June 2020

Reducing the throughput time at Machine-builder X

BSc Thesis

Industrial Engineering and Management

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Date:	June 2020
Place:	University of Twente, Enschede, The Netherlands
Faculty:	Behavioural management and social sciences
Programme:	Industrial Engineering and Management – Bachelor

Preface

This report is the result of the bachelor thesis conducted to complete the bachelor Industrial Engineering and Management at the University of Twente. The thesis is conducted at Machine-builder X, with supervision from both the COO of Machine-builder X and the University of Twente. To provide value, this thesis aims at reducing the throughput time of the machines produced at Machine-builder X.

First, I would like to thank my colleagues that have helped me during my time at Machine-builder X. Even though the corona circumstances made it impossible for me to visit the office often, I felt very welcome at Machine-builder X. My colleagues were always very open to help me and give input for my thesis. I would like to thank my supervisor at Machine-builder X. In weekly discussions, I have had the opportunity to discuss all my work and gather very useful feedback and input from him. Apart from his useful input, he gave me the opportunity to make the most of my learning experience by allowing me to be present at a meeting with suppliers and take responsibility. Furthermore, I would like to thank the employees of Machine-builder X for their input in discussions I have been able to have with them on the subject.

Secondly, I want to thank my first supervisor from the University of Twente, Eduardo Lalla. In our meetings, I have learned a lot about writing a project plan and executing this project academically. His feedback and opinions about my work helped me progress and guided me to the conclusion of this thesis. I would also like to thank Wouter van Heeswijk for being my second supervisor for this project.

Finally, I would like to thank my family and friends for their support throughout the execution of my thesis. I would like to thank Jan-Hein as my good friend and buddy for this thesis. We helped each other a lot to reflect on our work. His feedback and support improved my thesis and helped me to stay on track.

Jan van Dongen

June 2020

Management Summary

Introduction

Machine-builder X is a machine-building company that develops machines working on a specific principle (anonymized). Machine-builder X is growing rapidly, with the Machine X currently as the most important machine that is built. As multiple customers require a throughput time of four months, Machine-builder X needs to improve efficiency and decrease the throughput time. The action problem is identified as:

The throughput time measured by the chief operating officer (COO) of Machine-builder X is six months, however it should be four months at the start of 2021.

Several problems apparent at Machine-builder X lead to a throughput time of four months. Many suppliers have a higher lead time than is agreed upon with Machine-builder X, which delays the timeframe of building the machines. The identification of this core problem leads to the following main research question within this thesis:

How can Machine-builder X decrease the negative effect that inconsistent suppliers (with longer lead times than agreed upon) have on the throughput time?

Problem approach

To find answers to the main research question within this thesis, several steps are followed.

- The current situation of Machine-builder X is analysed. In this context analysis, relevant information of the processes is identified. This includes a visualisation of the throughput time, analysis of the suppliers, and identification of KPIs.
- Through conducting a literature study, relevant methods are found for reducing the supply base at Machine-builder X. The most important characteristics of a supply base reduction method can be identified and used for designing a specific method.
- The relevant and applicable aspects of the methods found in the literature study are combined into a method designed specifically for this thesis. A more general but wider approach is taken than found in literature, to find the most results in this thesis.
- The designed method is applied step by step on the data available from Machine-builder X. Possibilities for applying the method at Machine-builder X are identified and evaluated through numerical evaluation, possibly following from meetings with suppliers.
- The suggestions resulting from applying the method are combined to derive conclusions. The results are analysed to find out if a throughput time of four months can be reached through implementing the suggestions given.

The designed method

A method was designed based on supply base reduction methods and a lead time estimation tool to decrease the negative effect of suppliers with long lead times on the throughput time of the machines. The following steps are taken through applying this method:

- The purchasing decisions (materials to be ordered) that currently endanger the timeline of four months are identified with the lead time estimation tool
- The suppliers are ranked through evaluation based on the Key Performance Indicators
- The suppliers and purchasing decisions are classified and categorized
- Alternative approaches for the purchasing decision are identified (e.g., sourcing at alternative suppliers or tiering the supplies under another supplier) and numerically evaluated

- Suggestions are given for reduction of the throughput time and continuous improvement of the supplier base

Recommendations from applying the method
Based on the results from applying the method, several suggestions or recommendations can be given to Machine-builder X to achieve a throughput time of four months for the Machine X.

To achieve a throughput time of four months, twelve weeks is the baseline of available lead time for the materials within the order groups present in the Machine X (machines 11 and 15). Nine out of the fourteen order groups contain materials with an estimated lead time higher than twelve weeks. For the other five order groups, utilizing the lead time estimation tool for the planning of ordering materials with an estimated lead time lower than twelve weeks is suggested.

For the order groups with an estimated lead time slightly higher than twelve weeks (Order groups 3, 12), additional focus on these materials in the design phase of the process is deemed sufficient. The design of these materials should be finished before the end of the design phase such that all materials can be ordered in advance.

For the consumable and spare items present in the order groups that have an estimated lead time higher than eighteen weeks (Order groups 4, 6, 7, 8, 11, 14), capital investments should be done for inventory and ordering before intended release of PO (purchase order). The large customized parts within these order groups should only be ordered before intended release of PO, to minimize the capital investments. A total capital investment of €17,587.00 in these materials is suggested, with a direct inventory cost of €1,758.70 for keeping stock of the materials.

The sub-order group ‘Gas Panel’ in Order group 11 should be outsourced (i.e., a form of tiering as alternative approach) to the supplier ‘M-114’. For an additional cost of €1,364.51, a full sub-assembly can be delivered within the timeframe of twelve weeks.

Order group 5 consists of a special component (the laser) for which it is not essential to be delivered simultaneously with the rest of the machine. Ordering the laser on the release of PO is sufficient. When Machine-builder X notices problems with the delivery of the laser of Order group 5, it is suggested to negotiate with the supplier to be able to consistently achieve a throughput time of four months. Currently, capital investments are not recommended because of the financial risk and the possible delay in the delivery not being critical for the customer of Machine-builder X.

Finally, highly ranked alternative suppliers are available for the purchasing decisions in Order groups 6 and 11. Costs and agreed lead time need to be agreed upon and analysed to find out if alternative suppliers would have a beneficial impact on the throughput time.

Table of Contents

Reader's guide

To provide a clear overview of the structure in this thesis, a reader's guide is given. The content of the chapters apparent in the thesis is explained.

Chapter 1:
The first chapter introduces the reader to this thesis. Machine-builder X is introduced, and the most important problems are described and analysed. Furthermore, the approach that will be taken to solve the identified core problem is provided. The chapter is concluded with the design of the research.

Chapter 2:
The second chapter includes the context analysis done at Machine-builder X. The research questions intended to analyse the context of the company are answered through a visualization of the throughput time, an analysis of the suppliers and identification of the Key Performance Indicators (KPIs).

Chapter 3:
The third chapter of the thesis contains the literature study that is done to identify relevant methods to reduce and manage the supply base at Machine-builder X. Different methods are outlined and the relevancy for this thesis is given.

Chapter 4:
In the fourth chapter, the methods derived from literature study are combined into a method specifically designed for application at Machine-builder X. Requirements for designing an applicable method for Machine-builder X are outlined. All necessary steps for finding results in this thesis are explained in detail, in four different stages.

Chapter 5:
This chapter includes the application of the method designed in Chapter 4. The steps are followed, and suggestions are derived from the results of applying the method. Throughout this chapter, an example of applying the method on one sub-assembly is given, while the extended results are present in Appendix 4.

Chapter 6:
Chapter 6 is the final chapter of this thesis. In this chapter, the conclusions and recommendations based on the applied method are given. The results and relevancy of the thesis is evaluated. Suggestions for future research are given, as well as a discussion on the shortcomings of the research.

The text contains references to certain sections. On a device, these references can be clicked to jump to this section.

Appendices 4,5, and 6 are not complete in the public version as it contains confidential information.

1 Introduction

This bachelor thesis assignment is conducted at Machine-builder X. This research looks at the long throughput time, from now on referring to the time from release of customer order until machine delivery, which currently refrains Machine-builder X from further growth. Chapter 1.1 introduces the reader to the company, Chapter 1.2 provides information about the problem, Chapter 1.3 gives an overview of the, to be conducted, research, and Chapter 1.4 concludes the introduction of this thesis.

1.1 Company description

Machine-builder X is a fast-growing company that develops and sells machines. *(anonymized information).* Machine-builder X has sold around fifteen machines that are now active at their customers. The machines are ordered by companies worldwide and maintained by Machine-builder X. Limited inventory is only held for maintenance purposes and all materials necessary for the assembly of a machine are ordered after a customer PO (purchase order) is released. Machine-builder X then goes through a make-to-order process, which means the machines are built specific for the customer. To give an overview of the complete process, the phases are explained.

1. **Potential customer contact phase**: Potential customers get in contact to identify if a machine can be built by Machine-builder X that would conform the customer's needs. This phase includes communication, negotiation, and cooperation between the two parties and has a timeframe of around two years.
2. **Design phase:** When the potential customer orders the machine, the company finalizes the technical product design. This is a complete model consisting of the bill of materials, gas scheme, electrical scheme, manual and certification mark. This process takes around four to six weeks.
3. **Material order and delivery phase:** The technical product design is finished and the company orders materials that are necessary for the final assembly of the machine. Suppliers start the process of delivering the materials, which can take up to sixteen weeks.
4. **Assembly phase:** When all materials are delivered, the machine can be assembled. Several sub-assemblies are done partly during Phase 3 as sub-assemblies can be made with already supplied materials. This phase takes around four to six weeks.
5. **Concluding phase:** This phase is around two weeks and consists of final tests (for example on bugs within the software), factory acceptance test (customer checks the machine), executing corrections, cleaning up the machine, and packaging the machine for delivery.
6. **After-sale service phase:** After a machine has been built and delivered to the customer, the process is not finished yet. Machine-builder X provides maintenance at the companies to keep the machines up and running at the customers and provide more value.

The assembly of the machines at Machine-builder X requires components from more than fifty suppliers. This requires a substantial amount of time in the total throughput time of Machine-builder X. This thesis focuses on the Machine X, which is currently the most important machine. A new machine is being designed, however the insights on the Machine X will be relevant for the new machine as well. Not managing the suppliers properly brings an important risk in delays, causing the total throughput time to increase. The goal of this assignment is to provide solutions to the problems occurring at Machine-builder X and help building a basis for further growth.

1.2 The problem

At Machine-builder X, improvement is possible in the phases of the process as explained in Chapter 1.1. This section outlines the action problem present at Machine-builder X and identifies the core problem that needs to be solved.

1.2.1 The action problem

Improvements needs to be made to decrease the throughput time, which is the timeframe between Phase 2 (i.e., customer order and design phase) and Phase 5 (i.e., concluding phase). The current throughput time of six months is accepted by multiple customers. To extend the customer pool and grow however, the throughput time should be reduced.

Action problem

The throughput time measured by the chief operating officer (COO) of Machine-builder X is six months, however it should be four months at the start of 2021.

Norm and reality

The problem owner is the COO of Machine-builder X, who perceives a problem with the throughput time at the company. There is a demand from the potential customers within the industry to decrease this throughput time from six months, to the norm of four months. The variable, throughput time, is measured as the time from customer order until delivery of the machine which consists of Phases 2 up to and including 5.

Reality: At Machine-builder X, the throughput time currently is six months.
Norm: The throughput time should be a maximum of four months.

The concluding phase (i.e., Phase 5) is around two weeks and is difficult to reduce its timeframe because of the necessary checks. This means that the throughput time must be squeezed on Phases 2,3 and 4, i.e., customer order and design phase, material order phase and assembly phase.

1.2.2 Problem cluster and motivation of core problem

To come to the root of the problem at Machine-builder X, the causes for a long throughput time are identified and systematically analysed in terms of their relations.

1. **No clear overview of influences in supply chain**
   Currently, a clear overview of what influences processes (e.g. material supply) in the supply chain is missing. This causes phases to take longer than possibly necessary (problem 2).
2. **Phases taking a lot of time**
   Certain phases taking a lot of time within the supply chain (caused by problems 1 & 6) leads to a long throughput time of six months (problem 9). For example, Phase 3 might take longer because the influences on the supplier lead times are unknown and not acted upon.
3. **Many suppliers with a higher lead time than agreed**
   For the supply of materials, Machine-builder X currently has more than fifty suppliers. Several of these suppliers deliver later than agreed upon and cause delays in supplies (problem 6). The inaccuracy of the lead times endangers the planning, and materials are ordered late (problem 4). The lead time is the time between a supply being ordered by and delivered at Machine-builder X.
4. **Materials (with long lead times) ordered late**
   Because materials are ordered late (caused by problems 3 & 5), supplies are delayed (problem 6). Problem 3 is a cause of late orders, as Machine-builder X assumes the materials will be delivered on time. However, the extended lead times make it that Machine-builder X orders later than necessary. Some of the suppliers at Machine-builder X supply relatively special

materials. Because of several factors, the lead time of these materials are always long, i.e., around 16 weeks. This has a big impact on the flexibility as late supplies prevent finishing sub-assemblies, which require that material.

5. **Unclarity in ordering supplies**
   When an order comes in, there is a lack of procedures for the technical product design. Orders are not done immediately which results in delayed ordering of materials (problem 4).
6. **Late supplies**
   Because of late supplies (caused by problems 3 & 4), assembly is delayed. Employees wait for deliveries before assemblies can be made (problem 7).
7. **Delayed assembly**
   Delayed assemblies (caused by problem 6) will mean that the final machine cannot be finished on time. Process times will extend, and final deliveries will be delayed (problem 8).
8. **Delayed delivery**
   Delayed deliveries (caused by problem 7) mean an extension in the total throughput time. Because of the delay before a machine is ready for delivery, the throughput time is extended (problem 9).
9. **Long throughput time**
   The time from Phase 2 to and including Phase 5, is the throughput time. The throughput time currently is six months, where the norm is four months. This is the action problem perceived by the company and is caused by lengthy phases and delayed delivery (problems 2 & 8).

Problem cluster

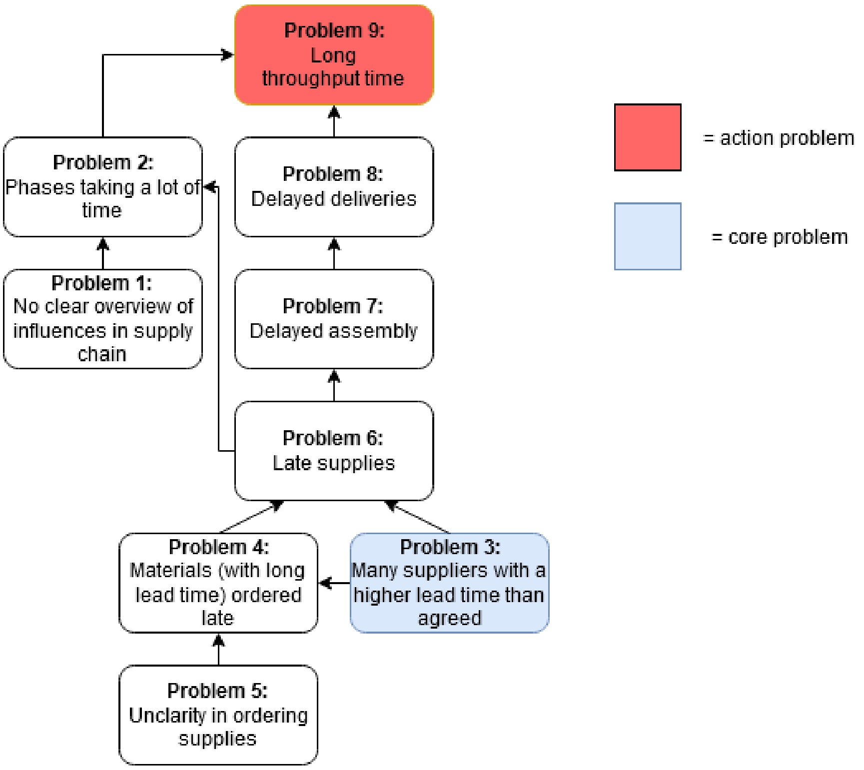

Figure 1: Problem cluster identified at Machine-builder X, including the relation between the problems

As seen in the problem cluster in Figure 1, delayed deliveries are caused only by late supplies. This is a result of the research boundary. The assignment will focus on the delayed supplies which results in a focus on these problems, where other possible causes are left out. This is explained in the motivation.

Core problem

There are many suppliers with a higher lead time than agreed upon with Machine-builder X.

Motivation and scope

To produce the machines, around fifty suppliers are active for Machine-builder X. These suppliers all supply materials with a lead time that is agreed upon with the company. If this lead time is delayed, the throughput time at the company risks being increased. This is a problem with relation to the suppliers of the company. Data is monitored over the past years for the agreed and actual lead time of the suppliers. By analysing this information, it is possible to find out which suppliers have a negative influence on the total throughput time at Machine-builder X. With this information, two types of solutions can be determined: reducing the supplier base and gaining a better insight in supplier lead times. A supply base is the pool of the suppliers that supply materials to the buying company. Supply base reduction can be applied to standardize and reduce the number of suppliers by for example clustering suppliers together. Reducing the number of suppliers strategically, will lead to less risks in late supplies. The throughput time will decrease through applying these types of solutions, as the risk of having late supplies is lowered. The core problem is chosen because of the relevancy through rule of thumb (Heerkens & van Winden, 2017). The rule states that you must find a problem that is apparent. Furthermore, the problem should not have a direct cause, should be influenceable and solving it should have the most effect. It seems possible to analyse all the information within ten weeks and identify possibilities for decreasing the risk of late supplies. This way the company will have a better insight making it possible to decrease the overall throughput time.

1.3 Research

This section gives an outline for the research and its limitations as well as the intended deliverables.

