform 8-12	Based on average between shop floor worker and product A project supervisor.
230	**Final inspection**	Uniform 10-20.	Based on estimate product A project supervisor and the shop floor worker. Because not too many problems are assumed.
	Delivery (administration)	Uniform 15-25.	Based on estimate of quality manager and customer relations.
	Delivery (expedition)	Uniform 10-20.	Based on estimate product A project supervisor of 15 minutes.

Appendix D: Contents of the simulation model

In this appendix, some screenshots of the simulation model will be displayed, to get an idea of how it looks. In addition, some code is displayed in flow charts in a simplified manner in order to understand the basic logic behind the code.

D.1: Screenshots of the simulation model

The production process

The production process displayed like the figure in appendix B.3.

Figure 35: An overview of the main frame of the simulation model.

Example of a table

An example of a table that stores data. In this case "productAsupportsstats", a table that stores relevant data for all processed products A. Based on this table, average waiting times, throughput times, total output, etc. are determined.

	integer	string	time	integer	time	time	time	time	time	tim
string	[redacted]									
1	[redacted]									
2	4	AC	13:00:00.0000	2	56:08:10:56.7733	5:12:49:56.7225	5:22:52:02.7269	4:16:50:04.1946	41:19:10:56.7733	55:
3	1	B	13:00:00.0000	2	56:09:19:00.8183	4:17:17:11.9735	6:18:56:17.3047	4:18:31:39.4249	41:20:19:00.8183	55:
4	3	B	13:00:00.0000	2	56:09:29:03.0161	5:06:30:35.6422	6:01:02:13.1770	4:17:16:19.2470	41:20:29:03.0161	55:
5	6	AC	13:00:00.0000	2	56:10:24:15.4490	6:04:05:24.7103	5:19:53:18.0493	4:00:22:52.5273	41:21:24:15.4490	55:
6	8	AC	13:00:00.0000	2	56:10:40:54.9438	6:18:52:38.6353	4:23:59:25.4262	3:16:49:07.2307	41:21:40:54.9438	55:
7	5	B	13:00:00.0000	2	56:11:11:31.7650	5:20:44:09.4445	5:22:20:23.9780	4:01:22:02.1867	41:22:11:31.7650	55:
8	10	AC	13:00:00.0000	2	56:11:43:06.3032	7:08:57:29.7990	4:23:53:16.4342	3:00:38:07.0903	41:22:43:06.3032	55:
9	7	B	13:00:00.0000	2	56:12:52:32.3391	6:12:08:44.0822	5:21:32:12.8010	4:01:15:19.5162	41:23:52:32.3391	55:
10	12	B	13:00:00.0000	2	56:13:05:00.8146	7:21:57:51.0198	4:21:33:31.0566	2:22:02:16.3428	42:00:05:00.8146	56:
11	11	B	13:00:00.0000	2	56:13:23:16.2000	7:15:41:30.9557	4:21:27:37.8060	2:21:29:43.8949	42:00:23:16.2000	56:
12	13	B	13:00:00.0000	2	56:13:43:50.7941	8:03:02:17.5363	4:19:10:24.9716	2:17:36:21.7329	42:00:43:50.7941	56:
13	16	B	13:00:00.0000	2	56:14:06:33.1035	8:03:22:59.6459	4:00:09:58.1144	38:27.0221	42:01:06:33.1035	56:
14	14	B	13:00:00.0000	2	56:14:25:37.9889	8:07:59:42.5222	4:18:30:51.6735	24:32.0572	42:01:25:37.9889	56:
15	15	B	13:00:00.0000	2	56:14:53:31.3343	7:22:20:05.5915	3:22:01:09.9449	5:33.2012	42:01:53:31.3343	56:
16	9	B	13:00:00.0000	2	56:15:12:06.6959	7:02:44:55.2184	5:18:02:59.6354	3:19:11:14.7655	42:02:12:06.6959	56:
17	18	AC	7:13:00:00.0000	2	63:08:06:42.9966	5:00:32:44.1628	6:21:33:06.7179	3:23:10:14.3773	41:19:06:42.9966	55:
18	20	AC	7:13:00:00.0000	2	63:08:19:35.3978	5:14:02:59.7016	6:01:29:22.8738	3:21:52:21.7405	41:19:19:35.3978	55:
19	19	B	7:13:00:00.0000	2	63:08:53:59.3184	5:07:56:55.0890	6:18:58:54.7331	3:22:41:57.7732	41:19:53:59.3184	55:
20	17	B	7:13:00:00.0000	2	63:09:28:53.3952	5:08:09:38.2616	6:18:50:36.5076	3:22:35:06.6008	41:20:28:53.3952	55:
21	24	AC	7:13:00:00.0000	2	63:10:06:07.5021	6:19:28:08.1881	5:18:13:07.3382	3:19:37:52.2962	41:21:06:07.5021	55:
22	21	B	7:13:00:00.0000	2	63:10:38:37.5842	5:22:11:56.3580	5:23:11:18.8291	3:21:24:30.0587	41:21:38:37.5842	55:
23	26	AC	7:13:00:00.0000	2	63:11:17:04.4440	7:09:52:54.8950	5:00:23:52.9366	3:17:03:44.8057	41:22:17:04.4440	55:
24	22	AC	7:13:00:00.0000	2	63:11:28:29.5435	6:05:38:00.2908	5:22:00:19.4448	3:20:58:19.9075	41:22:28:29.5435	55:

Figure 36: An example of a data-table within the simulation model.

Example of some code

Example of some code, with pseudocode. In this case, outsourcing to THE OUTSOURCING COMPANY.

```
if [redacted]
en[redacted]
```

Figure 37: Example of some code within the simulation model.