1.3.1 Research design

The research is based on the main research question, divided into sub-questions. These are identified based on the MPSM problem-solving method (Heerkens & van Winden, 2017).

Main question

To achieve the norm, which is a throughput time of four months, the identified core problem needs to be solved. This means that the negative effect of inconsistent suppliers on the throughput time of Machine-builder X needs to be reduced. Based on the core problem, the following main research question can be constructed:

How can Machine-builder X decrease the negative effect that inconsistent suppliers (with longer lead times than agreed upon) have on the throughput time?

Sub-questions

1. What is the context of Machine-builder X (considering the throughput time and suppliers)?
    a. How can the current throughput time of six months at the company be visually represented and how can this visual representation be squeezed towards four months?
    b. What are reasons for late deliveries from the supplier to the company?
    c. Which suppliers generally have a higher lead time than agreed upon (negatively inconsistent)?
    d. What are the Key Performance Indicators to be used for suppliers of Machine-builder X?
2. What are the relevant methods for reducing the supplier base at Machine-builder X?
3. How can a method be designed, based on the literature, for implementation at Machine-builder X?

4. What will be the results of implementing the method at Machine-builder X?
    a. What are the costs and benefits of the methods to be implemented?
    b. How does the implementation affect the throughput time?
5. What suggestions or conclusions can be made from conducting the thesis at Machine-builder X?

Sub-question 1 will be answered to serve as context to the thesis assignment. Chapter 2 will go into detail on this sub-question. Data is gathered and a broad analysis is done.

First, a visual representation will make it easier to identify gaps within the throughput time, the time from Phase 2 to and including Phase 5. Stakeholders will be interviewed to provide in-depth information about the processes and phases within the throughput time. Through diving into the details and looking at historical data, deep research will lead to clear process times and relations between the phases. This information is transformed into a visual representation of the throughput time, supported by textual explanations.

Explanatory research is done to gain an insight into the relations between late deliveries and the factors leading to these delays. Qualitative data is gathered from stakeholders within the company to form a better understanding on the reasons why suppliers might not be able to deliver on time. The internal stakeholders can provide information based on the reasons they have heard from suppliers as well as patterns that have emerged in the past. As the stakeholders are knowledgeable about the reasons from suppliers for late deliveries, direct contact with the suppliers was not expected to provide a lot of added value.

Furthermore, sub-question 1c provides insight into the suppliers of the company that affect the throughput time of Machine-builder X. With this insight, it is possible to find solutions to reduce the effect the identified negatively inconsistent suppliers have on the throughput time. Analysis of primary Excel data, provided by Machine-builder X, makes it possible to identify the suppliers that have higher lead times than agreed upon. Analysis is done on agreed and actual lead times of the suppliers over the past years. Through graphs and visualization, an overview will be given.

Finally, the most important variables to be considered when methods are chosen and implemented are identified. Descriptive research is conducted since opinions of stakeholders will be analysed to find out what is considered most important for suppliers, the Key Performance Indicators (KPIs). Literature research will provide general information about what is important for suppliers, both short- and long-term. This knowledge is necessary for applying the method matching the company's characteristics.

Sub-question 2 is based on providing the theoretical framework of the research. The negative effect of inconsistent suppliers on the throughput time can be reduced through supply base reduction extended with lead time estimation. The framework is built on the limitations of the research, integrating theories from literature study. Chapter 3 goes into detail on the supply base reduction theories.

Sub-question 3 will be answered in Chapter 4 to be able to implement the method correctly and achieve the goal of the thesis assignment. The methods from literature will be analysed with characteristics of and possibilities at the company to form a redesign of the method. Together with stakeholders in the company, possibilities of applying the method are identified and elaborated on. A redesign with parts of the methods from literature is taken as a basis for providing solutions to Machine-builder X. Lead time estimation is an extension of the Excel data analysis and will provide insights for the company which materials should for example be ordered earlier.

Sub-question 4 relates to the numerical evaluation of implementation. The main solution approaches to be chosen together with Machine-builder X are analysed on predicted costs and benefits to argue for implementation of the method. To see if the norm is reached, the impact of implementation on the throughput time will be identified. Possibilities are identified and suggestions can be made. Contact with stakeholders, data analysis and literature study will aid in analysing and evaluating the results. Sub-question 4 is answered in Chapter 5.

Sub-question 5 will be answered to conclude the research in Chapter 6. The whole process is conducted, and problems or points of attention will have appeared. This gives an opportunity to reflect and possibly provide further suggestions on these aspects. The results of the thesis are evaluated together with the COO of Machine-builder X.

1.3.2 Validity, limitations, and reliability issues

In the execution of the project, it is likely that issues might occur with a relation to validity, limitations, or reliability. These issues will be approached as follows.

Discrepancy between literature and reality at the company
Theory and methods found in literature have limitations. These limitations, such as assumptions, should be checked in relation with Machine-builder X to see if it is valid to work with results from literature. At all times, the literature is checked for reliability in relation with the company.

Limited data available to statistically prove results
The company is relatively small and is not overloaded with data. Analysis that requires this limited data makes it difficult to for example statistically prove results. Together with stakeholders at the company, results that cannot be statistically validated will be analysed to find conclusions and validate the results.

Precision of stakeholder's opinions and measurements
While conducting interviews and gathering data in a communicative approach, opinions and information is gathered from stakeholders within the company. The precision of these facts and opinions should be measured to explain how valid or reliable certain parts of the research are. The expertise of the stakeholders is relied on and taken as an important part of the research process. It will be identified which information must be validated by other stakeholders or data.

COVID-19 limitations
Due to the measures taken against COVID-19, it was not possible to work at the company for most of the bachelor thesis. All data that is gathered and analysed throughout the project is possible through online communication. Interviews are held online, and most work is done from home. Weekly online meetings with the company supervisor validated the progress of the thesis. Through effective communication, the impact of the COVID-19 limitations was minimized.

1.3.3 Intended deliverables

This section gives an overview of the deliverables that will result from the thesis assignment at Machine-builder X. The deliverables link to the sub-questions defined in Chapter 1.3.1.

1. Visual representation of current and desired throughput time (SQ 1)
2. Insights in delay caused by suppliers (SQ 1)
3. Overview of the most important KPIs at Machine-builder X (SQ 1)
4. Theoretical framework; literature study and review for relevant methods (SQ 2)
5. The design of the solution method based on the methods in literature (SQ 3)
6. Numerical evaluation of the to be implemented approaches (SQ 4)
7. Conclusions and suggestions from research and implementation (SQ 5)

1.4 Conclusion

The throughput time of the machines built by Machine-builder X must be decreased to be able to conform to customer requirements. The long throughput time is mainly caused by the suppliers that have a higher lead time than agreed upon with Machine-builder X, which delays the supplies and assembly of the machine. The negative effect that these suppliers have on the throughput time needs to be reduced by implementing a supply base reduction method combined with a lead time estimation tool. The context of the company must first be analysed, followed by a literature study on supply base reduction methods to finally design and implement a method applicable at Machine-builder X. These steps are followed in the next chapters, starting with an analysis on the context and characteristics of the company.

2 Context analysis

Chapter 2 contains the context analysis for the thesis assignment at Machine-builder X. The first sub-question is answered in three sections, aiming to get an overview of the characteristics relevant for this thesis.

What is the context of Machine-builder X (considering the throughput time and suppliers)?

At first, a visual representation is made to get a clear overview of the throughput time. To identify on which suppliers we need to focus, the suppliers in the supply base of Machine-builder X are analysed. The Key Performance Indicators for the suppliers are identified and weighted. This chapter concludes with the answer to the research question.

Cooperation with stakeholders was necessary for gathering the information within this chapter. The stakeholders are abbreviated as follows:

- TAM = Technical Account Manager at Machine-builder X
- SME = Senior Mechanical Engineer at Machine-builder X
- HoP = Head of Production at Machine-builder X
- COO = Chief Operating Officer at Machine-builder X

The stakeholder analysis can be found in Appendix 2.

2.1 Visual representation of the phases

To get a detailed overview of the phases occurring at Machine-builder X, as outlined in Chapter 1.1, a visualization is made in this section. Two builds of machine Machine X; machine 11 and machine 15, are analysed in detail. The accessible data of these machine builds are analysed and incorporated in a visualization of the phases as shown in Figure 2. Thereafter, the phases are elaborated on. The throughput time needs to be reduced from the current six months (the reality of +- 26 weeks) to four months (the norm of +- 18 weeks).

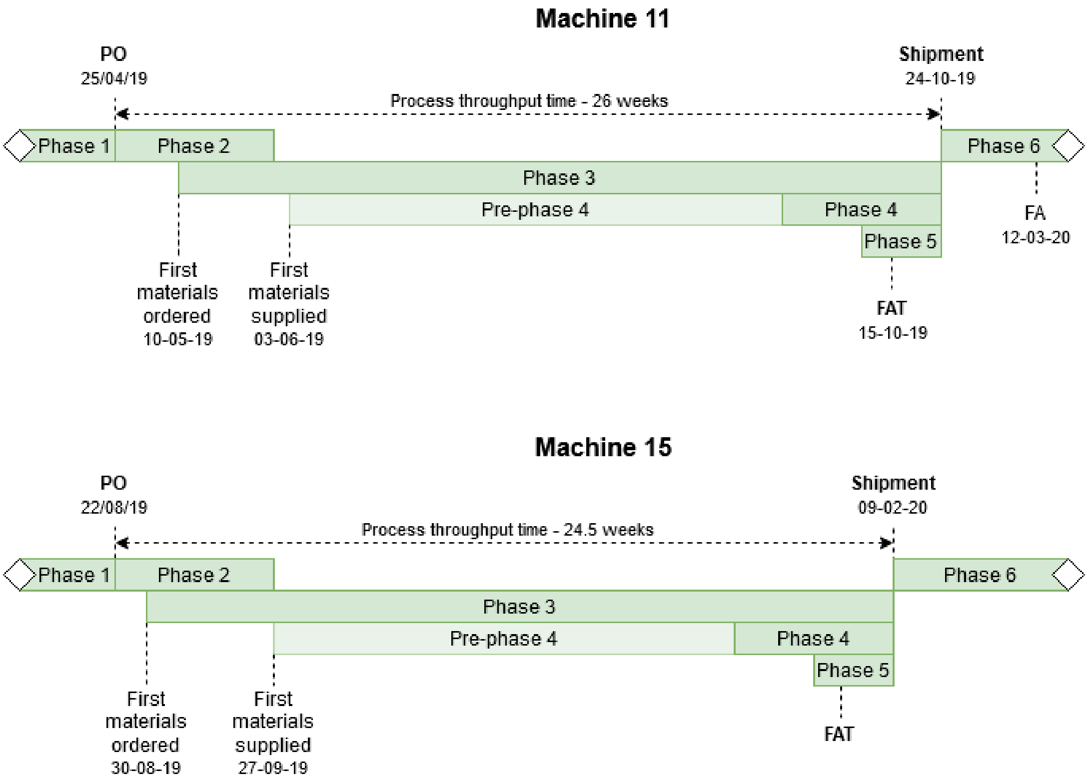

Figure 2: Timeline of the phases within the throughput time of the machines including important ‘checkpoints’

Phase 1 – Potential customer contact phase

In the first phase, the potential customer gets in contact with Machine-builder X. Multiple steps are completed to go from customer contact until the purchase order (PO) of the machine. Currently, Machine-builder X can offer a throughput time, the time from PO release until the machine is ready for delivery, of six months. Some potential customers require a throughput time of four months which leads Machine-builder X to make a strategical decision whether to take a financial risk and decrease the throughput time, as mentioned by the Technical Account Manager (TAM) of Machine-builder X. Normally, materials are ordered in Phase 3 which can take sixteen weeks by itself. This makes it difficult to offer a throughput time of four months. Machine-builder X has to make a strategical decision whether the potential customer is so important that a financial risk can be taken by ordering certain materials before the PO is released. Certain components of the machine have to be customly made by a supplier. If this component is ordered before PO, Machine-builder X risks that the PO will not be released and the ordered components are useless.

The machines are always customized to the customer’s needs. Because of this, it is difficult to start ordering materials before the PO is released and the technical product design is completed. The machine is currently being standardized. This could facilitate the possibility to order the standardized components of the machine before the PO is released by the customer.

Phase 1 can take around two years, depending on the type of customer, and ends when the purchase order is released by the customer.

Phase 2 – Design phase

In Phase 2, the technical product design for the to be built machine is finalized. When the PO is released, Machine-builder X already has a good view on how the machine needs to be built as the requirements are negotiated with the customer in Phase 1. The complete model of the machine, including the bill of materials, gas scheme, electrical scheme, manual and certification mark is finalized. The machine consists of standard components and specific components. These specific components need to be engineered in this phase. Sometimes, certain components of the machine are already partly engineered in Phase 1 to offer a view of how components can be designed into the machine.

The implementation of an order specification form, at the moment the PO is released, is necessary to integrate the knowledge professionaly throughout the company. Currently, the engineering department loses time for example when they need to be informed about how the customer wanted a specific component in detail. With the help of an order specification form, the knowledge is complete and the engineering department can work on their projects more efficiently. This way, the technical product design can be finished earlier, depending on the amount of NRE (non-recurring engineering).

Phase 2 takes around four to six weeks and ends when the technical product design is finished.

Phase 3 – Material order and delivery phase
In this phase, the required materials for the machine are ordered from and delivered by Machine-builder X' suppliers. Through experience, Machine-builder X has an idea of the materials and suppliers with a long lead time. At the moment the requirement of that component is certain, the order is already placed. For this reason, as seen in Figure 2, some materials are ordered simultaneously with Phase 2. Even though the technical product design is not complete, the necessity of that material might already be known in which case it is ordered.

Certain suppliers currently have a higher lead time than is agreed upon with Machine-builder X, which endangers the timely assembly of modules. To support ordering certain materials earlier and have more certainty of timely arrivals, it is important to have a good idea of the lead time performance of suppliers. When the lead time of materials and suppliers can be estimated more precisely, it can be known which supplies endanger the timeline the most. When this is known, Machine-builder X can focus on these supplies and identify if these materials can be ordered earlier. The lead time estimation of suppliers is part of the insight that will be given in this thesis and is elaborated on in Chapter 4.

Phase 3 takes around sixteen weeks and ends when the last materials for assembly are supplied.

A general insight into the data for the order and delivery date of the materials with an explanation can be found in Appendix 3. Certain critical component groups arrive late in the phase and delay the throughput time. Implementing a lead time estimation for these critical component groups will support Machine-builder X in ordering the products earlier and accelerating towards the shipment date.

Phase 4 – Assembly phase
The machine consists of different modules, mostly analogous to the order groups that Table 20 and Table 21 show. Figure 2 also shows the Pre-phase 4. Some materials with a shorter lead time are delivered early. When the first necessary materials are delivered, the materials are stored together and sometimes the assembly of that module is started. In Phase 4, the modules and the final machine are assembled. The assembly, for mechanical construction, of a module takes at most one day. When the modules are assembled, the machine can be assembled with all the modules which takes another two days. Fitting the wires and cables takes around one and a half week and could be shortened by preparing the wires and cables when no modules can (continued to) be assembled.

As mentioned by the Head of Production (HoP) of Machine-builder X, the assembly from start to finish should be completed in around four weeks. This is not always possible, as sometimes critical materials for that module are missing. The delivery of that material is for example delayed which extends the assembly time and thus also the throughput time. Sometimes, multiple modules need to wait for assembly because of the delay at one or more suppliers. The mechanics that assemble the modules, must change which module they are working on because at certain points they miss critical components. Late or incomplete arrivals extend Phase 4 as the assembly cannot be finished early.

As can be seen in Table 20 and Table 21 in Appendix 3, there is a big difference in the earliest and latest delivery dates for most of the order groups. These order groups consist of multiple specific components and general components. The specific components are engineered and cannot be ordered immediately after PO. Furthermore, components have different lead times. This results in the differences in the order and delivery dates of the components. The late arrival of critical materials endanger the timeline and the throughput time. To accelerate the (complete) arrival of products, an insight in and improvement of the performance of suppliers is necessary. Analysing the current supply base at Machine-builder X will make it possible to identify suppliers that risk the desired throughput time of four months. By applying certain methods to reduce the supplier base, it will be possible to increase importance of good performing suppliers and decrease importance of bad performing suppliers. This will bring up for example possibilities to outsource certain modules or have good performing suppliers deliver assembly-packages such that arrivals are complete and have a higher chance of being on time. A literature study will be done for applicable methods in Chapter 3, and the application of the method will be elaborated on in Chapter 4.

Phase 5 – Concluding phase
In Phase 5, the machine is finalised and tested before shipment to the customer is initialized. In Phase 1, a shipment date is agreed upon with the customer and Machine-builder X works to achieve this date of shipment. When the assembly of the machine is finished for the basic functionalities of the machine, the machine is tested. These tests, for example for mechanical movements and vacuum spaces, are documented and stored in a map. Actual processes will only be executed at the customer but are expected to work with the basic functionalities.

The FAT (factory acceptance test) is a principle where the customer ideally visits Machine-builder X and checks the documented tests. This is done around two weeks before shipment where the customer can get to know the machine and Machine-builder X also has an opportunity to improve customer contact. As seen in Figure 2, the FAT for machine 11 was nine days before shipment, on 15-10-19. The tests were also done for machine 15, however the customer could not visit Machine-builder X due to the coronavirus circumstances. Principally, the FAT is planned three days to a week after the assembly for the basic functionalities is completed, such that tests can be done before the customer arrives. After the FAT, there is still some time allowed to make corrections, clean up the machine and package the machine for delivery. Phase 5 ends when the machine is out for shipment.