D.2: Flow charts

Deburring department

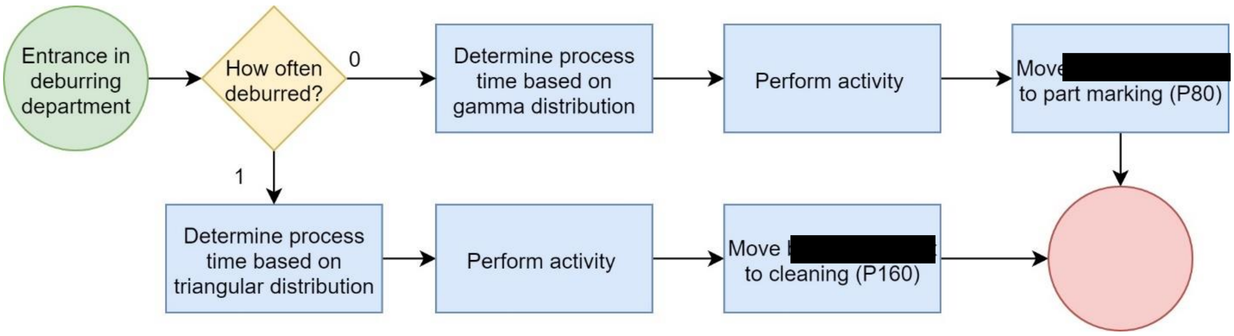


Figure 38: Flow chart of how the deburring department is programmed.

If a product A enters the deburring department, it will first be determined how often it already visited the deburring department. This is displayed in a table. Based on the stage in the process, a different probability distribution is used to determine the activity time. In addition, it also determines where product A will continue its process.

Outsourcing company

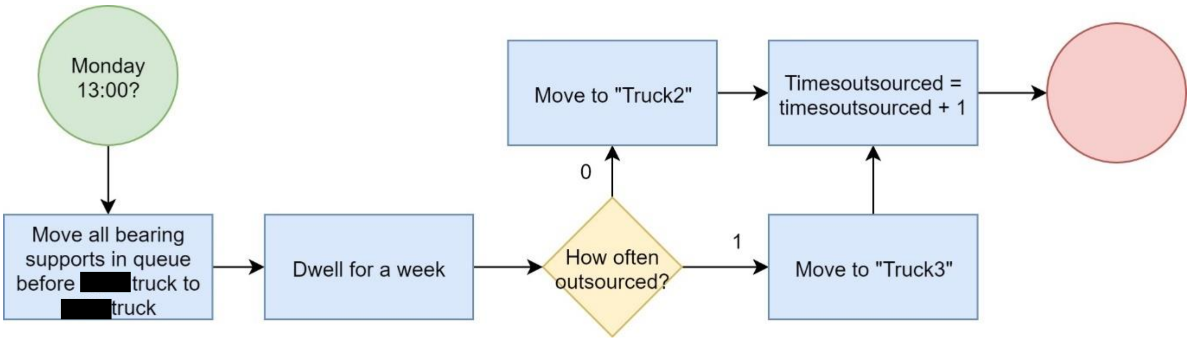


Figure 39: Flow chart of how outsourcing is programmed.

All products A in the queue are moving to THE OUTSOURCING COMPANY, regardless of how often they already visited THE OUTSOURCING COMPANY. Since outsourcing takes a week, the dwell time at THE OUTSOURCING COMPANY is a week. When the truck comes back, it will be determined where product A should resume its process, based on how often it was already outsourced.

Locking the Machine 2 and Sandblasting machine

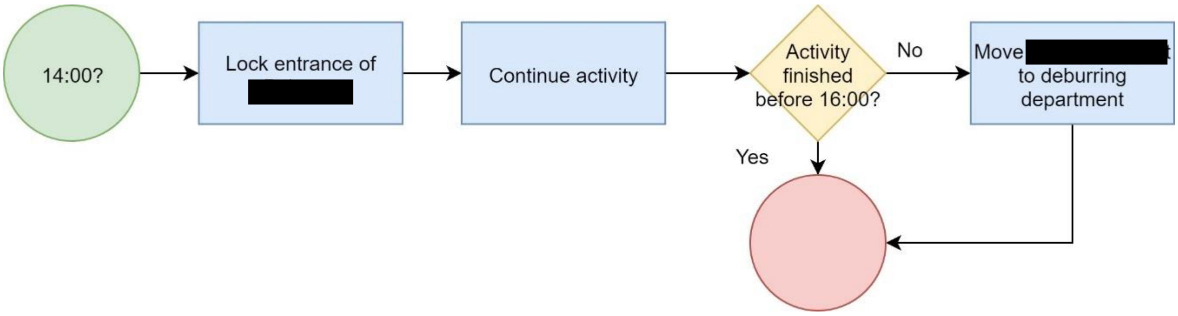


Figure 40: Flow chart of how the Machine 2 and sandblasting machine are locked after a certain time.

If it is 14:00 on a given day, it is likely that an operator will not pick up a new product A since it cannot pause its activity and the average process time is 2 hours and 18 minutes. Therefore, the Machine 2 entrance is locked such that no new products A can enter the Machine 2. The activity that is still in the Machine 2 will be finished. If it is finished, it will automatically move on to the deburring department. Though, if it is after 16:00, it is assumed that the operator will finish its activity before going home. In this case, the model needs an external trigger that moves the model to the deburring department.

The model for the Sandblasting machine is similar. Though, for Sandblasting the machine is locked after 14:35 since the average throughput time is 75 minutes. Furthermore, the next department is cleaning (P210) and not the deburring department.

When a new day starts, both departments are unlocked again.

Determining the processing time of the Machine 1 machine

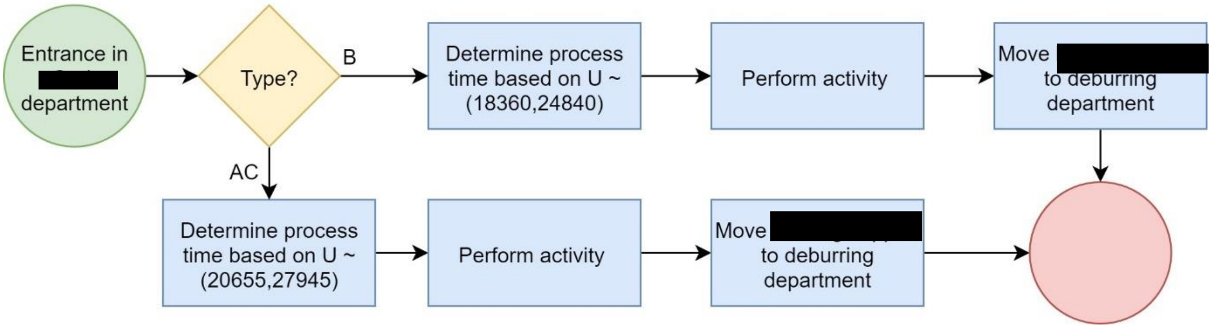


Figure 41: Flow chart of how the Machine 1 machine is programmed.

Whereas the process time for deburring is dependent on the stage within the process, the process time for the Machine 1 machine is dependent on product A type. Based on the type, the process time distribution will be determined.

Waiting KPI

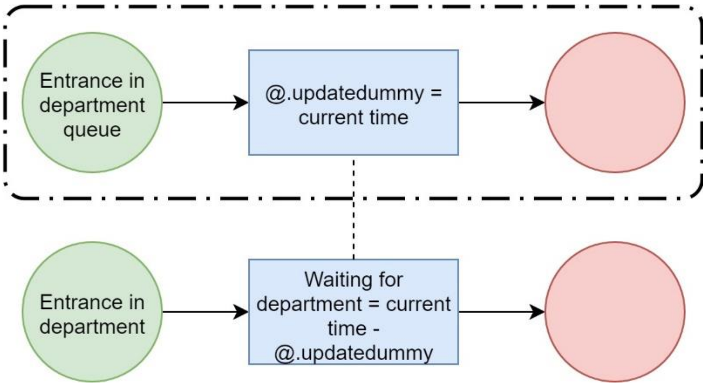


Figure 42: Flow chart of how waiting times are calculated.

In the model, multiple waiting times in front of the Machine 1 machine, deburring department, Machine 2 machine, and outsourcing truck are tracked. "@.updatedummy" is a dummy that updates a certain time that is attached to a product A entity in the model. When a products A enters the queue of one of the aforementioned departments, this dummy gets updated to determine its waiting time.

Planning algorithms

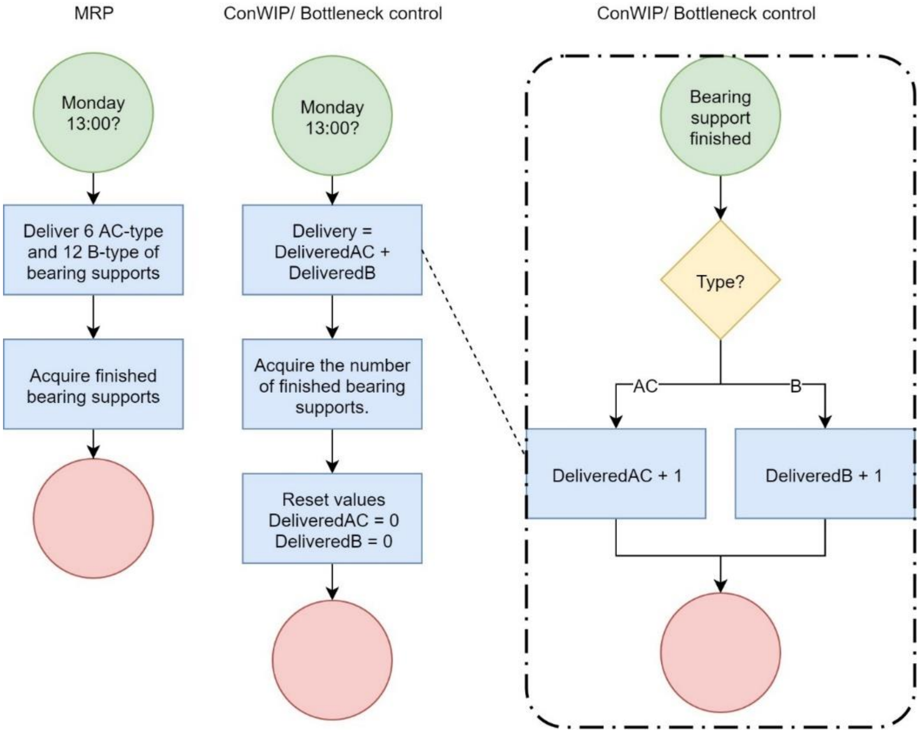


Figure 43: Flow chart of the different planning approaches.

The MRP-model is self-explanatory.
For ConWIP control, the model basically delivers the exact number of AC-types and B-types. This is counted by the variables "deliveredAC" and "deliveredB". At the same time, it acquires all finished products A such that the WIP remains constant. The method stops by resetting the values, such that a new week can begin.
Bottleneck control works similarly to ConWIP. Though, the WIP does not remain constant for the entire process, but for the process up until the bottleneck.

Appendix E: Experimental set-up

In this appendix, the experimental set-up will be determined for all experiments. In the end, simulation output will be shown.