Phase 6 – After-sale service phase
Service is one of the core values of Machine-builder X. The customers are of two types, either institutes or production companies. Institutes are generally more lenient in their requirements, where production companies often have strict requirements for the machines. Agreements are made between the customer and Machine-builder X for after-sale service mostly in terms of maintenance of the machines. These agreements are made dependent on the customer’s wishes and vary. The customer can for example ask for a two-year maintenance contract, but also for maintenance training. A relatively standard agreement is a one-year warranty for the machine. Typically, the machines are maintained twice a year, dependent on the intensity of use of the machine. The sales department closely cooperates with the service department at Machine-builder X to ensure satisfaction at the customer.

As can be seen for machine 11 in Figure 2, the FA (factory acceptance) was also completed after shipment. The FA is where the customer confirms that the machine satisfies the requirements on the specifications that the machine was bought. The specifications for the hardware as well as the actual processes are tested. It generally takes a couple of months before the FA can be completed. For this reason, the FA for machine 15 is not yet checked off.

Even though Phases 3 through 5 are already finished, it is possible that certain materials are delivered to the customer after shipment. This can be seen in Table 20 where the 'Quartz group' was not fully delivered before shipment. These are non-critical materials that do not affect the functionality of the machine. The assembly and testing of the machine can still be done.

The timeframe of Phase 6 is thus very dependent on the agreements made with the customer.

Improved timeline

This thesis has the goal of squeezing the throughput time from six months to four months through the application of lead time estimation and supply base reduction. The throughput time is the time from Phase 2 until the end of Phase 5. With lead time estimation, the process of ordering materials will be supported and it will be clearer. In the past, certain components are generally delivered later than expected. Analysing the historical data will provide the knowledge which components should be ordered earlier. For example, the component group 'Mirror box' for machine 11 could have been ordered, and because of that also delivered, at an earlier stage. With supply base reduction (elaborated on in Chapter 3), the good performing suppliers can grow in importance through for example possibilities of tiering the suppliers. Supply base reduction will make it possible to lower the risk of delayed supplies by bad performing suppliers and therefore eliminate most outliers and accelerate the arrival of the materials.

Because of this, Phases 2 through 4 can be squeezed somewhat which allows for an earlier concluding phase and shipment of the machine. Figure 3 gives an example of how the timeline could look ideally, which would hopefully be the effect of the implications of this thesis. This timeline is linked to the norm of the throughput time, as explained in Chapter 1.2.1.

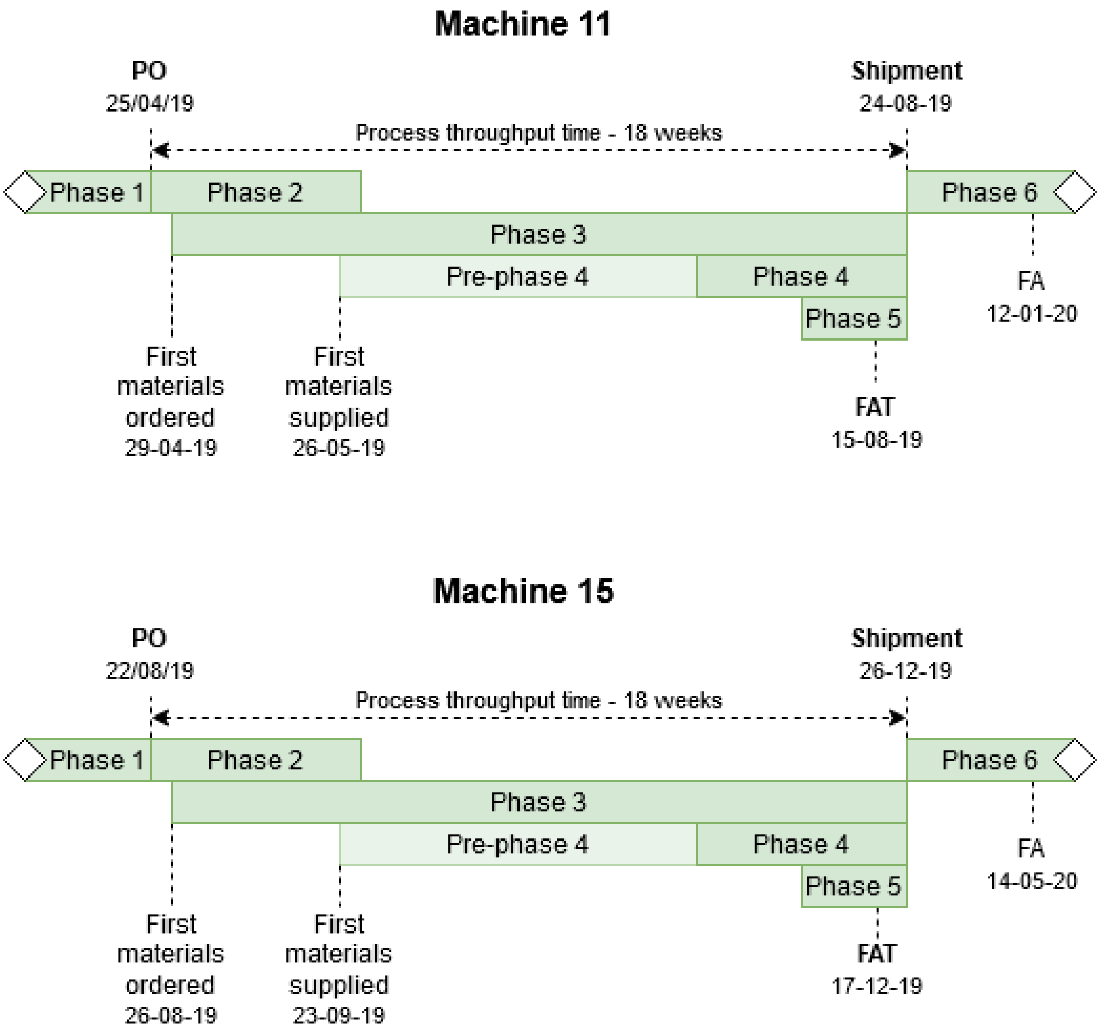

Figure 3: Potential timeline of the phases through application of lead time estimation and supply base reduction

2.2 The suppliers

This section has the purpose to gain an insight into the suppliers that have a negative impact on the throughput time at Machine-builder X. An analysis of the historical data on supplier lead time is performed, after which the bad performing suppliers (in terms of lead time) are identified. To have a better overview of these suppliers, the general and specific reasons for late deliveries are identified.

2.2.1 Supplier analysis

The historical data present at Machine-builder X contains the order date, the delivery date that is agreed upon with the supplier and the actual delivery date of the PO. The PO is the purchase order that is made for certain materials. One PO can consist of multiple materials, but all the materials in the PO are supplied by the same supplier. Through Excel data analysis, it can be distinguished which POs were on time and which POs were too late. The suppliers are analysed on the delivery performance for these POs and an overview is given in Table 1. Within this table, the suppliers that have an on-time delivery percentage over 25 percent, are grouped together. The suppliers are anonymized to a supplier ID. The supplier ID consist of the type of part they supply; make (M), buy (B) and engineering (E). Make-parts are engineered by Machine-builder X and custom made by the supplier. Buy-parts are components that are standard in production at the supplier. Engineering parts are mostly licensing and services for example for software of the machine. The number of the supplier ID is the count of the supplier. The supplier IDs relate to the suppliers, as can be found in Appendix 5. The third column shows how many unique POs that supplier has delivered. The analysis is done on suppliers that have delivered at least four POs. The fourth column is the percentage of POs that were on time, i.e., delivered on or before the agreed delivery date. The grouped suppliers are given a range for the on-time delivery percentage. This percentage is calculated by the number of distinct POs that were on time, divided by the total number of distinct POs. The fifth column is the average agreed lead time, which is the result of an agreement between Machine-builder X and the supplier. The sixth column shows the average lead time of that supplier. The seventh column shows the average lateness calculated over the POs that were too late.

As to be seen in Table 1, there is a large difference in lead time performance from the different suppliers. Some suppliers are always on time and are very specific, and others are almost always too late. The suppliers that have a bad lead time performance risk delays in the whole throughput time for Machine-builder X. The planning can be endangered because materials arrive late and for example assemblies cannot be finished on time. To be able to achieve the goal of a throughput time of four months, the performance of the suppliers needs to be improved. Furthermore, for suppliers that supply unique items and alternatives are lacking, the lead time must be estimated such that the orders of those supplies can be made earlier. It can be concluded from Table 1 that there are suppliers with a low on-time delivery percentage, e.g. M-68, M-48, and B-79.

Excel data analysis is extended specifically on bad performing suppliers. Graphs can be made that present the lead time performance over the years. These graphs can provide additional information where for example certain suppliers could have improved their lead time performance over the years. An example of the specific analysis is presented in Figure 4. In this figure, supplier M-42 is analysed on the lead time performance. The percentage of POs that were on time and too late (Y-axis) are presented over the years (X-axis). The green and red stacked columns relate to the on-time and too late delivery percentages, respectively. Additionally, the average lateness is depicted on the additional Y-axis. The figure is supported by Table 2 which also includes the number of POs that were delivered in that particular year together with the agreed and actual lead time. Supplier M-42 can be evaluated throughout the years and conclusions can be made.

Table 1: The difference in lead time performance of the suppliers at Machine-builder X

# of suppliers	Supplier ID	# of POs	% On time	Avg agreed lead time (wk)	Avg lead time (wk)	Avg lateness IF late (wk)
15	-	184	75-100%	3.34	2.57	1.93
21	-	211	50-75%	6.16	5.65	1.65
16	-	155	25-50%	5.69	6.54	2.13
1	M-71	24	25.00%	10.35	11.92	3.02
1	M-87	8	25.00%	3.75	4.46	1.12
1	M-140	4	25.00%	5.75	8.21	3.33
1	B-101	4	25.00%	8.50	11.32	4.81
1	M-42	40	25.00%	4.64	5.68	1.57
1	M-144	39	23.08%	9.69	12.98	4.49
1	M-145	35	22.86%	6.80	8.29	2.25
1	M-63	22	22.73%	8.86	10.97	3.07
1	M-114	9	22.22%	6.78	7.10	0.78
1	M-25	19	21.05%	7.32	8.71	1.92
1	B-79	22	18.18%	7.86	9.86	2.69
1	M-85	21	9.52%	5.95	7.88	2.32
1	M-68	8	0.00%	6.10	12.23	6.14
1	M-48	7	0.00%	14.00	16.63	2.63

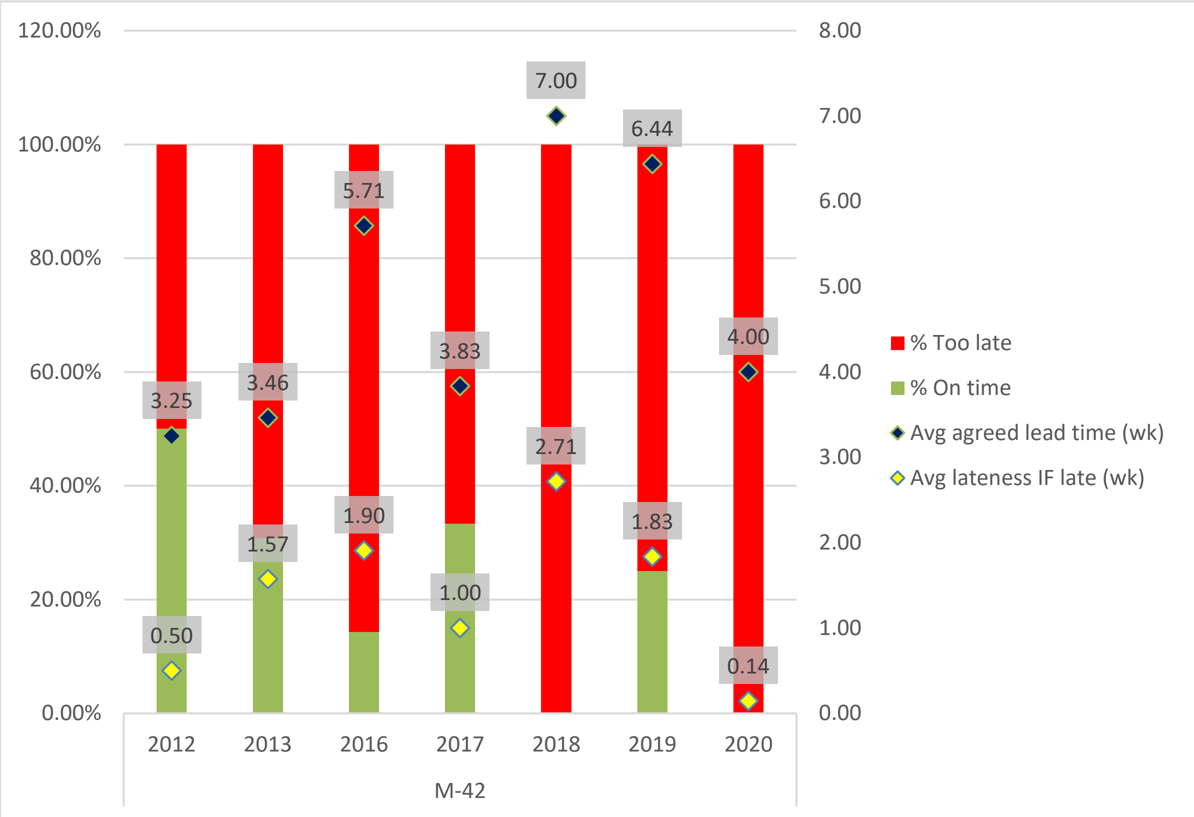

Figure 4: Lead time performance over the years for supplier ‘M-42’

Table 2: Lead time performance of supplier ‘M-42’ over the years

Supplier ID	Years	# of POs	% On time	% Too late	Avg agreed lead time (wk)	Avg lateness IF late (wk)
M-42	2012	4	50.00%	50.00%	3.25	0.50
	2013	13	30.77%	69.23%	3.46	1.57
	2016	7	14.29%	85.71%	5.71	1.90
	2017	6	33.33%	66.67%	3.83	1.00
	2018	2	0.00%	100.00%	7.00	2.71
	2019	8	25.00%	75.00%	6.44	1.83
	2020	1	0.00%	100.00%	4.00	0.14

2.2.2 Reasons for late deliveries

It is important to know the reason behind late deliveries such that the right approach can be taken. There are multiple (external or internal) reasons why some suppliers have a bad lead time performance. To have the right approach for supply base reduction, these reasons need to be considered. When there is no relation between the reason for late deliveries and a possible solution with supply base reduction, other suggestions need to be made. The reasons for late deliveries are determined through interviews with the COO of Machine-builder X. Some of the reasons are quite general, where other reasons are more specific to certain suppliers.

- **Scarce materials**
  Some materials that are necessary components in the machines that Machine-builder X produce, are made from rare raw materials (for example for suppliers M-48 and M-71). Sometimes, the raw materials are unavailable worldwide, which means that the supplier cannot supply the materials to Machine-builder X.

- **Lack of inventory**
  It happens that supplies are delayed because of a lack of inventory at the supplier. One time, all ball bearings that were produced in batches at the supplier, were bought up by another buyer. The ball bearings were produced in batches, where Machine-builder X needed to wait for the next production batch. Sometimes this can lead to a 52-week lead time in which alternatives need to be found. The production schedule of the materials at the supplier is important to prevent these situations from occurring.
- **Production mistakes**
  Sometimes, supplies are delayed because of production mistakes. The quality and cleanliness of most materials is very important for the assembly of the machines. Once production mistakes are made at the supplier, the supply can be of insufficient quality. The production needs to be repeated and the lead time is extended.
- **Priority**
  As already mentioned, Machine-builder X is not the biggest organization in its field. A lot of the suppliers that are active for Machine-builder X, are also active for a larger organization within its industry. When the supplier is busy in production, the priority is given to these larger organizations to produce the materials. This means that the delivery performance to Machine-builder X is not the highest priority for these suppliers and supplies are postponed more easily. The busyness can arise when for example the branch is growing rapidly, which makes it impossible for the supplier to answer the demand of all customers immediately. Seasonality is not a factor for the busyness at suppliers. This is difficult to identify from the limited available data and is not observed by stakeholders of Machine-builder X.
- **Unrealistic**
  Some suppliers (such as suppliers M-85, M-25, and M-42) sometimes agree on a very ambitious lead time, which is concluded to be too optimistic. The production processes simply take too much time to have a successful delivery on time.
- **Specific components**
  Most of the time, multiple components are ordered at a supplier. For some suppliers (such as supplier M-68), some components require more time than others to produce. These components cannot be delivered on the agreed time. The supplier contacts Machine-builder X to ask if they should do a split-shipment or deliver all components later. Some components could thus be delivered on time, but sometimes Machine-builder X decides themselves that all components should arrive at the same time.

2.3 Supplier KPIs

The analysis of the suppliers as performed in Chapter 2.2.1 is focused on the lead time of the suppliers. Apart from the lead time of the suppliers, there are multiple factors that give an indication about the performance of suppliers. This is necessary as a tool to get an insight into the performance and capabilities of suppliers. Even though only the lead time can be analysed from the data, opinions from stakeholders can give a different perspective on the actual performance of a supplier. In this chapter, the Key Performance Indicators (KPIs) for the suppliers of Machine-builder X are identified. Through literature research and gathering opinions from stakeholders, a list of KPIs is identified. To determine the importance of the factors, the KPIs will be analysed by the stakeholders.