E.1 Determining the warm-up period

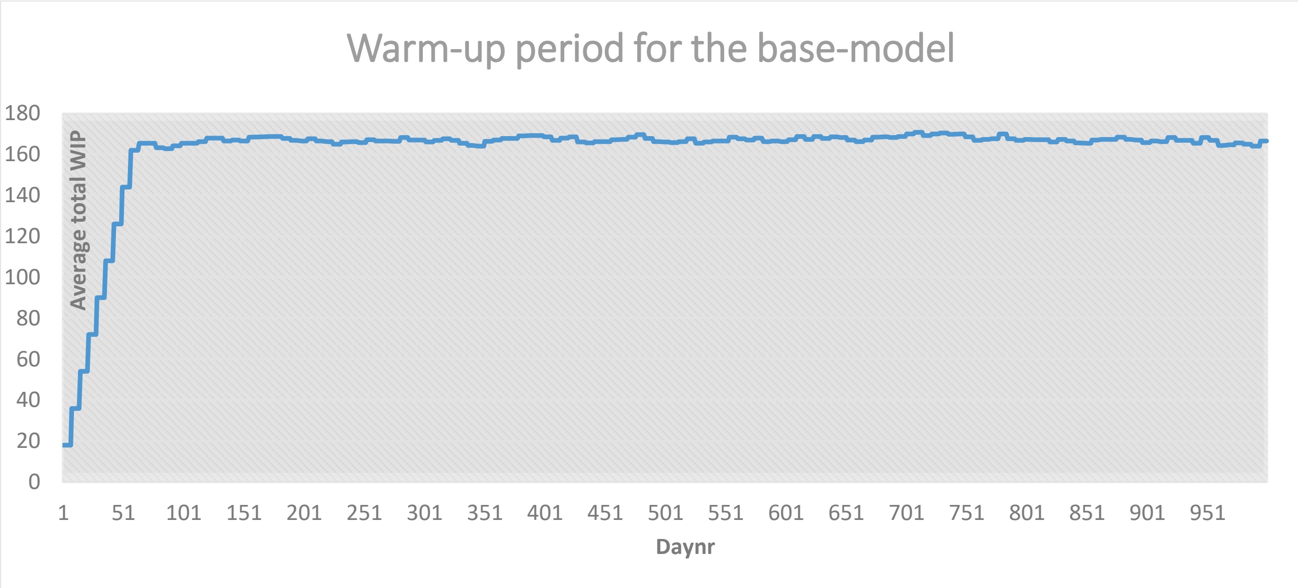


Figure 44: Graph for determining the warm-up period.

E.2 Determining the run-length

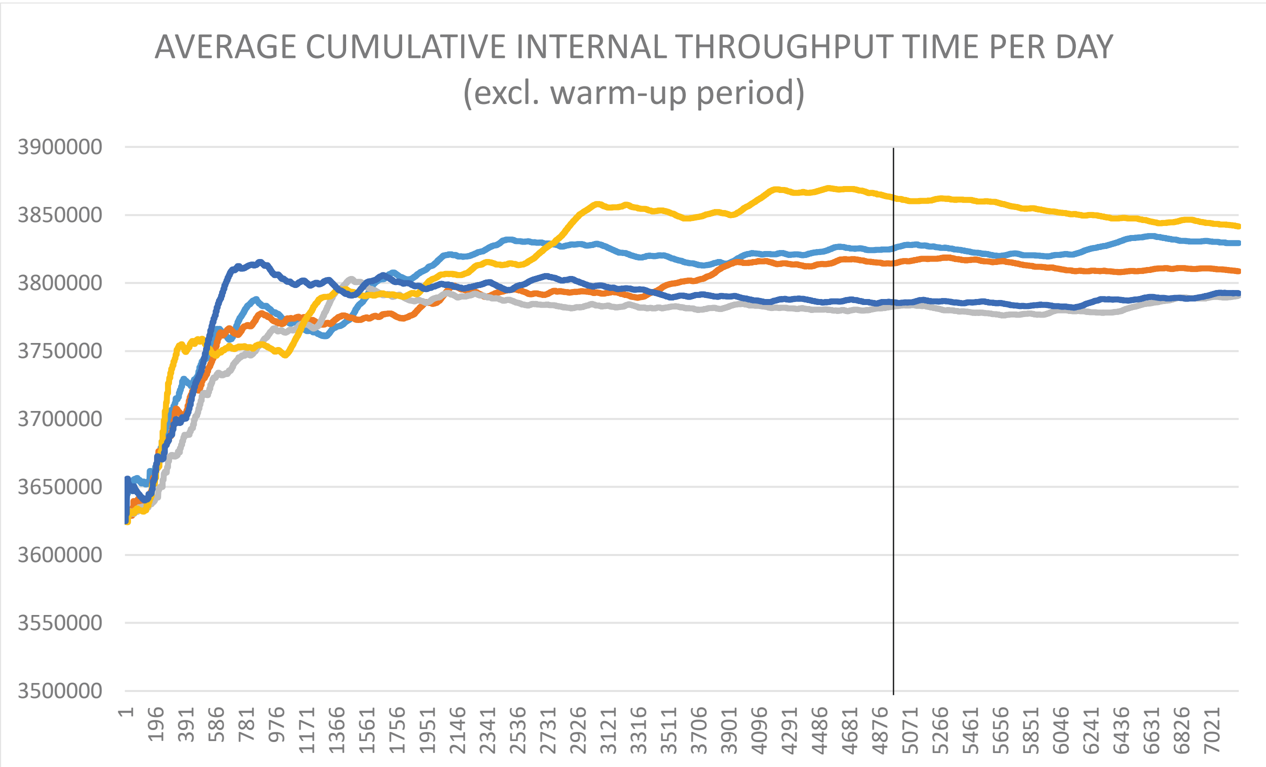


Figure 45:Graph for determining the run-length (zoomed-in version).

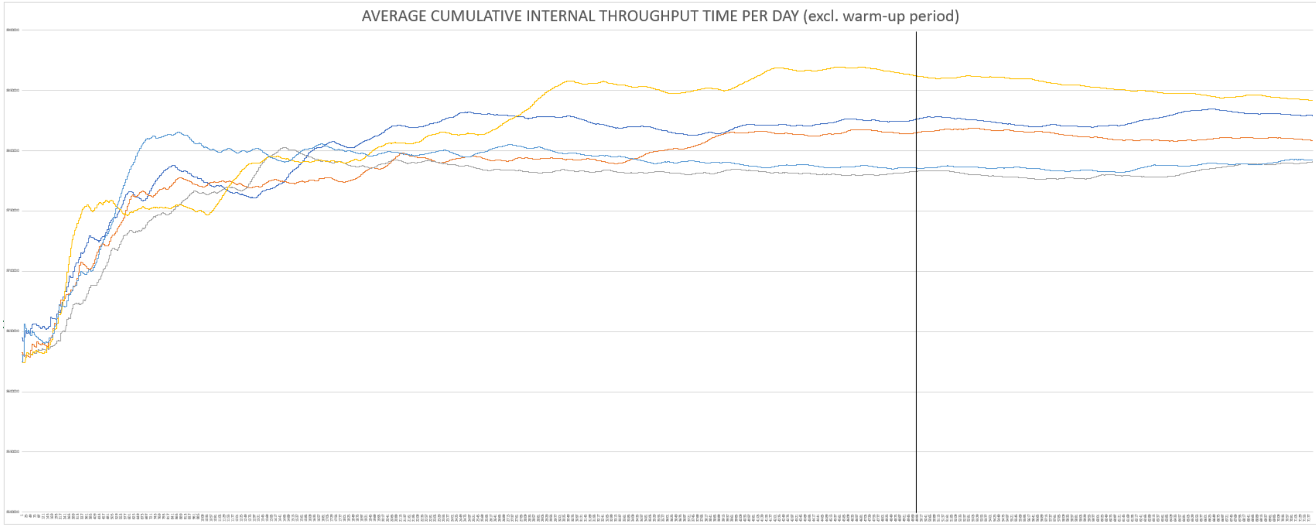


Figure 46: Graph for determining the run-length (zoomed-out version).

E.3 Simulation output

In order to get a feeling for simulation output, some screenshots of how simulation output looks are provided. Experiments are run with the "experiment manager", which looks like this:

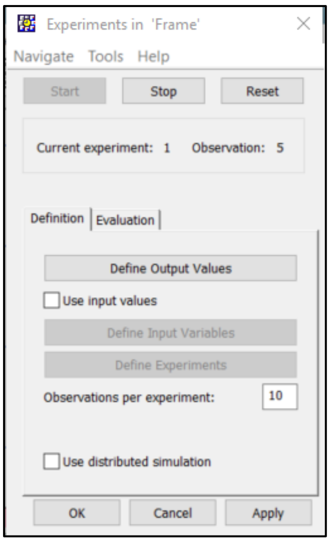


Figure 47: The experiment manager.

The KPI's for the experiments can determined by dragging KPI's in the following table:

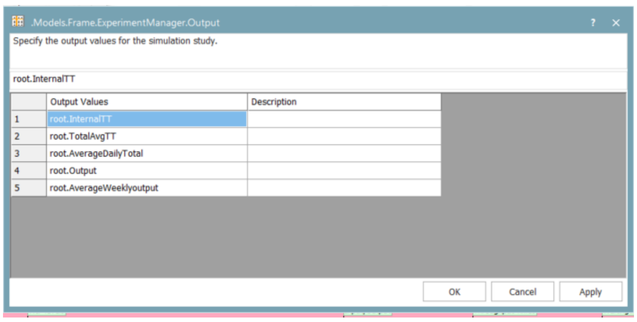


Figure 48: Determining KPI's for experimentation.

After an experiment is finished, the following pop-up is created:

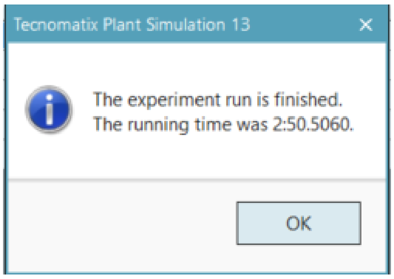


Figure 49: Pop-up after experimentation.

The program automatically creates a report for the experiment. Which looks something like this:

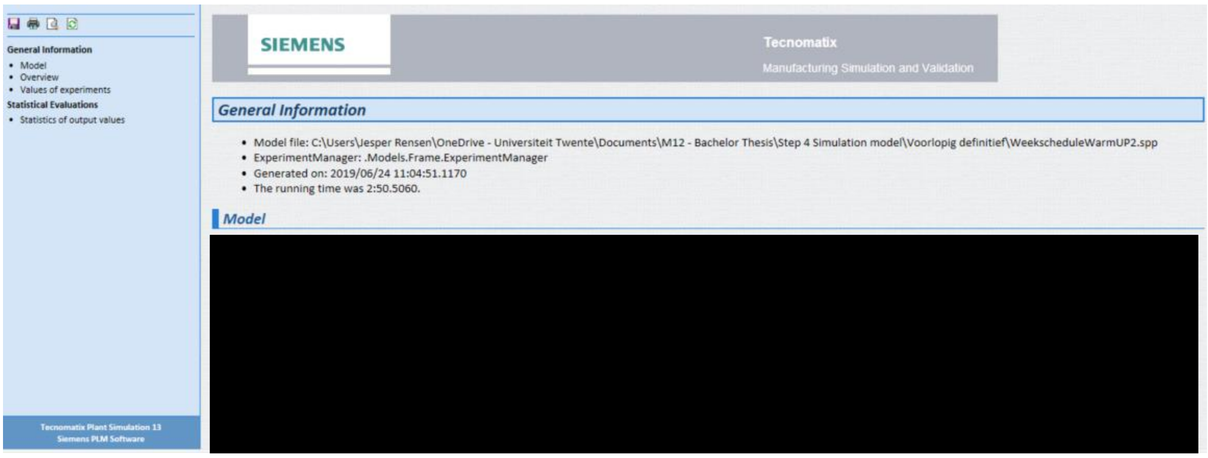


Figure 50: The top of the simulation report, created by the program.