2.3.1 Identification of KPIs

The performance of suppliers should be measured both on short- and long-term factors. Even though some suppliers might perform good in the present, they might not have the right foundation to sustain this performance in the long-term. The short-term requirements in the supply chain relates to the current performance of the supplier. The long-term requirements relate to the capability of the supplier. Sarkar and Mohapatra (2006) propose different short- and long-term factors. Relevant factors for Machine-builder X are chosen and discussed with the stakeholders. Due to limitations within this thesis, the KPIs are explained for its relevancies at Machine-builder X, without going deep into the weights that different characteristics of a KPI might have. This results in the following list of KPIs:

1. **Lead time**
   This KPI refers to the lead time of the suppliers active at Machine-builder X. It is important for Machine-builder X to receive their supplies on time such that the assemblies of the modules can be completed, and the machine can be shipped on time. The agreed and actual lead time of the supplies are stored and can be analysed on for example the average lead time, the reliability, and the lateness of certain suppliers. The performance of suppliers on the lead time can be quantitatively measured as it is possible to analyse the data. Most suppliers have a maximum lead time of around sixteen weeks, which needs to be a criterium for Machine-builder X to be able to achieve the norm of a throughput time of four months.
2. **Total costs**
   The price of the materials is always important. If the offered price is not a competitive price, it is unavoidable to search for another supplier. The supplier performance on the price can be analysed by comparing offers from different suppliers. For Machine-builder X, the price is important for the profit margin of the machine.
3. **Quality of delivery**
   The quality standard of the components of the machines that Machine-builder X make is high. When a supply arrives, the quality is visually inspected. The cleanliness and first look of the materials might seem of good quality, however if there are certain critical measure errors, the assembly cannot be completed. These errors are identified at a later stage. When the materials are identified as insufficient at this late stage, the materials need to be reordered which endangers the timeline and makes it impossible to ship the machine on time. For materials with a higher lead time, it is critical for the first supply to be of sufficient quality.
4. **Supplier availability**
   The supplier availability relates to the knowledge if the suppliers can supply the materials that Machine-builder X requires. It is known what most suppliers offer, and as the demand from Machine-builder X is reasonable to the suppliers' capabilities, almost all demands are answered. For the standard components, it is possible that the lead time is delayed for example when bigger companies have bought up the materials. It is important that suppliers have a high availability such that all necessary materials can be ordered on time.
5. **Precision of delivery**
   Apart from the visual inspection on the quality of the supplies, the precision of the delivery is checked at arrival. The right materials need to be supplied in the right quantities, to prevent necessary reorders. Like insufficient quality of supplies, if a new order must be made because pieces are missing, the timeline is endangered. It is critical that the supply is accurate when a reorder would endanger the timeline.
6. **Communication**
   Communication between the supplier and Machine-builder X is key when unexpected events pop up. At the moment the supplier knows that the lead time is in danger and communicates this to Machine-builder X, solutions can be found and for example certain parts of that order can be ordered at another supplier to prevent the timeline from extending. Furthermore, if small deviations are measured in production, this can be communicated with Machine-builder

X to see if it is sufficient or not. A lot of suppliers do not communicate these unexpected events. It is critical that communication is valued as it can prevent an extension to the timeline.

7. **Flexibility**
   It is possible that Machine-builder X encounters unexpected deviations in the design of certain materials of the machine. When this occurs, it is important that the suppliers of those materials are flexible and can adapt their production to Machine-builder X' needs. Apart from this, if the precision of the supply is insufficient, but the production at the supplier can be adapted quickly such that the supply can be improved, an extension to the timeline can be prevented.
8. **Available expertise**
   This KPI relates to how the expertise of the supplier can be utilised. As mentioned by the HoP of Machine-builder X, it is very useful if designs or ideas can be discussed with knowledgeable people to find out if the design can be optimized in certain ways. This also relates to the location of the supplier, where it could be even more useful to discuss these ideas in person. Furthermore, it is important that the materials are ordered at suppliers that have a relevant core-business. If the production of the materials is outsourced by the tier-1 supplier to a tier-2 supplier and the tier-1 supplier cannot directly help Machine-builder X, the effectiveness of communication and possible design improvements is lower. Apart from this, the lead time is generally also extended. If the overall performance of the tier-1 supplier is so good that the quality can be trusted however, this is less relevant as the direct communication might seem sufficient.
9. **Capability**
   This KPI is mostly a combination of the long-term factors as identified by Sarkar and Mohapatra (2006). The KPI relates to the general stability of the company, and the possibilities of high-quality cooperation in the future. Some suppliers for Machine-builder X are crucial for Machine-builder X as they provide a lot of value through their capabilities. The agreements that can be made with suppliers to increase the performance is also relevant, as sometimes it might be crucial to for example agree to have the supplier hold inventory such that Machine-builder X can be guaranteed a timely delivery.

2.3.2 Relative importance

To find the importance of the KPIs relative to each other, two stakeholders (SME, COO) were asked to compare the KPIs in terms of relative relevance. The Analytical Hierarchy Process (AHP) method is used as a model to find the relative importance of the KPIs. The AHP method is a decision-making method that gives a priority to the different criteria that need to be considered, as is the case for the KPIs for the suppliers of Machine-builder X. This method can be used to compare the different opinions of the experts (the stakeholders) and find the aggregated weights for the criteria. (Hruska, Prusa, & Babic, 2014)

The AHP method is used to identify the relative weights of the KPIs because of the easy implementation. It is effective for identifying the weights for multiple attribute decision making, with simple pairwise comparisons. Multiple judgements can be considered to improve the validity of the weights as well (Sutadian, Muttil, Yilmaz, & Perera, 2017). The two stakeholders are asked to give their opinion on the relative importance of the KPIs following Saaty's method (Hruska et al., 2014). The relative performance is evaluated and a number between 1 and 9 is given for the importance of the leading KPI (the KPI in the row) relative to the KPI in the column. Inverse values are given if the importance of the KPI in the column is higher relative to the leading KPI in the row.

The identified KPIs are put in a table and evaluated by the COO and the SME of Machine-builder X in Tables 3 and 4 respectively:

COO:

Table 3: Relative importance of the KPIs as identified by the COO of Machine-builder X

	KPIs	#1	#2	#3	#4	#5	#6	#7	#8	#9
#1	**Lead time**	1	2	2	4	2	4	4	3	3
#2	**Costs**	1/2	1	1	3	1	3	3	4	4
#3	**Quality**	1/2	1	1	4	1	3	3	3	3
#4	**Availability**	1/4	1/3	1/4	1	1/4	1	1	2	3
#5	**Precision**	1/2	1	1	4	1	3	2	3	2
#6	**Communication**	1/4	1/3	1/3	1	1/3	1	1/2	1	2
#7	**Flexibility**	1/4	1/3	1/3	1	1/2	2	1	2	3
#8	**Expertise**	1/3	1/4	1/3	1/2	1/3	1	2	1	1
#9	**Capability**	1/3	1/4	1/3	1/3	1/2	1/2	1/3	1	1

SME:

Table 4: Relative importance of the KPIs as identified by the SME of Machine-builder X.

	KPIs	#1	#2	#3	#4	#5	#6	#7	#8	#9
#1	**Lead time**	1	5	1/3	5	1/5	1	3	3	5
#2	**Costs**	1/5	1	1/5	5	1/5	1/3	1/5	1/3	5
#3	**Quality**	3	5	1	7	3	3	5	5	7
#4	**Availability**	1/5	1/5	1/7	1	1/7	1/5	1/3	1/5	7
#5	**Precision**	5	5	1/3	7	1	1	5	5	7
#6	**Communication**	1	3	1/3	5	1	1	5	7	9
#7	**Flexibility**	1/3	5	1/5	3	1/5	1/5	1	3	5
#8	**Expertise**	1/3	3	1/5	5	1/5	1/7	1/3	1	5
#9	**Capability**	1/5	1/5	1/7	1/7	1/7	1/9	1/5	1/5	1

To find the weights of the KPIs, a calculation is done. As Hruska et al. (2014) shows, the following equations are done:

In the calculation, ‘s’ refers to the relative importance, ‘i’ to refers the number of the KPI in the row, ‘k’ refers to the total number of criteria, and ‘j’ refers to the number of the KPI in the column. The product of the relative importance ‘s’ is calculated for each KPI in the row;

$s_i = \prod_{j=1}^{k} s_{ij}$ *Equation 1*

After that, the geometric average ‘R_i’ of the KPIs in the rows is calculated by taking the ‘k’ power root of ‘s_i’ with equation 2;

$R_i = \sqrt[k]{s_i}$ *Equation 2*

Next, the sum from the geometric averages of the rows (the KPIs) is taken. To determine the weight of the KPI in the row ‘v_i’, the geometric average of that KPI is divided by the sum of the geometric averages of the KPIs in the rows as follows;

$\sum_{i=1}^{k} R_i$ *Equation 3*

$v_i = \frac{R_i}{\sum_{i=1}^{k} R_i}$ *Equation 4*

This method can be applied to the results of the opinions of the stakeholders as shown in Table 3 and Table 4. The results gathered from the stakeholders can be evaluated to the weight vector v by using Equations 1 up to and including 4 (Hruska et al., 2014):

$$v = (v_1, v_2, \dots, v_k) \qquad \textit{Equation 5}$$

The number in the vector relates to the number of the KPI as shown in Table 3 and Table 4. To make the final list of the KPIs including their weights, the average weight is taken from the weight vectors of the stakeholders. This means that the weight vectors are summed and divided by two. Table 5 shows the weights of the KPIs (in percentage) as calculated from the different stakeholders. The averages of the weights are given in the fourth column.

Table 5: Weights of the KPIs, per expert and as an average through evaluation of the stakeholders

Stakeholder / KPI	COO	SME	Average
#1 Lead time	23.5%	12.2%	17.8%
#2 Costs	16.7%	4.1%	10.4%
#3 Quality	16.2%	28.8%	22.5%
#4 Availability	6.3%	2.7%	4.5%
#5 Precision	14.8%	21.1%	17.9%
#6 Communication	5.5%	17.1%	11.3%
#7 Flexibility	7.5%	7.1%	7.3%
#8 Expertise	5.5%	5.4%	5.5%
#9 Capability	4.1%	1.5%	2.8%

2.3.3 Final list of KPIs

The weights of the KPIs are identified in the previous section. The KPIs and the relative weights for multi criteria analysis are given summarized in Table 6.

Table 6: An overview of the identified KPIs with the relative weights

KPI	Weight (%)
#1 Lead time	17.8%
#2 Costs	10.4%
#3 Quality	22.5%
#4 Availability	4.5%
#5 Precision	17.9%
#6 Communication	11.3%
#7 Flexibility	7.3%
#8 Expertise	5.5%
#9 Capability	2.8%

2.4 Conclusion

The throughput time of Machine-builder X is currently around six months and needs to be reduced to four months. The phases have a different impact on the throughput time. It can be concluded that the throughput time should be reduced by squeezing Phases 2, 3 and 4 primarily, focusing on the supply base at Machine-builder X.

From the supplier analysis, it can be concluded that a lot of suppliers in the supply base of Machine-builder X perform badly in terms of lead time. These delays have multiple causes and must be worked around to reduce the negative effect on the throughput time.

The suppliers of Machine-builder X can be evaluated based on nine KPIs. These KPIs have a specific weight based on their relative importance, as identified with the AHP method. The evaluation of the suppliers based on these KPIs can lead to a ranking of the suppliers, which is necessary for comparison of suppliers and finding optimal suppliers for the materials.

The contents of this chapter explained the situation of Machine-builder X. The characteristics found in this chapter can be used to design a method for application of supply base reduction and lead time estimation as is provided in Chapter 4. The next chapter introduces the reader to the methods that come forward in literature, which are used for the designed method.

3 Supply base reduction: literature study

For this thesis, supply base reduction needs to be applied to minimize the effect of bad performing suppliers on the throughput time. Through supply base reduction, the risks of late supplies will be decreased and the timeline as outlined in Chapter 2.1 can be shortened.

Even though applicable theory is limited in literature, relevant concepts are found and studied. Answers to the following sub-question will be researched within literature:

What are the relevant methods for reducing the supplier base?

Chapter 3.1 includes an outline for the theoretical framework, including the main constructs, the theoretical perspective and research boundaries. The concepts discussed are explained. Answers to the sub-question will be given through three sections with three outlined methods in total. In Chapter 3.2, these methods found in literature are explained. Finally, Chapter 3.3 will conclude this chapter by answering the sub-question.

3.1 Theoretical Framework

In this section, a theoretical framework is set-up for the approach of this thesis. The core problem is approached based on the theoretical perspective of supply base management. Supply base management can be used to manage a supply base strategically, which is necessary during this thesis project. It is based around managing minor and major suppliers, scouting suppliers and transition management (Melnyk, Cooper, Griffis, & Phillips, 2010). Effective use of supply base management should contribute to the strategic objectives of the firm.

At Machine-builder X, there are a lot of suppliers which all risk late supplies. This has a negative influence on the throughput time. Supply base reduction must be applied at Machine-builder X to lower the number of active suppliers and reduce the risk of late supplies while maintaining good buyer-supplier relationships. The idea is to identify for example how suppliers can be clustered together such that instead of ten suppliers delivering ten raw materials, there would be two suppliers delivering the same ten raw materials. This supply base reduction needs to be done systematically such that criteria can be assessed, and all success factors are considered resulting in the optimal solution.

The theoretical perspective of supply base management will be used in order to find relevant theories and models for solving the core problem addressed in Chapter 1.2.2. The relevance of the literature study will come primarily from the usefulness in solving the action problem. Furthermore, the literature study might seem relevant for learning purposes for future research.

Supply base reduction is applied to work more effectively with fewer suppliers. Supply base reduction is defined by Ogden (2006) as "the process of and activities associated with reducing the number of suppliers that an organization utilizes or actively manages". Supply base reduction is performed with a general objective of reducing costs, improving quality, responsiveness, flexibility and more (Cousins et al., 2008). Closer relationships can be formed with important suppliers, as more time is available for suppliers in a reduced supply base (Goffin, Szwejczewski, & New, 1997). The benefit of supply base reduction in this thesis should be found primarily in reducing the risk of late supplies and thus being able to decrease the throughput time.

More concepts that come forward in this chapter are given:

- Sourcing is obtaining the necessary materials, suppliers etc. from a source. It is the "location, acquisition and management of all the vital inputs required for an organisation to operate.

This includes raw materials, component parts, products, labour in all its forms, location and services" (Hinkelman, 2008).

- A supply chain is the system in which products or services are produced and delivered. This starts at sourcing raw materials and ends with the final delivery of a product to the customer ("Supply Chain," n.d.). Related to this concept is the supplier pool, which is the pool of suppliers available for a purchasing decision. A supply base compasses all suppliers that supply materials for a company.
- Purchasing or procurement is "the organized acquisition of goods and services on behalf of the buying entity" (Bragg, 2019). Purchasing is a necessary concept as materials need to be purchased to be delivered at the company.
- A component group or order group is a group of materials that are either similar or used for the same sub-assembly within the machines built by Machine-builder X.

3.2 Literature study

In this section, all the methods derived from the literature study are given in the sub-chapters. Multiple articles are analysed and the articles that described relevant methods for application at Machine-builder X have resulted. These methods include several steps which needs to be followed to successfully apply supply base reduction at Machine-builder X. Because of the limited research on the topic, there are not many references or methods in this section. Via a systematic literature review, the literature was collected and the methods that have the most relevancy for the goal of this thesis are used. The methods are constructed with an outline of the steps followed in the method, as well as a general view on the applicability at Machine-builder X.

3.2.1 Method 1 (Sarkar & Mohapatra, 2006)

The methodology provided by Sarkar and Mohapatra (2006) is developed for the supply base reduction process. Suppliers need to be evaluated on performance and capability to incorporate both short and long-term goals within the supply chain. These criteria need to be identified and weighted to rank the suppliers, which is necessary before reducing the supply base. This model evaluates the (potential) suppliers based on the performance and capability factors, resulting in final weighted scores determining the ranks. The method is outlined in Figure 5.

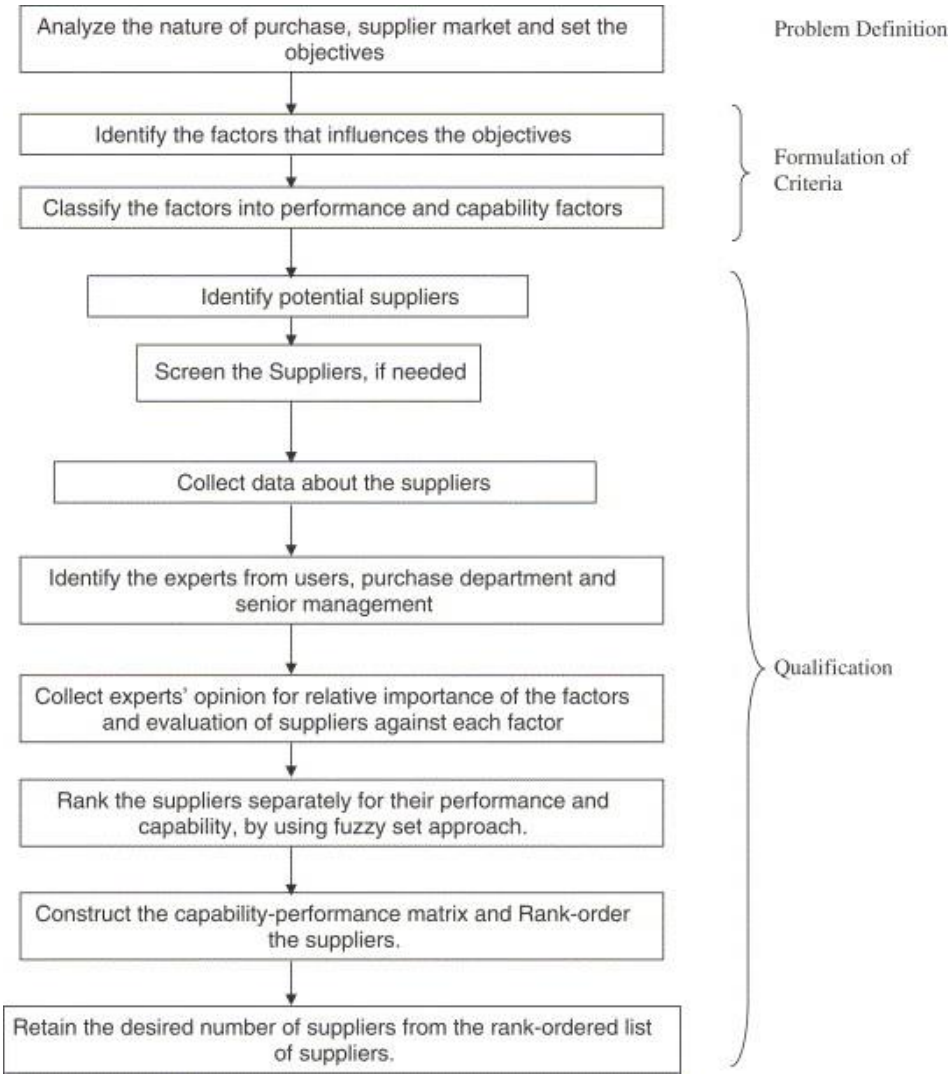

Figure 5: The step-by-step supply base reduction process as identified by Sarkar and Mohapatra (2006)

The method is applicable for the situation in which the supply base is analysed for sourcing a purchase. For the application of this method at Machine-builder X, this means that the supply base of a material must be analysed. The purpose of applying supply base reduction at Machine-builder X is to reduce the total amount of suppliers for all materials. The method described does not have the same aim, however the purpose of reducing the supply base for a purchase is relevant. To reduce the supply base at Machine-builder X, the different component groups must be analysed to find out if the supply base can be reduced.