This report also contains graphs and tables, which look like this:

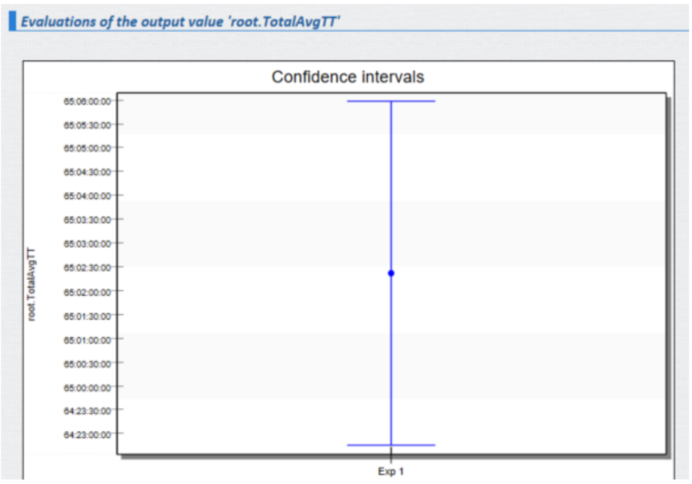


Figure 51: Confidence interval within the report of the simulation experiment.

root.TotalAvgTT	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
65:02:21:54.6540	5:02:43.3449	64:19:25:56.0619	65:09:34:54.8239	64:22:45:11.1453	65:05:58:38.1628

The analysis of variance is impossible.
At least two experiments with random output for 'root.TotalAvgTT' are needed.

Figure 52: Tables within the report of the simulation experiment.

Consequently, summarized results can be acquired:

.Models.Frame.ExperimentManager.Results

44:03:46:57.3114

		root.InternalTT	root.TotalAvgTT	root.AverageDailyTotal	root.Output	root.AverageWeeklyoutput
1	Exp 1	44:03:46:57.3114	65:02:21:54.6540	167.39406122449	12703.6	17.9992857142857

Figure 53: Summarized results after an experiment.

Though, also more detailed results can be acquired. In this table, the program automatically calculates confidence interesting statistics:

.Models.Frame.ExperimentManager.DetailedResults

To open a subtable, select the cell and press F2.

	Experiment	root.InternalTT	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound	Observations
1	Exp 1	44:03:46:57.3114	4:59:39.1002	43:20:55:01.8799	44:10:54:45.4614	44:00:12:25.7072	44:07:21:28.9157	Table 1

Figure 54: Detailed results after an experiment.

The results from single replications are saved in a table for each KPI, which looks like this:

.Models.Frame.ExperimentMan...

1	44:00:43:42.4390
2	44:09:52:29.4559
3	43:20:55:01.8799
4	44:00:14:39.7833
5	44:01:59:01.8666
6	44:05:21:12.3444
7	44:05:03:30.1625
8	44:08:50:53.7506
9	43:21:54:15.9707
10	44:10:54:45.4614

Figure 55: Replication-output after an experiment.

These replication-results are interesting for, for example, the paired-t test.

Appendix F: Analysis of experimental output

In this appendix, outputs of experiments will be outlined and analyzed. The functions of different tables are explained in the main text.

F.1 ConWIP cards

In order to determine the right number of ConWIP cards, the output is checked for different card values. The output that is closest to 6 AC-types and 12 B-types as output are chosen. The following data is collected from the simulation model, based on 10 replications.

Table 60: Determining the number of ConWIP cards.

ACcards	BCards	Weekly AC output	Weekly B output	Average weekly output
34	72	5,895714	11,94529	17,841
34	73	5,871714	12,069	17,94071
34	74	5,848	12,19486	18,04286
35	72	6,032857	11,889	17,92186
35	73	6,01	12,01443	18,02443
35	74	5,985286	12,12229	18,10757
36	72	6,175571	11,84371	18,01929
36	73	6,144429	11,93814	18,08257
36	74	6,118857	12,03971	18,15857

So the configuration AC-cards:B-cards will be 35:73. Actually, the configuration 37:72 is closer to 18 as weekly output, however, the individual output of the AC-types and B-types deviate more.

F.2 Bottleneck control results

Determining the number of cards for bottleneck control

Similar, the number of bottleneck control cards have been determined. However, this data is based on only three replications in order to save time. Furthermore, only 5 experiments have been run, whereas actually 3x3=9 experiments should have been run to check all combinations. Again, the deviation of the individual output of AC-types and B-types is more important than the deviation from the total output.

Machine 2

Table 61: Determining the number of bottleneck control cards if the Machine 2 is the bottleneck.

root.ACcards	root.BCards	root.AvgweeklyAC	root.AvgweeklyB	root.AverageWeeklyoutput
21,00	46,00	5,80	12,16	17,96
22,00	46,00	5,99	12,10	18,09
23,00	46,00	6,17	12,03	18,20
22,00	45,00	6,05	11,90	17,95
22,00	47,00	5,93	12,27	18,20

So the configuration ACcards:Bcards will be 22:46 if the machine 2 is the bottleneck.

Machine 1

Table 62: Determining the number of bottleneck control cards if the Machine 1 is the bottleneck.

root.ACcards	root.BCards	root.avgweeklyAC	root.avgweeklyB	root.AverageWeeklyoutput
5	18	4,999048	13,04095	18,04
7	18	6,37619	11,93333	18,30952
6	17	5,967619	11,71571	17,68333
6	18	5,967619	12,20476	18,17238
6	19	5,892381	12,54333	18,43571

So the configuration ACcards:Bcards will be 6:18 if the Machine 1 is the bottleneck.

THE OUTSOURCING COMPANY1

Table 63: Determining the number of bottleneck control cards if the first time outsourcing to THE OUTSOURCING COMPANY is the bottleneck.

root.ACcards	root.BCards	root.avgweeklyAC	root.avgweeklyB	root.AverageWeeklyoutput
14	33	5,620952	12,05143	17,67238
16	33	6,281429	12,01	18,29143
15	32	5,960952	11,7081	17,66905
15	33	5,961429	12,04333	18,00476
15	34	5,957619	12,38286	18,34048

So the configuration ACcards:Bcards will be 15:33 if THE OUTSOURCING COMPANY1 is the bottleneck.