First, the nature of the purchase and the supplier relationship is identified. The purchase is classified into either a routine, bottleneck, leverage, or strategic purchase. The buyer-supplier relationship will depend on the purchase classification as explained in Figure 6.

Purchase Category	Features
Routine Items	➢ More number of suppliers available ➢ Very short term supplier relationship ➢ Supplier Monitoring ➢ Simplification and automation of purchasing procedure ➢ Delegation of decision making power to lower level of management
Bottleneck Items	➢ Monopolistic supplier market ➢ Longterm supplier relationship ➢ Security of inventories ➢ Internally develop alternatives ➢ Contingency planning ➢ Delegation of decision making power to higher level of management
Leverage Items	➢ More number of suppliers available ➢ Short term supplier relationship ➢ Exploitation of full purchasing power ➢ Delegation of decision making power tomedium level of management
Strategic Items	➢ Few suppliers are available ➢ Medium/ long termsupplier relationship ➢ Detailed evaluation of suppliers ➢ Supplier development efforts ➢ Delegation of decision making power to top level of management

Figure 6: Characteristics of different purchase categories and the supplier-buyer relationship (Sarkar & Mohapatra, 2006)

As shown, strategic and bottleneck items have a limited supplier pool. In this case it might not be the right approach to reduce the supplier base. In this case, lead time estimation will be the right focus. For materials with a limited supplier pool in the supply base of Machine-builder X, lead time estimation will be applied to for example order the materials earlier if a delay in lead time can be expected. The number of suppliers that the supply base should consist of, for a specific purchase, is assumed to be determined already and is not part of the method.

Suppliers need to be evaluated on multiple factors that have an impact on the objectives of the company. These factors are identified as short-term performance factors and long-term capability factors. The KPIs for the suppliers of Machine-builder X as identified in Chapter 2.3 contain multiple short- and long-term factors. The capability of the company, however, is taken as one specific KPI that relates to most long-term factors as identified by Sarkar and Mohapatra (2006).

The method continues with identifying potential suppliers for that purchase. This includes the identification of suppliers which are not yet in the supply base. For the thesis and application of supply base reduction at Machine-builder X, no new suppliers will be identified. The current supply base is analysed and the alternatives which are currently already present in the supply base are part of this analysis.

The (potential) suppliers for the purchase are evaluated through the opinion of experts on the different capability and performance factors. When historical data is limited, qualitative assessment needs to be applied on these factors. Fuzzy measures are used because the supplier evaluation factors must be qualitatively assessed and cannot be measured precisely. Hereby, the fuzzy nature of the assessment is dealt with. The suppliers are ranked on the capability and performance factors after which a final order of preference is given for the suppliers. The desired number of suppliers are retained from the supply base. For this thesis, this approach could be taken resulting in a possible suggestion for retaining the best performing suppliers at Machine-builder X.

This method is applicable at Machine-builder X as a systematic approach is followed to rank the suppliers. For certain current purchases, it is possible to apply this method and reduce the supply base for that purchase. The idea of for example clustering suppliers together is not necessarily what comes from this method. It is possible however, to identify the possibilities that are apparent with well-performing suppliers and find what-if scenarios for these possibilities case by case.

3.2.2 Method 2 (Ogden & Carter, 2008)

The supply base reduction methods; systematic elimination, standardization and tiering, described by Ogden and Carter (2008) have a similar underlying process. The article combines these methods into a more generally applicable approach. This process consists of six steps including establishing a cross-functional team, developing commodity-sourcing strategy, identifying potential suppliers, supplier selection, implementing changes and continuous improvements. The steps, as presented in Figure 7, can be followed as a baseline for supply base reduction.

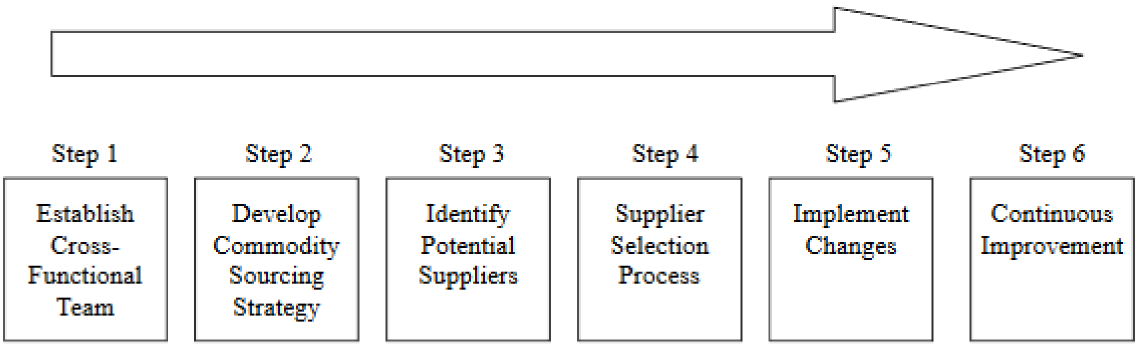

Figure 7: The basic steps in the supply base reduction process (Ogden & Carter, 2008)

Three supply base reduction approaches: systematic elimination, standardization, and tiering, are examined. Systematic elimination is the process of reducing the number of suppliers in the supply pool for a specific purchase. Suppliers can be eliminated if the performance is insufficient. Standardization can result in a reduced number of suppliers by simplifying or standardizing the product design or the components. Finally, tiering reduces the number of suppliers that is dealt with directly. Control of specific parts or assemblies is delegated to first-tier suppliers. The analysis of the application of these methods at organizations lead to a general supply base reduction approach consisting of the basic steps in Figure 7.

First, a cross-functional team needs to be established. Stakeholders' input and feedback are important for supply base reduction efforts. Different perspectives will be necessary throughout the steps in the process. Stakeholders for the supply base reduction approach at Machine-builder X are identified and will be important throughout the process.

Next, the commodity-sourcing strategy must be developed. The goals of purchasing need to be understood and historic data needs to be collected. The sourcing strategy for that purchase has to be identified. This is important to achieve the right goals and apply the right method for these goals. At Machine-builder X, it is possible to identify the types of items that are purchased. The strategy for supply base reduction can be adapted to the type of purchase.

Identifying the potential suppliers is the third step in the supply base reduction process. The short-list of qualified suppliers is created. As already mentioned, the supply base reduction approach will be solely on the current supply base at Machine-builder X. The potential suppliers for a sourcing decision are identified from the active supply base of Machine-builder X.

From the list of qualified suppliers, the suppliers will be selected that meet the organization's needs. The suppliers are analysed on the developed supplier-selection criteria. Suppliers are selected after they are analysed, and negotiations have been conducted. This is applicable at Machine-builder X in the sense that suppliers can be analysed based on the supplier-selection criteria. These criteria have already been outlined. For that specific purchase, the best performing suppliers will remain. The negotiations might be better suited as a suggestion in this thesis. Once the suppliers are analysed, suggestions can be made how to reduce the supplier base for example by outsourcing a sub-assembly to a good performing supplier. Together with the stakeholders, these opportunities can be identified.

The supply base reduction needs to be applied after the suppliers are selected. As multiple issues can arise here, this is seen as an all-important step. A plan for implementation must be developed, including the exit of suppliers from the current supply base. The new strategy for the selected supplier(s) must be developed to achieve the benefits. The plan for implementation of the supply base reduction approach is to be made by Machine-builder X. The suggestions of the different supply base reduction cases are given with what-if scenarios, where the decision must be made by the stakeholders within Machine-builder X.

After the supply base reduction cases are implemented, the performance of the project needs to be measured. The supplier performance needs to be tracked to find out if the suppliers are still the one for the job. Continuous improvement is possible through establishing better buyer-supplier relationships. This step is applicable during this thesis, as the supplier performance can be tracked with the Key Performance Indicators that are setup. This will give an insight into the results of a supply base reduction project. The way of approaching the benchmarking process can be given as a suggestion within the thesis.

The standardized supply base reduction approach can be used for supply base reduction at Machine-builder X. The limited time available for this thesis, makes it impossible to follow each step into detail. However, the steps outlined in the method can be used as a baseline.

3.2.3 Method 3 (Kumar, Clemens, & Keller, 2014)

Aligning and managing the supplier base with the strategy of the company is important for a profitable future. The method described by Kumar et al. (2014) identifies, classifies, reduces and maintains the supplier base. It needs to be determined which suppliers benefit the company's strategy and goals, such that good performing suppliers can be made important for the company. Hereby, suppliers must be chosen, and trade-offs need to be made. The factors that need to be considered must be determined through cross-functional cooperation. Discrete choice analysis (DCA) can be used to determine and align these factors relative to each other, which would be different for other types of companies. The relative weights of these indicators are assessed. The suppliers can be analysed based on these indicators to find out which suppliers are essential to the strategy of the company. The TCO (total cost of ownership) model can be applied on the weighted DCA to assess the suppliers. This can help to identify, classify, reduce, and maintain the supplier base.

The right supplier base must be identified based on the indicators. Building relationships with the supplier is increasingly important. The decisions made on the supplier base must be in line with the strategy of the company, which can be supported by classifying the suppliers. Strategic suppliers are long-term partners and are valuable suppliers with limited alternatives. Preferred suppliers are suppliers of mostly routine products and have low costs associated with them. Approved suppliers bring limited customization to the products and limited value to the company, with mostly raw materials. Identifying the suppliers can help to know where to focus the reduction of the supply base. This can be applied at Machine-builder X in the sense that there are different component groups for the materials that are purchased. In these groups, alternative suppliers are present. These suppliers can be categorized, supporting the supply base reduction process.

When the suppliers are classified, supply base reduction should be carried out per component group. The supply base is reduced based on the performance of suppliers to meet the company's objectives. Different sourcing strategies are possible. Single sourcing is when there is one chosen supplier that fulfils the orders. With dual sourcing, there is a back-up supplier for the chosen supplier. The right strategy must be chosen for that component group to meet the objectives. Supply base reduction can be applied at Machine-builder X by identifying the component groups, ranking the suppliers, and giving suggestions which strategy to use.

To maintain and ensure future success, the supplier performance needs to be maintained. A scorecard system will make it possible to assess the suppliers on different short- and long-term objectives. Both quantitative and qualitative data can be assessed, and scores can be given such that the suppliers can be evaluated. At Machine-builder X, the suppliers can be ranked in the future on the identified KPIs such that a better image of the suppliers can be given. This will make it possible to maintain and manage the supplier base effectively.

3.3 Conclusion

Supply base reduction methods can be used to decrease the risk of late supplies, delaying the throughput time of the machines built by Machine-builder X. The methods approach the supply base reduction process on one purchasing decision. The applicable parts of these methods can be combined to design a more general approach. This approach can then be applied at Machine-builder X to achieve the desired throughput time of four months.

The methods and theories discussed include a general overview of the applicability of the method for solving the core problem at Machine-builder X. Through setting up criteria from stakeholders within the company, it is possible to choose or combine the right methods to apply at Machine-builder X. With certain limitations and assumptions, a method tailored for the aim of this thesis can be designed in Chapter 4. This method will be based on the applicability of different stages within the methods.

4 Design of the solution method

The methods found in literature need to be combined to be applicable at Machine-builder X and find results within the scope of the thesis. A redesign or combination is made because the methods found in literature are applied to one specific purchasing decision generally. This does not conform the goal of this thesis, where the whole supply base and all purchasing decisions need to be analysed. With the goal of decreasing the negative impact that suppliers with a long lead time have on the throughput time, all purchasing decisions that endanger the desired throughput time of four months need to be analysed. Where the methods from literature dive deep into one purchasing decision, a more general method needs to be designed to incorporate all purchasing decisions that endanger the desired throughput time of four months. The following research question is answered:

How can a method be designed, based on the literature, for implementation at Machine-builder X?

In this chapter, requirements are first set-up in Chapter 4.1. In Chapter 4.2, the methods from literature are used to design a method for implementation at Machine-builder X. Also, the applicability of lead time estimation as an addition to this method will be presented to be further examined in the next chapter. The explanation of the lead time estimation tool described in these stages is given in Chapter 4.3. The research question is answered as a conclusion in Chapter 4.4.

4.1 Requirements

To design an effective method, requirements need to be set up and followed. The methods found in the literature may contain steps that are less relevant for Machine-builder X specifically. To select the applicable parts from the methods found in literature, a list of requirements needs to be followed. In this section, the requirements are identified and explained.

- **Characteristics of Machine-builder X**
  The method needs to be designed such that it will conform the characteristics of Machine-builder X. Machine-builder X is a relatively small enterprise, with limited available data. The suppliers in the supply base of Machine-builder X have different functions for Machine-builder X, where some suppliers are more specialized or irreplaceable than others. Apart from that, Machine-builder X has a specific view on the suppliers and their performance, as indicated with the KPIs set up in Chapter 2.3. Finally, Machine-builder X is a high-tech machine building company active in a potentially large market with few competitors. Supplier cooperation is therefore important for the suppliers as well, as Machine-builder X can become a potentially big client for these suppliers.
- **Future applicability**
  The throughput time at Machine-builder X needs to be reduced with the help of supply base reduction and lead time estimation. To make sure that Machine-builder X can find positive results from implementing these methods, a foundation for further application should be formed. The steps should be undertaken with the idea in mind that Machine-builder X can evaluate the suppliers and the changes that happen through the suggestions that are made within this thesis.
- **Results**
  No value is provided if applying the method does not give results. Following the stages in the designed method should lead to suggestions that are relevant for Machine-builder X.
- **Numerical evaluation**
  The suggestions that are given to Machine-builder X should be based on a numerical evaluation. The method needs to result in the possibility to estimate the outcome and

evaluate how changes in the supply base will affect the throughput time. This will make it possible to find out to what extent the suggestions can be applied at Machine-builder X.

- **Validation**
  The results from applying the designed method should be validated. Applicable suggestions should be supported by for example the numerical evaluation. The opinion of stakeholders within Machine-builder X should help to quantify why certain suggestions are applicable or not.

4.2 Stages of the method

Different stages within the methods are combined and presented in this section, with several assumptions and limitations. The stages are explained and analysed for the applicability at Machine-builder X and the requirements of an effectively designed method. Figure 8 gives an overview of the designed method, including the stages and steps within these stages. The rationale behind these stages is given in the subsections of this chapter.

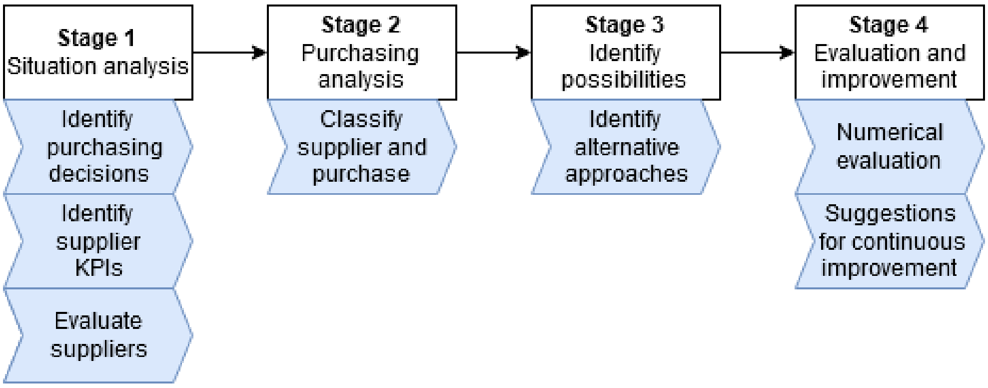

Figure 8: Stages of the designed method applicable at Machine-builder X including the steps to follow within the stage

4.2.1 Stage 1 – Situation analysis

The first stage in the supply base reduction approach consist of a situation analysis. The company is analysed to get an overview of the relevant purchasing decisions and supplier characteristics. The suppliers are evaluated to form a basic overview of the rankings and apply this throughout the analysis of different purchasing decisions. This stage is divided into three steps as explained.

Identify purchasing decisions

The supply base reduction method will be applied on the purchasing decisions that are relevant for the goal of this thesis, reducing the throughput time at Machine-builder X. The goal of this step is to identify the purchasing decisions that currently risk delays and need to be focused on to reduce the throughput time.

To identify which materials risk the delays, the lead time estimation tool is used. This tool is explained in Chapter 4.3, and is necessary to predict the lead time of the supplies. This prediction will inform us about which supplies risk the desired throughput time of four months that need to be analysed in this designed method. It would not make a difference if only one or a few purchasing decisions are analysed in-depth. The designed method makes it possible to analyse all purchasing decisions that currently risk delays in the throughput time.

The output of this step is the overview of which purchasing decisions will be analysed throughout the application of the designed method.

Identify supplier KPIs

The goal of the second step is to identify the KPIs for the suppliers of Machine-builder X. The KPIs need to be identified to evaluate the performance of the suppliers. This is important for comparing the current and possible alternative suppliers of the purchasing decisions identified in the first step.

As identified by Sarkar and Mohapatra (2006), the KPIs should contain both short- and long-term factors. Kumar et al. (2014) describe the use of discrete choice analysis and total cost of ownership to determine and align the different factors to assess the performance of suppliers. The factors that are important for the company are identified and compared relatively to one another. Weights are determined through the comparison of the relative importance of the KPIs.

The result of this step is an overview of the KPIs, which will be used throughout the application of this method. The KPIs are already identified in Chapter 2.3.

Evaluate suppliers

To identify the optimal supplier for a purchasing decision, the suppliers must be evaluated. The evaluation will make it possible to rank and compare the suppliers.

The relevant suppliers are evaluated based on these criteria by stakeholders within the company. The identification of the stakeholders is part of Method 2 as described by Ogden and Carter (2008). The stakeholder analysis already part of this thesis (see Appendix 2) is used to identify the relevant stakeholders and gather important opinions throughout applying the method.

Furthermore, as comes forward in Method 1, the evaluation of the suppliers is done after the potential suppliers for that purchasing decision are identified. With the aim of making a more general approach, all suppliers are evaluated on the KPIs simultaneously, without the use of the fuzzy approach as described by Sarkar and Mohapatra (2006). This will make it possible to easily evaluate the potential suppliers for each purchasing decision. The goal of applying the supply base reduction approach is mainly to reduce the risk of late supplies. Historical data will make it possible to evaluate the suppliers quantitatively on their lead time performance. The other KPIs will be qualitatively assessed by the COO of Machine-builder X.

The output of this step will be a ranking of the suppliers, which can be used to compare the current supplier with alternative suppliers of a purchasing decision.

4.2.2 Stage 2 – Purchasing analysis

In Stage 2, a purchasing analysis is conducted. The aim of this stage is to identify the nature of the purchasing decisions selected in Stage 1. The nature of the purchasing decision is related to supplier characteristics, which is used to classify suppliers. This will make it easier to identify how supply base reduction methods can be applied to that purchasing decision, which is done in the next stage. The nature of the purchasing decisions can be identified with the help of the supplier categories.

Classify supplier and purchasing decision

The goal of this step is to classify the purchasing decisions that are identified in the previous stage. The classification of the purchasing decision will give an insight into the characteristics of a purchasing decision, which makes it possible to identify the alternative approaches in the next stage.

Classifying the suppliers can help identifying the nature of the purchasing decisions, as well as to know where to focus the reduction of the supply base. The suppliers can be classified by looking at the capabilities of the supplier, the types of materials that are supplied, as well as the importance of cooperation with this supplier. Different suppliers have different characteristics. The characteristics of the supplier have an impact on how the purchasing decision can be classified, and how the supply base reduction methods can be applied.

In Method 3, Kumar et al. (2014) indicate that the purchasing decision needs to be in line with the strategy of the company. Because of the different types of purchases within the supply base of Machine-builder X, the purchase decisions will be classified with the help of the purchase categories outlined in Figure 6 (see Chapter 3.2.1). Sarkar and Mohapatra (2006) link these purchase categories to a specific supplier relationship. The classification of the suppliers can help identify this supplier relationship. The purchase categories are shortly explained:

- **Routine items** are items that are a standard purchase for the buyer, with multiple alternative suppliers.
- **Bottleneck items** are items that can only be ordered at one supplier.
- **Leverage items** are important items for the profit of the company, however with multiple alternative suppliers.
- **Strategic items** are important items for the profit of the company, with limited alternative suppliers.

The output of this step will be the categorization of the purchasing decision, such that alternative approaches can be identified in the next stage. To give an example; strategic and bottleneck purchases characterize a limited supplier pool. For the purchasing decisions related to these purchasing categories, the current supplier might be the only choice. In this case, the application of lead time estimation will be the focus as further explained in the next stage.

4.2.3 Stage 3 – Identify possibilities

The main aim of Stage 3 is to identify the routes that can be taken for a purchase from the supplier. The supply base reduction methods or alternative approaches, supported by the lead time estimation tool, for that purchasing decision are identified in this section.

Identify alternative approaches

The goal of this step is to identify what alternative approaches are possible for the purchasing decisions identified in the first stage, based on the nature of the purchasing decision as identified in the second stage. The current approach for the analysed purchasing decision is not sufficient to achieve a throughput time of four months. In Method 1, the potential suppliers for a purchasing decision are identified, including suppliers outside the current supply base (Sarkar & Mohapatra, 2006). The application of the supply base reduction process at Machine-builder X will be focused on the current supply base because of the limitations and relevancy for Machine-builder X.

Alternative approaches can be identified from for example supply base reduction methods, or application of the lead time estimation tool. Lead time estimation can be applied to for e.g. bottleneck items that are specific buy-parts supplied by unique suppliers. These suppliers are crucial for Machine-builder X and the function of these suppliers is limited to supplying this product. In this case, there is no possible application of the supply base reduction method and lead time estimation is focused on. This might go hand in hand with for example keeping inventory or ordering that component before the intended release of PO.

When supply base reduction can be applied to a purchasing decision, this could be done through systematic elimination, standardization, or tiering (Ogden & Carter, 2008).

- **Systematic elimination** is reducing the number of suppliers in the supply pool for a specific purchase, which is applicable when alternatives are available within the current supply base and the current supplier performs badly relative to alternative suppliers.

- **Standardization** reduces the number of suppliers through standardizing components or the design of the product. Opportunities for standardization might arise when for example multiple components can be standardized into one component with the same functionality.
- **Tiering** reduces the supply base through delegation of specific parts or components to first-tier suppliers. Tiering is applicable at Machine-builder X when for example a sub-assembly package can be delivered by a first-tier supplier that has the capability of ordering the required components that are currently being supplied directly to Machine-builder X. Another form of tiering might be possible when for example a certain supplier has the capabilities of assembling a whole sub-assembly that is currently being assembled by Machine-builder X themselves.

Cooperation with the stakeholders of Machine-builder X comes into play when these possibilities are identified. A general knowledge of the suppliers and the purchasing decisions is present from Stage 2, however the possibilities can become more applicable through cooperation with stakeholders.

The output of this stage is a list of alternative approaches possible for a purchasing decision, which can be analysed and evaluated in the next stage. The evaluation will then make it possible to suggest the optimal approach to Machine-builder X.

4.2.4 Stage 4 – Evaluation and continuous improvement

The aim of this stage is to provide suggestions to Machine-builder X based on a numerical evaluation of the identified approaches. This stage will include a numerical evaluation as well as recommendations for monitoring and continuously improving the performance of suppliers.

Numerical evaluation

The possibilities identified in Stage 3 are evaluated on the costs and benefits that are associated with implementing the change, providing a numerical evaluation as required. The goal of this step is to identify which approach is optimal in terms of costs and benefits, such that a suggestion can be made to Machine-builder X. All purchasing decisions are analysed through application of this method making it possible to provide solutions to achieve a throughput time of four months.

The costs and benefits associated with an approach are evaluated. The benefits will focus on how the risk for late supplies is decreased and how this affects the throughput time. The risk for late supplies is quantified with the lead time estimation tool as discussed in Chapter 4.3. The estimated lead time will give an idea about the chance for a supply to have a lead time over twelve weeks, endangering a throughput time of four months. Apart from this, it is of course also relevant to for example conclude that a change can mean that less purchase orders need to be made by Machine-builder X which wins time. Some of these changes, however, could include higher costs because of outsourced activities such as an outsourced sub-assembly at a highly capable supplier. In this stage, solely suggestions will be made. The possibilities are analysed to identify to what extent the recommendations can be applied, and what can be concluded from the application of supply base reduction at Machine-builder X.

For purchasing decisions where supply base reduction methods are not possible, lead time estimation is vital for reducing the throughput time at Machine-builder X. With the help of lead time estimation, Machine-builder X can plan the orders of the supplies more effectively such that the throughput time can be reduced. Supplies can risk the timeline when the lead time is longer than is expected by Machine-builder X, which can be resolved by applying lead time estimation on the purchasing decisions. For items that have a lead time that endangers a timeline of four months, materials can be held on inventory for example. The benefit of having the items on inventory is compared with the costs of holding inventory. Note that lead time estimation does not reduce the supplier base, however it can have the results related to the goal of applying the method.

The output of this step is the numerical evaluation of the alternative approaches identified in Stage 3. The costs and benefits are compared, making it possible to provide the optimal solution as a suggestion to Machine-builder X.

Suggestions for continuous improvement

The goal of this step is to enable Machine-builder X to continuously improve in managing their supplier base. Providing suggestions how to further utilize the results of this thesis, enables Machine-builder X to further improve the performance of its supplier base.

As described by Kumar et al. (2014) in Method 3, the supplier performance needs to be maintained in order to ensure future success. Via a scorecard system, it is possible to track and evaluate the suppliers on the short-and long-term factors. The KPIs, as they are already identified for Machine-builder X, can be tracked in the future. Recommendations can be given on how certain KPIs can be tracked more effectively through quantitative data analysis in the future. At the current moment, only the lead time KPI can be tracked quantitatively. However, in the future it is possible to track KPIs like quality through gathering and analysing data on this factor. This will make it possible to maintain and manage the (reduced) supplier base of Machine-builder X effectively and enhance further improvement.

Ogden and Carter (2008) also describe tracking the performance of the project, in Method 2. The supplier performance can be tracked with the identified KPIs, however continuous improvement can also be enhanced through establishing better buyer-supplier relationships and identifying new opportunities in the future. Some suppliers that are very capable can continuously become more important for Machine-builder X, where new possibilities may arise in the future. These need to be identified and analysed such that these possibilities can be acted upon and further improvement is possible.

The output of this step is an overview of suggestions to continuously improve the management of the supplier base. These suggestions can be considered by Machine-builder X for further application in the future.

4.3 Lead time estimation tool

Lead time estimation is a tool used to get a better insight into the lead times of the supplies. The goal is to be statistically 95 percent confident of the lead time, such that the risks of delays in the planning can be reduced. With the use of the historical data, it is possible to calculate a 95 percent right-sided interval. This means that the value of the lead time will be within this interval, with a 95 percent confidence.

The historical data contains both the agreed lead time with the supplier, as well as the actual lead time of the supplier for that purchase order. This data is used to calculate the actual lead time as the factor of the agreed lead time with the supplier (actual lead time divided by the agreed lead time). When the data is not strongly non-normal, the Z-test should be used (Sprinthall, 2011). This means that the normal distribution is used for finding the confidence interval for the lead time. With the number of distinct POs that the supplier has delivered, as well as the standard deviation for the actual lead time as the factor of the agreed lead time, all variables are present that are necessary to calculate the estimated lead time with a 95 percent right-sided interval with the formula:

$CI_{bounds} = \mathrm{X} \pm \mathrm{Z} * (\frac{\sigma}{\sqrt{n}})$ *Equation 6* (Georgiev, n.d.)

- n is the number of observations (the number of POs)
- X is the mean of the sample (the average actual lead time as factor of the agreed lead time)
- σ is the standard deviation of the sample
- Z is the value that corresponds to the confidence level for a normal distribution as desired in the calculation (1.6449).

4.4 Conclusion

The three methods found in literature can be combined into a more general method designed for the situation at Machine-builder X. Because of the general approach of a supply base reduction method, combined with lead time estimation, the entire supply base of Machine-builder X can be analysed. The method is designed such that the main goal, to reduce the throughput time, can be achieved most effectively. Applying the method will result in a general overview of the order groups that currently endanger the desired throughput time of four months, including suggestions how the approach to these order groups can be changed to eliminate the risk of delays in the throughput time.

The designed method resulting from this chapter is implemented in the next chapter to find practical solutions for Machine-builder X in terms of suggestions.

5 Results of applying the method

The aim of this thesis is to reduce the throughput time at Machine-builder X. There are suppliers that risk delays in the throughput time because of late supplies. In order to solve this problem, the supply base reduction method designed in Chapter 4 is applied. This method incorporates lead time estimation as a tool for getting a better insight in the lead time of the suppliers, such that delays in the throughput time can be prevented. The different steps are taken and will provide value for Machine-builder X through suggestions and lead time estimation support tools. The results of applying this method are presented in this chapter, answering the following research question:

What will be the results of implementing the method at Machine-builder X?

The different sections in Chapter 5.1 refer to the stages of the designed method. Chapter 5.2 will give a general overview of the results from applying the method. The conclusion, and answer to the research question, will be given in Chapter 5.3. In Appendix 4, a complete analysis is done on all of the assemblies to support these results.

5.1 Implementing the method

In this section, all the stages of the designed method are followed. A detailed example of one of the purchasing decisions will be given throughout all the stages.

5.1.1 Situation analysis

In this section, the steps outlined in Stage 1 of the designed method are followed to get an overview of the company.

Identify purchasing decisions

In the first step of the first stage, the purchasing decisions that would risk delays in the throughput time of four months are identified. This is done by limiting the research to the materials and supplies that will provide the most value to Machine-builder X. The identification of the purchasing decisions is given through multiple limitations of the purchasing decisions that are relevant to be analysed.

First, the supply base reduction method will be applied on the Machine X (for machines 11 and 15), as the results of applying the method on these machines is deemed most valuable. Because of this, the purchasing decisions are analysed for materials that are present in machines 11 and 15 of the Machine X. This limitation reduces the source of purchasing decisions to be analysed from all fifteen machines, to only two machines.

Secondly, the analysis will be done on the basis of sub-assemblies that are present in both machines 11 and 15. With the use of the lead time estimation, the sub-assemblies where applying supply base reduction methods is relevant, are distinguished. No alternative approaches are necessary for sub-assemblies with an estimated lead time that does not endanger the ideal throughput time of four months. Instead, the lead time estimation tool will be used to improve the planning of ordering these materials to achieve the throughput time of four months. This will be elaborated on in Stage 4. The supply base reduction methods will not be applied to sub-assemblies that have an estimated lead time lower than twelve weeks. This is chosen as the norm is a throughput time of around 4 months. Phase 2 and Phase 5, as explained in Chapter 2.1, altogether take around six to eight weeks. These phases are not completely parallel with Phase 3 (the material order and delivery phase), which leaves twelve weeks for Phase 3 which is the phase that can be affected by supply base reduction methods.

As explained, alternative approaches will be identified for sub-assemblies where the estimated lead time is more than twelve weeks. This is calculated with the help of the lead time estimation tool, where the agreed lead time of materials within the sub-assembly are multiplied by the right-sided bound of the confidence interval that is calculated for that specific supplier. The lead time estimation tool is described in Chapter 4.3. In Table 7, an example is given of the maximum estimated lead time for a specific sub-assembly. The maximum lead time per supplier that supplies materials within that sub-assembly (i.e., 'Main Chamber') is given, multiplied by the right-sided bound of the confidence interval for that specific supplier. For the sub-assembly, the suppliers are given in the first column. The materials that have an estimated lead time higher than twelve weeks are included. We can say that with 95 percent confidence, all materials of the 'Main Chamber' can be delivered within the number of weeks given in the red marked box (19.74 weeks). This value is evaluated for each sub-assembly, after which we decide whether it is relevant to apply the supply base reduction method, or suggestions for planned ordering are sufficient. As the example shows an estimated lead time of maximum 19.74 weeks, a deep analysis will be applied on the 'Main Chamber' sub-assembly.

Because of this second limitation, the amount of purchasing decisions that require deeper analysis are reduced to the purchasing decision that endanger the desired throughput time of four months within machines 11 and 15.

Table 7: The maximum estimated lead time for a specific sub-assembly based on the lead time estimation tool

	Agr. lead time (wk)	Avg est. lead time (wk)	Est. lead time (95%) (wk)
Main Chamber	**14.00**	**18.50**	**19.74**
B-31	3.00	2.26	2.44
B-68	3.00	3.94	4.06
M-144	14.00	18.50	19.74
Process chamber bottom plate	14.00	18.50	19.74
Process main chamber side cover	14.00	18.50	19.74
Process chamber top plate - weld assembly	14.00	18.50	19.74
M-50	8.00	7.48	7.67
M-85	7.00	9.12	9.28

Finally, purchasing decisions of materials that are supplied by suppliers that have delivered at least four POs are focused on. The suppliers will be evaluated in the process of applying this method. The evaluation is considered relevant when the historical data of at least four POs can be analysed. Purchasing decisions that already have a high on-time delivery percentage are neglected in the analysis. To reduce the late supplies, it is mostly relevant to analyse the purchasing decisions where the on-time delivery percentage is at most 70%. Table 10 shows all the, already evaluated, suppliers.

The final limitation focuses the application of the designed method on the purchasing decisions that need an alternative approach. The order groups where alternative approaches are necessary, are identified and can be used throughout the rest of the steps within the designed method. The identification of the purchasing decisions is important to know where to focus the rest of the application of the method, limiting possible wasted time.

Identify supplier KPIs

In the second step of the first stage, the Key Performance Indicators for the suppliers of Machine-builder X are identified. The KPIs that result from this step can be used in the evaluation of the suppliers, such that suppliers can be compared on their performance.