THE OUTSOURCING COMPANY2

Table 64: Determining the number of bottleneck control cards if the second time outsourcing to THE OUTSOURCING COMPANY is the bottleneck.

root.ACcards	root.BCards	root.avgweeklyAC	root.avgweeklyB	root.AverageWeeklyoutput
29	61	5,849048	12,12667	17,97571
30	61	6,030952	12,03762	18,06857
31	61	6,205238	11,93429	18,13952
30	59	6,065714	11,76952	17,83524
30	60	6,045238	11,90952	17,95476
30	62	6,005714	12,14143	18,14714

So the configuration ACcards:Bcards will be 30:61 if THE OUTSOURCING COMPANY2 is the bottleneck.

The number of bottleneck cards for the Machine 2 with ten replications

Since bottleneck control on the Machine 2 performed as best bottleneck control method, this method is rerun with 10 replications in order to determine the number of cards. This resulted in similar numbers as before.

Table 65: Determining the number of bottleneck control cards if the Machine 2 is the bottleneck (10 replications).

root.ACcards	root.BCards	ACoutput	Boutput	Totaloutput
21	45	5,846857	11,95429	17,80114
21	46	5,804	12,15971	17,96371
21	47	5,751429	12,35957	18,111
22	45	6,049714	11,90514	17,95486
22	46	5,982714	12,08986	18,07257
22	47	5,927	12,271	18,198
23	45	6,239714	11,84343	18,08314
23	46	6,17	12,01929	18,18929
23	47	6,099714	12,18457	18,28429

F.3 Average waiting times in the MRP and ConWIP model

Table 66: Waiting times for different planning approaches.

	Avg. Waiting for Machine 1 (s)	Avg. Waiting for Machine 2 (s)	Avg. Waiting for Deburring (s)	Avg. Waiting for THE OUTSOURCING COMPANY (s)
ConWIP-model	239259	265425	47712	415738
MRP-model	223710	250231	46245	418640
Bottleneck control	229623	251005	48345	415850

F.4 Paired-T approach for the influence variability

Table 67: Paired-T approach for testing variability.

	Different intervals		**Different numbers**		**Combined**	
Base model	-515623	-374850	-396888	-190674	-750257	-487803

F.5 Paired-T approach for the transport day to THE OUTSOURCING COMPANY

Base model

Table 68: Paired-T approach for a different transport day to THE OUTSOURCING COMPANY (base model).

	Tu		**We**		**Th**		**Fr**	
Mo	70399,24	86631,65	132147,2	158594,25	145437,6	173572,4	268864	290320
	Mo > Tu		*Mo > We*		*Mo > Th*		*Mo > Fr*	
Tu			51999	81711,559	65331,87	96647,27	186223,2	215930,6
			Tu > We		*Tu > Th*		*Tu > Fr*	
We					-3878,78	32147,37	123069,2	145374
					No sign. Difference		*We > Fr*	
Th							103761,5	136413,2
							Th > Fr	

MRP-model

Table 69: Paired-T approach for a different transport day to THE OUTSOURCING COMPANY (MRP-model).

	Tu		**We**		**Th**		**Fr**	
Mo	108604,3	128078,9	320647,7	338114,5	422137,4	453958,4	348303,4	370873,7
	Mo > Tu		*Mo > We*		*Mo > Th*		*Mo > Fr*	
Tu			203727,3	218351,62	307349	332063,5	236153	246340,8
			Tu > We		*Tu > Th*		*Tu > Fr*	
We					92140,63	125192,9	21783,05	38631,84
					We > Th		*We > Fr*	
Th							-92817,7	-64100,9
							Th < Fr	

F.6 Paired-T approach for multiple transport days to THE OUTSOURCING COMPANY

Base model

Table 70: Paired-T approach for multiple transport days to THE OUTSOURCING COMPANY (base model).

	Mo-We		**Tu-Th**		**Tu-Fr**		**We-Fr**		**Mo-We-Fr**	
Mo-Th	- 30829,6	5055,623	55462,49	79971,97	222137,2	238770,8	293622,2	318525,1	296563,2	319236
	No sign. Difference		*Mo-Th > Tu-Th*		*Mo-Th > Tu-Fr*		*Mo-Th > We-Fr*		*Mo-Th > Mo-We-Fr*	
Mo-We			62635,2	98573,2	231761,9	254920,1	302291	335630,3	305083,4	336489,7
			Mo-We > Tu-Th		*Mo-We > Tu-Fr*		*Mo-We > We-Fr*		*Mo-We > Mo-We-Fr*	
Tu-Th					147710,6	177763	219716,6	256996,2	225384,1	254980,6
					Tu-Th > Tu-Fr		*Tu-Th > We - Fr*		*Tu-Th > Mo-We-Fr*	
Tu-Fr							66318,2	84921,09	66823,91	88067,23
							Tu - Fr > We-Fr		*Tu-Fr > Mo-We-Fr*	
We-Fr									-7370	11021
									No Sign. Difference	

MRP-model

Table 71: Paired-T approach for multiple transport days to THE OUTSOURCING COMPANY (MRP-model).