As part of the context analysis of Machine-builder X, the KPIs of the suppliers are already identified, and are summarized in Table 8. The weights of the KPIs are calculated with the opinions of the stakeholders (COO, SME) within Machine-builder X, who are identified in the stakeholder analysis in Appendix 2. The identification of the KPIs and its weights can be found in Chapter 2.3. The KPIs for the suppliers of Machine-builder X contain multiple short-and long-term factors. The capability of the company, however, is taken as one specific KPI that relates to most long-term factors as identified by Sarkar and Mohapatra (2006).

The KPIs will be used to evaluate the suppliers in the next step, this is important to compare the suppliers and evaluate which suppliers would perform the best on a purchasing decision for example.

Table 8: KPIs for the suppliers of Machine-builder X including the weights.

KPI	Weight (%)
#1 Lead time	17.8%
#2 Costs	10.4%
#3 Quality	22.5%
#4 Availability	4.5%
#5 Precision	17.9%
#6 Communication	11.3%
#7 Flexibility	7.3%
#8 Expertise	5.5%
#9 Capability	2.8%

Evaluate suppliers

In the final step of the first stage, the suppliers are evaluated based on the KPIs as identified in the previous step. The evaluation of suppliers is important to rank and compare the suppliers, making it possible to identify the best performing supplier for a purchasing decision. The suppliers are evaluated on all KPIs. The lead time KPI can be assessed quantitatively, and all other KPIs are assessed qualitatively. With the ranking of the different KPIs, the total KPI score can be calculated by multiplication with the weights of the different KPIs as resulted from the previous step.

First, the KPIs (excluding the lead time KPI) are evaluated qualitatively and simultaneously, because of the lack of historical data on the KPIs. All suppliers, that are relevant based on the identified purchasing decisions in the first step, are given a grade between one and five by the COO of Machine-builder X. The ranking scale between one and five is chosen as it can be easily associated with the following quantitative measurements:

- Bad performance (1)
- Below average performance (2)
- Average performance (3)
- Above average performance (4)
- Good performance (5)

Secondly, the lead time KPI can be evaluated quantitatively through the analysis of the available historical data. To grade the suppliers on their lead time performance, three indicators are analysed and given in Table 9. How the suppliers are ranked on these indicators is given in the table as well. The average of these ratings will be the overall rating for the lead time KPI of the supplier.

Table 9: Indicators for quantitative analysis of the lead time KPI based on grading bins

Lead time performance indicator	Explanation	Grading
Average agreed lead time	The average agreed delivery time for a unique PO from the supplier to Machine-builder X.	1 = >11 weeks 2 = 9-11 weeks 3 = 6-9 weeks 4 = 3-6 weeks 5 = <3 weeks

On-time delivery percentage	The percentage of unique POs that have been delivered no later than the agreed delivery date.	1 = <25% 2 = 25-50% 3 = 50-70% 4 = 70-85% 5 = >85%
Average lateness	The average lateness of a unique PO, calculated for POs that were supplied later than the agreed delivery date.	1 = >3.5 weeks 2 = 2.5-3.5 weeks 3 = 1.5-2.5 weeks 4 = 0.5-1.5 weeks 5 = <0.5 weeks

Finally, with the weights of the different KPIs, the ranking of the relevant suppliers can be found in Table 10. The rankings of the KPIs of all suppliers are multiplied with the weights, and the total score for the suppliers is calculated. The last column in Table 10 shows the total score of the KPIs for all suppliers. The other columns give general information about the number of POs that are fulfilled by the supplier as well as the percentage of these POs that were delivered in time at Machine-builder X.

Table 10: Analysis of the relevant suppliers, focused on the evaluated KPIs (last column) for comparison and evaluation

Supplier ID	# of POs	% On time	KPI score
B-106	12	66.67%	2.80
M-20	6	66.67%	3.34
B-113	18	66.67%	3.30
B-96	9	66.67%	3.33
M-126	11	63.64%	3.34
M-53	8	62.50%	3.52
B-142	15	60.00%	3.12
B-143	25	60.00%	2.85
M-97	5	60.00%	2.93
B-150	7	57.14%	3.12
B-47	7	57.14%	3.15
B-3	17	52.94%	3.66
B-102	6	50.00%	3.12
M-83	10	50.00%	3.06
M-100	16	43.75%	3.49
B-70	12	41.67%	3.37
B-124	22	40.91%	2.94
B-75	15	33.33%	3.20
B-68	15	33.33%	3.34
B-86	11	27.27%	3.09
M-87	8	25.00%	3.38
M-42	40	25.00%	3.64
M-71	24	25.00%	2.77
M-140	4	25.00%	2.89
M-144	39	23.08%	3.23
M-145	35	22.86%	3.16
M-63	22	22.73%	3.31
M-114	9	22.22%	3.41
M-25	19	21.05%	3.56
B-79	22	18.18%	2.72
M-48	7	0.00%	2.34

The evaluation of the suppliers will give a general overview of the performance of the suppliers which is useful when possibilities for the purchasing decisions are identified and evaluated. When alternative approaches are identified in Stage 3, the evaluation of suppliers can say something about which alternative supplier would possibly be a better fit for that purchasing decision.

5.1.2 Purchasing analysis

In this stage, the suppliers are grouped and analysed to make it possible to identify the nature of purchase.

Classify supplier and purchase

Step 1 in the second stage of the method is used to classify the nature of the purchasing decisions that require further analysis, as is identified in the first stage. The classification of the purchasing decision is done with the help of the supplier classification. This step is important to gain knowledge about the suppliers and the purchasing decisions that they supply, such that alternative approaches can be identified in the next stage. The suppliers of the purchasing decisions that are analysed within this method are divided into categories, which relate to purchase categories. With this information, the purchasing decisions can be classified easier, and alternative approaches can be identified in the next stage.

Some suppliers have the capability to have a sub-assembly outsourced, some suppliers can supply sub-assembly packages if suppliers are tiered behind them, and some suppliers are so unique that lead time estimation is the only way to decrease the negative effect on the timeline that certain suppliers have. All relevant suppliers are analysed together with the COO of Machine-builder X to identify the supplier category, possible alternatives, and supply base reduction applicability. The suppliers of Machine-builder X can be categorized into the options as provided in Table 11. All suppliers in the supply base of Machine-builder X can be divided into these categories. The supplier category has characteristics that are usually related to one of the purchasing categories as explained in the third column of Table 11, which makes it easier to relate a purchasing decision from a supplier to a purchase category. The relation between supplier characteristics and purchase categories can be found in Figure 6 in Chapter 3.2.1.

Table 11: Explanation of the supplier categories and their relation to purchase categories

Category #	Supplier category	Explanation
1	Customized parts – general	Supplies customized parts mostly from aluminium or stainless steel. With generally multiple alternative suppliers and a variating importance, most purchasing decisions can be classified as either: Routine, Leverage, or Strategic Items
2	Customized parts – more capabilities	Like Category 1, however with additional capabilities (e.g. making a whole sub-assembly). Purchasing decisions can be classified as either: Routine, Leverage, or Strategic Items
3	General buy parts – (wholesaler)	Supplies standard products that are not custom made for Machine-builder X. With always multiple alternatives and a variating importance of the product, the purchasing decisions can be classified as either: Routine or Leverage items
4	Specific buy parts	Supplies specific products that are not custom made but not widely available. With generally limited alternative suppliers, the purchasing decisions can be classified as either: Bottleneck or Strategic Items

5	Engineering / services	Supplies services for Machine-builder X, such as the software custom for the machine. There are limited alternative suppliers for the purchasing decisions within this category, which suggests a classification of either: Bottleneck or Strategic Items

Information about the supplier that currently supplies the relevant purchasing decision is identified in the form of a table for which an example is shown in Table 12. To give an example; as seen in Table 7, supplier M-144 supplies the components that have an estimated lead time higher than twelve weeks. These parts of the 'Main Chamber' sub-assembly can be expected to be delivered in up to 19.74 weeks, which endangers the aimed at throughput time of four months. The supply base reduction methods will for example be applied on this purchasing decision. In Table 12, information is gathered for the supplier on which the purchasing decision is analysed. For supplier M-144, it is shown that there are alternatives in the form of all big suppliers of customized parts currently in the supply base. Because supplier M-144 is one of the most capable suppliers and not a lot of alternatives are present, this is a strategic purchasing decision for Machine-builder X.

Table 12: Characteristics of a supplier based on the supplier categorization

Vendor / Supplier	Supplier category	Alternatives (in supply-base)	Possibility for sub-assembly/tiering	Comments
M-144	Customized parts - more capabilities	M-87, M-145, M-83	Capable of making sub-assemblies.	Supplies customized parts of aluminium or RVS. Potentially assembling the whole machine in the future.

The result of this stage is increased knowledge about the suppliers and the purchasing decisions. With the classification of the purchasing decision, alternative approaches can be identified easier.

5.1.3 Identify possibilities

The relevant purchasing decisions within the assemblies are identified and analysed based on the supplier and purchasing categories. This makes it possible to identify the possibilities of lead time estimation and supply base reduction methods in this stage.

Identify alternative approaches

This step is followed to identify alternative approaches for the purchasing decisions that currently have a negative impact on the throughput time. Alternative approaches can be identified with the help of the nature of the purchasing decision as well as the supplier categorization from the previous stage. The fourth column in Table 12, for example, mentions the possibilities for tiering or outsourcing a module to that supplier. Different approaches will be proposed and evaluated in the next stage to find the optimal approach.

The suppliers have different kind of capabilities, which relate to what type of alternative approaches can be used. Alternative approaches can be based on the supply base reduction methods; systematic elimination, standardization and tiering, as explained in Chapter 4.2.3. Some suppliers, mostly from Category 2 (i.e., customized parts – more capabilities), can have sub-assemblies outsourced. Apart from this, some suppliers can have other suppliers within the supply-base tiered under them, meaning that they could supply a sub-assembly package including materials from the other current suppliers. These are examples of the application of tiering on a supply base. For other suppliers, mostly from Category 4 (i.e., specific buy parts), direct order from Machine-builder X is the only option.

As shown in Table 12, supplier 'M-144' has alternatives within the supply base of Machine-builder X. This supplier has the capabilities of supplying an assembled sub-assembly or have other purchasing decisions tiered under them. For the purchasing decisions with alternatives, it is possible to compare the supplier with the alternative suppliers. This will make it possible to rank these suppliers and see if the allocation of this supplier to the purchasing decision is the optimal one. This ranking is shown in Table 13, supported by Figure 9. In Figure 9, the suppliers are compared on their on-time delivery percentage (% Too late and % On time) as well as their average agreed lead time and average lateness. To find solutions to reduce the lead time of the 'Main Chamber' order group, possibilities for alternative approaches are identified.

- The whole 'Main Chamber' can be outsourced to supplier 'M-144'. A meeting with supplier 'M-144' will give an insight into the expected results of this possibility. A lead time of fourteen weeks will be available for the delivery of the assembled 'Main Chamber'. The other suppliers currently present in the supply base of the 'Main Chamber' can be tiered under 'M-144' or Machine-builder X can order these materials to have them delivered at 'M-144' for assembly. All customized parts present in the 'Main Chamber' can be manufactured by supplier 'M-144'.
- For the components currently supplied by 'M-144', semi-finished products can be held on inventory at supplier 'M-144' to decrease the manufacturing time of the final products. As this would decrease the lead time by around four weeks, lead time estimation would be sufficient to order these products at the start of the design phase.
- Supplier 'M-144' has a lower overall KPI score than supplier 'M-87' as can be seen in Table 13. However, because of the long-term relationship with this supplier, the cooperation with supplier 'M-144' is preferred. Supplier 'M-144' will be the primary supplier for these purchasing decisions within the 'Main Chamber' sub-assembly. However, when 'M-144' cannot supply the components for whatever reason, alternative suppliers are available. Supplier 'M-87' is the best performing supplier and could be the first choice when 'M-144' is not capable of supplying the components.
- The components from 'M-144' can also be ordered before the intended PO is released. With an estimated lead time of maximum 19.74 weeks, these components should be ordered four weeks before the intended PO is released. Machine-builder X estimates to be 90 percent sure the PO will be released, four weeks before intended release of PO. Because of this, the components must be held on stock in 10 percent of the cases.
- When the expected PO is not released, it might be a possibility to cancel the order of the materials. The meeting held with supplier 'M-144' should result in the possibilities of cancellation including a possible cancellation fee.

These possibilities are identified for all relevant purchasing decisions. The implementation of this step will result in an overview of possible approaches for the purchasing decisions to achieve the desired throughput time of four months. These approaches can be evaluated to find the optimal solution in the next stage.

Table 13: Ranking of alternative suppliers to supplier 'M-144' for comparison and evaluation

Supplier ID	# of POs	% On Time	KPI score
M-83	10	50.00%	3.06
M-87	8	25.00%	3.38
M-144	39	23.08%	3.23
M-145	35	22.86%	3.16

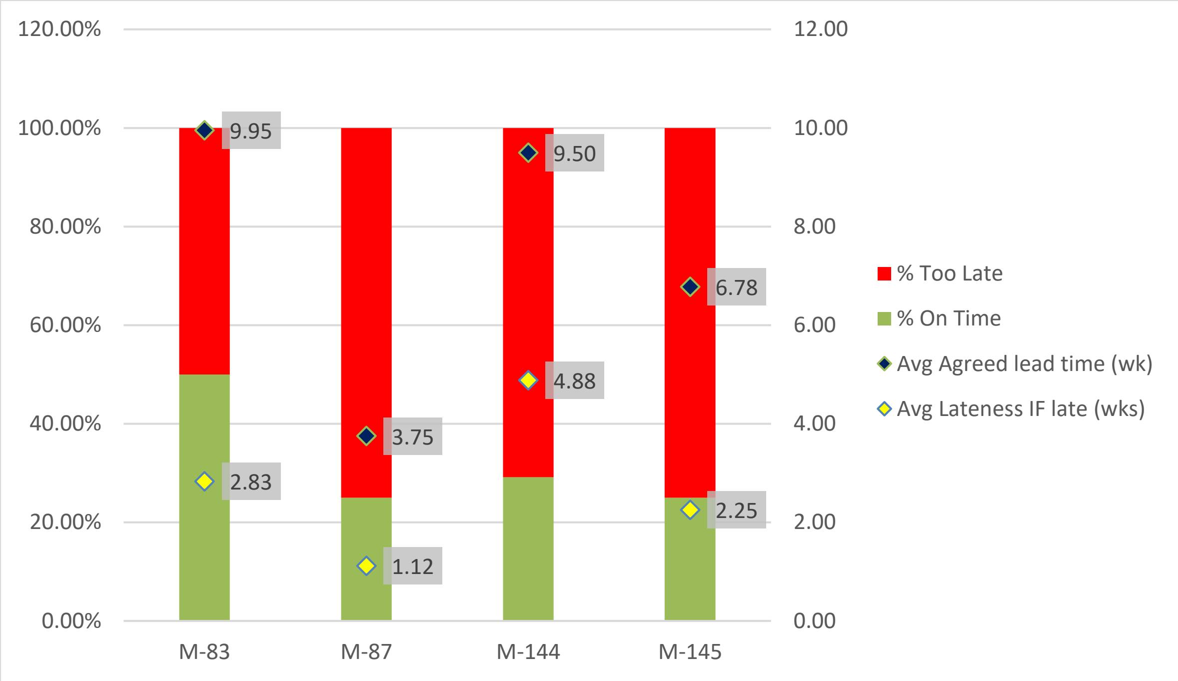

Figure 9: Evaluation of alternative suppliers for supplier 'M-144' based on the lead time performance

5.1.4 Evaluation and continuous improvement

To further analyse the purchasing decision, an evaluation is required. The identified possibilities are numerically evaluated to provide suggestions for implementation. On all relevant purchasing decisions, lead time estimation is conducted to be able to suggest an improved way of planning the order of materials at Machine-builder X. Recommendations will be given for continuous implementation of the method and improvement of the supply base management at Machine-builder X.

Numerical evaluation

The first step in the final stage is followed to suggest the optimal approach to Machine-builder X based on a cost-benefit analysis. A throughput time of four months can be achieved by applying the optimal approach for each purchasing decision. In this step, all potential different approaches are numerically evaluated through an analysis of the costs and benefits associated with the approach. Assumptions are made and benefits are furthermore expressed in terms of achieving a throughput time of four months.

The example throughout this chapter was focused on the purchasing decisions within the 'Main Chamber' assembly, supplied by supplier 'M-144'. The possibilities as identified in the previous stage are considered. The possibility of holding semi-finished products on inventory at 'M-144' is deemed improbable because of the lower shelf life of semi-finished products. In Table 14, the different explained strategies are analysed in terms of costs. The options include, from left to right, the current situation, outsourcing the 'Main Chamber' to 'M-144' and ordering the components from 'M-144' four weeks in advance of the intended release of PO with possible capital investments or a cancellation fee.

Certain assumptions and estimations are made to calculate the costs for these identified possibilities:

- The component costs for the 'Main Chamber' assembly, to be assembled by Machine-builder X, are the average of the total costs of the components within the 'Main Chamber' in machines 11 and 15 (respectively €18,925.00 and €18,825.69).

- One man-hour is worth €70.00.
- One unique order within the 'Main Chamber' sub-assembly takes one man-hour to place and fulfil.
- One machine is built and sold each half a year by Machine-builder X.
- In-house management costs (updating drawings etc.) of the customized parts come down to a cost of €100.00 per part per year.
- The total component costs of the 'Main Chamber' sub-assembly does not differ for the different situations.
- Four weeks before intended release of PO, Machine-builder X is 90 percent sure that the PO will be released. As a customized part for the customer, the components are expected to be held on inventory in 10 percent of the cases. These capital investments bring a cost of 10 percent of the value of the materials as inventory costs. This number is an estimate derived from previous experiences and knowledge within Machine-builder X.
- Cancellation of the order will be linear to the agreed lead time of that component. The expected cancellation of the order is assumed to be four weeks after the order, with a cancellation fee of 30 percent of the component price.