	Mo-We		**Tu-Th**		**Tu-Fr**		**We-Fr**		**Mo-We-Fr**	
Mo-Th	-141729	-117678	-76681,9	-33828,78	27816,89	44694,66	25221,5	44926,15	165357,8	190201
	Mo-Th < Mo-We		*Mo-Th < Tu-Th*		*Mo-Th > Tu-Fr*		*Mo-Th > We-Fr*		*Mo-Th > Mo-We-Fr*	
Mo-We			57568,2	91328,175	152875,8	179042,8	156785	172769,8	298297,3	316668,6
			Mo-We > Tu-Th		*Mo-We > Tu-Fr*		*Mo-We > We-Fr*		*Mo-We > Mo-We-Fr*	
Tu-Th					69021,31	114000,9	76163,52	104494,8	217165	248904,5
					Tu-Th > Tu-Fr		*Tu-Th > We - Fr*		*Tu-Th > Mo-We-Fr*	
Tu-Fr							-12243,3	9879,402	126127,5	156919,8
							No sign. Difference		*Tu-Fr > Mo-We-Fr*	
We-Fr									134576	150835
									We-Fr > Mo-We-Fr	

F.7 Paired-T approach for adding an extra machine

Extra Machine 1 in the base model

Table 72: Paired-T approach for adding an extra Machine 1 (base model).

	S2		**S3**		**S4**	
S1	-10254,3	10328,87	-10254,3	10328,87	-237102	-218478
	No sign. Difference		*No sign. Difference*		*S1 < S4*	
S2			0	0	-234511	-221144
			No difference		*S2 < S4*	
S3					-234511	-221144
					S3 < S4	

Extra Machine 1 in the MRP model

Table 73: Paired-T approach for adding an extra Machine 1 (MRP-model).

	S2		**S3**		**S4**	
S1	-5174	13661	-3325	17538	-45244	-33678
	No sign. Difference		*No sign. Difference*		*S1 < S4*	
S2			-4902	10629	-51634	-35775
			No sign. Difference		*S2 < S4*	
S3					-56052	-37083
					S3 < S4	

Extra Machine 2 in the base model

Table 74: Paired-T approach for adding an extra Machine 2 (base model).

	S2		**S3**		**S4**	
S1	168247,6	194265,3	168247,6	194265,3	-17016,8	37782,95
	S1 > S2		*S1 > S3*		*No sign. difference*	
S2			0	0	-194804	-146943
			No difference		*S2 < S4*	
S3					-194804	-146943
					S3 < S4	

Extra Machine 2 in the MRP-model

Table 75: Paired-T approach for adding an extra Machine 2 (MRP-model).

	S2		**S3**		**S4**	
S1	207373,7	235946,4	207373,7	235946,4	65977,28	91346,92
	S1 > S2		*S1 > S3*		*S1 > S4*	
S2			0	0	-151998	-133998
			No difference		*S2 < S4*	
S3					-151998	-133998
					S3 < S4	

F.8 Paired-T approach for the delivery and acquiring day

One delivery and acquiring day

Table 76: Paired-T approach for delivery and acquiring day (MRP-model).

	Tu		**We**		**Th**		**Fr**	
Mo	252988,3	282518,7	335725,4	354090,66	147703,7	174561,2	56816	72632
	Mo > Tu		*Mo > We*		*Mo > Th*		*Mo > Fr*	
Tu			63921,7	90387,32	-117030	-96211,6	-213616	-192443
			Tu > We		*Tu < Th*		*Tu < Fr*	
We					-196731	-170820	-290047	-270321
					We < Th		*We < Fr*	
Th							-103649	-89168,1
							Th < Fr	

Two or three delivery and acquiring days

Table 77: Paired-T approach for different delivery and acquiring days (MRP-model).

	We		**Mo - We**		**Mo - Th**		**Tu - Th**		**Tu - Fr**		**We - Fr**		**Mo - We - Fr**	
Mo	335725	354091	588144	607751	504149	533182	545091	591037	525187	544067	498096	526910	566693	597491
	Mo > We		*Mo > Mo - We*		*Mo > Mo - Th*		*Mo > Tu - Th*		*Mo > Tu - Fr*		*Mo > We - Fr*		*Mo > Mo - We - Fr*	
We			244390	261688	159741	187774	202683	243629	178494	200945	155295	179895	223378	250990
			We > Mo - We		*We > Mo - Th*		*We > Tu - Th*		*We > Tu - Fr*		*We > We - Fr*		*We > Mo - We - Fr*	
Mo - We					-96462	-62101	-53533	-6234	-72485	-54155	-98294	-72595	-26415	-5296
					Mo - We < Mo - Th		*Mo - We < Tu - Th*		*Mo - We < Tu - Fr*		*Mo - We < We - Fr*		*Mo - We < Mo - We - Fr*	
Mo - Th							35209	63587	-1484	33407	-21122	8797	46266	80586
							Mo - Th > Tu - Th		*No sign. Difference*		*No sign. Difference*		*Mo - Th > Mo - We - Fr*	
Tu - Th									-57489	-9384	-73364	-37757	-7030	35086
									Tu - Th < Tu - Fr		Tu - Th < We - Fr		*No sign. Difference*	
Tu - Fr											-39301	-4947	30418	64511
											Tu - Fr < We - Fr		Tu - Fr > Mo - We - Fr	
We - Fr													62985	76192
													We - Fr > Mo - We - Fr	

F.9 Determining the required capacity

By running the model, the following average occupations have been acquired. Note that for deburring two FTE’s are present and the Machine 1 is running a 24-hour shift from Monday to Saturday.

Table 78: Utilization levels in the combined models.

Number	Activity	Occupation
	Reception of products	0,05
10	Documentation/instructions and order intake	0,09
20	Part marking	0,06
30	Sawing/material inspection	0,15
50	Inspection	0,13
60	[redacted]	0,78
70		
150	Secondary Operations	0,78
80	Marking	0,18
90	Cleaning	0,06
100	Inspection	0,06
110		0,04
	[redacted]	0,04
120	Visual inspection	0,13
130	Assembly	0,35
140	Grinding	0,51
160	Cleaning	0,11
170	Inspection	0,06
180		0,04
	[redacted]	0,04
200	Visual inspection	0,13
190	Sandblasting	0,37
210	Cleaning	0,11
205	Visual inspection	0,09
220	Assembly	0,05
230	Final inspection	0,11
	Delivery (administration)	0,15
	Delivery (expedition)	0,11