The assembly of the 'Main Chamber' sub-assembly takes a total of eight man-hours at 'Machine-builder X', where an additional four hours are necessary for engineering. These costs are included in the outsourcing costs for outsourcing the 'Main Chamber' to 'M-144' which are estimated at €4.000.00. These costs include warehouse management costs, handling parts, and manhour costs for thirty hours necessary for assembly and fulfilling the order. Furthermore, costs are calculated for management and communication from Machine-builder X for outsourcing the sub-module. Finally, the money already spend by Machine-builder X on employees and uninterchangeable work, resulting from the start-up nature of the company (discussed in Chapter 6), is added.

When the 'Main Chamber' sub-assembly is outsourced to 'M-144', the amount of orders that need to be fulfilled for the 'Main Chamber' can be reduced from four orders to one order. The capital investment for ordering the 'M-144' components before the intended release of PO are estimated at €1,770.00 as in 10 percent of the cases, the components would have to be held on stock. The associated inventory costs are 10 percent of the capital investments, resulting in inventory costs of €177.00. The cancellation costs of the components supplied by 'M-144' are 30 percent of the component costs of €17,700.00. These costs would be made in 10 percent of the cases. This comes down to a cancellation cost of €531.00. To conclude, six parts in the 'Main Chamber' sub-assembly are customized parts and hold in-house management costs. As one machine is assumed to be built in half a year, these costs are €50.00 per part.

Table 14: Cost analysis for alternative approaches for the 'Main Chamber' sub-assembly

	Current situation	**'Main Chamber' outsourced to 'M-144'**	**Order before PO** Possible inventory	**Order before PO** Cancellation fee
Component costs	€18,875.35	€18,875.35	€18,875.35	€18,875.35
Outsourcing costs	€0.00	€4,000.00	€0.00	€0.00
Engineering costs	4 * €70.00 = €280.00	€0.00	€280.00	€280.00
Assembly costs	8 * €70.00 = €560.00	€0.00	€560.00	€560.00
Costs of making orders	4 * €70.00 = €280.00	1 * €70.00 = €70.00	€280.00	€280.00

Cancellation costs	€0.00	€0.00	€0.00	€531.00
Inventory costs	€0.00	€0.00	€177.00	€0.00
In-house management costs	6 * €50.00 = €300.00	€0.00	€300.00	€300.00
Total costs	**€20,295.35**	**€22,945.35**	**€20,472.35**	**€20,826.35**
Capital investment	€0.00	€0.00	€1,770.00	€0.00

Apart from the costs, the effect on the lead time, time-dependency and stress need to be analysed as well. With a maximum estimated lead time of 19.74 weeks for the 'Main Chamber' sub-assembly in the current situation, a throughput time of four months is highly improbable. The second option, outsourcing the 'Main Chamber' to 'M-144' would enable achieving the goal as the lead time would be a maximum of fourteen weeks. Ordering the components four weeks before intended release of PO would result in a maximum estimated lead time that would not endanger the throughput time of four months either. Outsourcing the whole module would have the most effect on reducing the time-dependency and stress levels, where the other two new situations would also influence these variables.

With an additional cost of €2,650.00, outsourcing the 'Main Chamber' sub-assembly to 'M-144' is significantly more expensive than other approaches. Similar benefits would be the result of ordering the components from 'M-144' before intended release of PO. The option to hold inventory when the PO is cancelled by the customer is less expensive and is thus suggested for Machine-builder X. With an expected capital investment of €1,770.00, the desired throughput time of four months is made possible for this sub-assembly.

The implementation of this step resulted in a suggested approach for all identified purchasing decisions, where implementation of the suggestion will resolve the negative impact of that purchasing decision on the throughput time. In Appendix 4, all order groups are analysed and examined to find the right application of the methods and lead time estimation. Practical suggestions are given for the specific order groups, such that Machine-builder X can achieve a throughput time of four months.

Suggestions for continuous improvement

The second step in the final stage is applied to make suggestions for further improvement of the supply base of Machine-builder X in the future. The implementation and results of the method are analysed to find opportunities for further improvement in the future. An overview of suggestions is given.

- To continuously improve the supply base of Machine-builder X, it can be suggested to track the KPIs more effectively. For certain important KPIs, as can be seen by the weights in Table 8 (Chapter 5.1.1), it will be important to track these KPIs in terms of data. Where most of the KPIs are currently evaluated with qualitative measurement, quantitative data analysis might provide better insights into the suppliers. For example, the precision of deliveries can be tracked by measuring how often the supplies have exactly the right components. This is important as reorders of supplies would endanger the timeline. Being able to quantitatively analyse the precision of delivery of suppliers, will enable a better evaluation of suppliers.
- Furthermore, it would be beneficial to track whether supplies are late because Machine-builder X agreed on later deliveries because other parts of the order are delayed. In the data, it might seem that certain suppliers deliver all their products late, while certain components of an order are finished on time.

- Finally, as some suggestions in Appendix 4 also mention, Machine-builder X should keep looking at opportunities to apply methods to decrease the throughput time even more. As Machine-builder X is currently growing, it is plausible that for example outsourcing sub-assemblies would be more realistic in the future.

The final step of the method, designed for implementation at Machine-builder X, resulted in the suggestions given above. Machine-builder X can further improve the management of the supply base by implementing these suggestions in the future. All the steps of the method are applied and to conclude, multiple suggestions can be followed by Machine-builder X to achieve a throughput time of four months.

5.2 Overview of the results

In this section, an overview of the results from implementing the designed method in Chapter 5.1 is given. The norm, a throughput time of four months, can be achieved by implementing certain strategies. These strategies, however, bring certain costs which of course need to be considered. Please find a more in-depth analysis of these results in Appendix 4, where the complete method is applied on all order groups of the Machine X, machines 11 and 15. Finally, the suppliers that relate to the supplier IDs can be found in Appendix 5.

The designed method is applied on the order groups that include materials that risk a delay in a desired throughput time of four months. For the other order groups, lead time estimation is sufficient to know when certain materials must be ordered. The lead time for these materials do not exceed twelve weeks and can thus be ordered after Phase 2 is concluded (i.e., the design phase). For a few other order groups, an insignificant number of materials have an estimated maximum lead time just exceeding the twelve weeks. These materials can be ordered slightly earlier and do not endanger the timeline either. The to be ordered laser, within the 'Laser' order group, will have to be ordered when PO is released. Because of the high unit price, investments for inventory are not made and thus not evaluated either. The estimated lead time can be found in the lead time estimation tool provided to the company.

The 'Gas Panel' sub-module within the 'Sub-Modules' order group can be outsourced to supplier 'M-114'. At the current moment, materials can be delivered up to a maximum estimated lead time of 13.47 weeks. As summarized in Table 15, the whole sub-module can be outsourced to supplier 'M-114' for an additional cost of €1,364.51. This supplier would guarantee a maximum lead time of twelve weeks, where the current situation would endanger a throughput time of four months. A complete and more in-depth analysis is found in Appendix 4.11.

Table 15: Cost analysis for outsourcing the 'Gas Panel' sub-module to supplier 'M-114'

	Assembly at Machine-builder X	Outsourced to 'M-114'
Component costs	€12,350.64	€13,815.15
Outsourcing costs	€0,00	€1,450.00
Engineering costs	4 * €70.00 = €280.00	€0.00
Assembly costs	4 * €70.00 = €280.00	€0.00
Costs of making orders	8 * €70.00 = €560.00	1 * €70.00 = €70.00
In-house management costs	10 * €50.00 = €500.00	€0.00
Total costs	**€13,970.64**	**€15,335.15**

For the 'Heater', 'Main Chamber', and 'Wafer Stage' order groups, similar results are found. These order groups all include Category 3 (i.e., large customized parts) materials currently supplied by supplier 'M-144' that endanger a throughput time of four months.

- There is a possibility to outsource these order groups to supplier 'M-144', where the risk in delays in the desired throughput time of four months are limited. This approach is not viable at this moment in time, as the additional expense is excessive compared to other possible approaches. At the moment more machines are built by Machine-builder X, a more frequent order will make it possible to decrease the additional expense associated with outsourcing these order groups to supplier 'M-144'.
- All the materials within these order groups can be ordered four weeks before the intended PO is released, to limit the risk of delays in the throughput time. This option brings a risk of capital investments for inventory which is given in Table 18. The amount given in the column 'Capital investment – risk no PO' is necessary when the products are ordered before the intended PO is released. It is also possible to calculate a cancellation fee when the PO is cancelled by the customer of Machine-builder X. At that moment, Machine-builder X can cancel the order of the parts from supplier 'M-144' for a cancellation fee of 30 percent of the component costs. Inventory cost of 10 percent of the component costs is associated with keeping the materials on stock. More in-depth analysis is found in Appendix 4.4 ('Heater'), Appendix 4.7 ('Main Chamber') and Appendix 4.14 ('Wafer stage'). As found from the in-depth analysis, this approach is more cost-effective than outsourcing and is thus suggested to Machine-builder X.

For the order groups shown in Table 16 and 17, materials need to be held on inventory and/or ordered before the intended release of PO to achieve a throughput time of four months. The capital investments required for holding components on inventory and ordering materials before intended release of the PO is conducted and outlined in Table 19. Materials that risk the throughput time of four months are considered.

Three categories are evaluated in Table 19. Tables 16 up to and including 18 show the materials and the related capital investments within these categories.

1. Category 1: Consumables
   These materials can be used in all machines and are often used for reparation and maintenance issues. Several components are held on inventory, normally for maintenance purposes. These materials are held on inventory, and before the intended PO is released, the necessary quantity of materials is ordered once again. The risk analysis is only conducted on the inventory that would be necessary for building the machines and achieving a throughput time of four months, the additional stock for maintenance purposes is neglected.

Table 16: Capital investments necessary for Category 1 items

Supplier ID	Order group	Component	Quantity in stock	Quantity ordered	# of weeks to order before PO	Capital investment inventory	Capital investment risk no PO
M-48	'Quartz Group'	Quartz Shield	1	1	8	€2,690.00	€538.00
M-71	'Quartz Group'	Crown assy transfer holder	2	2	8	€4,220.00	€844.00
Total						€6,910.00	€1,382.00

2. Category 2: Spare items

The spare items are the materials that cannot be used in any machine. Because of the high estimated lead time however, these materials are kept on limited inventory to reduce the risk of delays in the throughput time. As spare items, these materials will not be ordered before intended release of PO.

Table 17: Capital investments necessary for Category 2 items

Supplier ID	Order group	Component	Quantity in stock	Quantity ordered	# of weeks to order before PO	Capital investment inventory
B-86	'OSS & BDM'	Mirror holders	6	6	0	€1,896.00
B-79	'Loadlock' and 'Baratron tree'	Pressure transducer - ATM	2	2	0	€1,080.00
B-79	'Baratron tree'	1 Torr Process Baratron, 1/2" VCR	1	1	0	€1,329.00
B-79	'Foreline'	Pressure - Cold Cathode / MicroPirani	1	1	0	€788.00
			Total			€5,093.00

3. Category 3: Large customized parts
   The large customized parts refer to the expensive customized parts that have a high estimated lead time. Because of the high price, these are usually not kept on inventory. These materials can be ordered before the intended PO is released. With a 10 percent possibility that the PO is cancelled by the customer of Machine-builder X, risked capital investments are present.

Table 18: Capital investments necessary for Category 3 items

Supplier ID	Order group	Component	Quantity in stock	Quantity ordered	# of weeks to order before PO	Capital investment risk no PO
M-144	'Heater'	Top heater solder assy	0	1	4	€622.00
M-144	'Heater'	Bottom heater solder assy	0	1	4	€829.00
M-144	'Main Chamber'	Process chamber bottom plate	0	1	4	€569.00
M-144	'Main Chamber'	Process main chamber side cover	0	1	4	€208.00
M-144	'Main Chamber'	Process chamber top plate - weld assembly	0	1	4	€993.00
M-144	'Wafer Stage'	Wafer stage weld assy	0	1	4	€981.00
			Total			€4,202.00

Table 19: Total capital investments necessary for inventory at Machine-builder X

	Category 1	**Category 2**	**Category 3**
Capital investment inventory	€6,910.00	€5,093.00	€0.00
Capital investment risk no PO	€1,382.00	€0.00	€4,202.00
Total capital investments	€8,292.00	€5,093.00	€4,202.00

The results given in Table 19 show us the capital investments that need to be done to achieve a throughput time of four months. Machine-builder X can make use of the cancellation fee for the Category 3 items or risk capital investments in inventory. As the costs for inventory (10 percent of the component costs) are lower than the cancellation costs (30 percent of the component costs), the components are held on stock. This results in a total capital investment, for all categories combined, of €17,587.00 (€8,292.00 + €5,093.00 + €4,202.00). The inventory costs are 10 percent of the capital investments, which comes down to a direct cost of €1,758.70.

5.3 Conclusion

The results of implementing the designed method at Machine-builder X have been found systematically. All relevant purchasing decisions present at Machine-builder X have been identified and analysed, with the help of the lead time estimation tool, to provide suggestions for achieving a throughput time of four months. The numerical evaluation of these suggestions is given for Machine-builder X to decide whether to implement these suggested changes of approach. For all the order groups that are present in machines 11 and 15, the approach is suggested such that a throughput time of four months can be achieved. These suggestions include possible investments for outsourcing sub-assemblies or holding inventory for timeline endangering materials.

To achieve a throughput time of four months, the following suggestions are made in this chapter:

- The ‘Gas Panel’ can be outsourced to supplier ‘M-114’ for an additional cost of €1,364.51
- Additional focus is suggested on order groups where a few materials have an estimated lead time slightly above twelve weeks
- Keep inventory and/or order materials with an estimated lead time higher than eighteen weeks before intended release of PO for a capital investment of €17,587.00 and direct inventory costs of €1,758.70

6 Conclusions, recommendations & future research

Within this thesis, supply base reduction methods were investigated and combined with a lead time estimation tool. Through analysis of historical data and implementing the designed method, suggestions were provided to achieve a throughput time of four months. Each chapter was related to a sub-question, that was answered in the concluding section of these chapters. These conclusions contribute to the goal of answering the main research question which will be answered in the conclusion in Chapter 6.3.

How can Machine-builder X decrease the negative effect that inconsistent suppliers (with longer lead times than agreed upon) have on the throughput time?

The results from this thesis are evaluated in Chapter 6.1. Chapter 6.2 will outline simplifications, limitations, and possibilities for further research. Finally, recommendations are included, based on the conclusions, in Chapter 6.4.

6.1 Evaluation

The results of this thesis contain several suggestions for Machine-builder X as can be found in the conclusion and recommendations sections. The usefulness of the results from this thesis are assessed in this section through an evaluation survey presented to the COO of Machine-builder X together with a presentation given to all stakeholders. The complete statements including the feedback from the stakeholders can be found in Appendix 7. This section summarizes the results from the survey.

Machine-builder X had a goal for this thesis to achieve a throughput time of four months. It is expected that the results of this thesis are useful for Machine-builder X, for finally achieving this desired throughput time. Some further effort needs to be made to consistently achieve this throughput time and incorporate the suggestions of this thesis. This thesis was focused, where further research on improvements in the design phase could also be required to achieve the desired throughput time of four months. Machine-builder X is quite dependent on supplier 'M-144', because of their influence in the lead time of a lot of sub-assemblies within the machines of Machine-builder X. Good agreements need to be made such that the performance of the suppliers can be relied upon. Within this thesis, creative solutions were found for different kinds of problems. With a deep knowledge about the construction of the machine and the processes within Machine-builder X, it was possible to incorporate most if not all factors that influence the throughput time.

The results of this thesis can be used as a reference document for the supply base of Machine-builder X. Knowledge transfer will be easier and more validated through the data available from this thesis. This knowledge transfer includes information about suppliers and the process of building a machine. The lead time estimation tool can be used, in addition to general information about suppliers, to deepen the knowledge about suppliers.

To summarize, Machine-builder X sees added value from the results of this thesis. With some additional research it is possible to achieve the desired throughput time of four months.

6.2 Future research

Because of the scope of this thesis, some limitations appeared in the research. Apart from that, further research can be done on relevant subjects.

- This thesis focused on decreasing the throughput time at Machine-builder X. Designing and implementing the method was based on this goal. Because of this, the method was primarily applied on order groups where the lead time of materials endangered the timeline. Even though it is not necessarily beneficial for the throughput time, it is interesting to look at the supply base reduction methods applied on other order groups as well for other benefits. Outsourcing a sub-assembly to a supplier might be beneficial in terms of costs and stress within the company. A lot less energy and time needs to be put in outsourced sub-assemblies, possibly for less overall costs.

- As time continues, more data will be available to have more valid insights into the suppliers. More accurate estimations of lead times can result from more available data. With more available data, the suppliers can be analysed per year for example, to see the improvement of suppliers. Because of the limited data, it was ineffective to analyse the suppliers throughout the years. The improvement of a supplier overtime might result in a different relationship with that supplier.
- To further validate the weights of supplier KPIs, more stakeholders can be asked for their opinions and sensitivity analyses can be done. Because of time limitations, and the limited added value, this was deemed unnecessary within the scope of this thesis. This can, however, be researched further in the future.
- The historical data available at Machine-builder X included the order- and delivery date of the supplies. For some materials, the supplies are generally late because they are delivered within the same package as another component that required a longer lead time. Sometimes, this is chosen by Machine-builder X themselves. The result of this is that the materials that could be delivered on time, are delivered later than was necessary. The historical data does not track this information, which made it impossible to analyse the suppliers considering this occurrence. It would be better to, in the future, track this information and have a more accurate view of the supplier performance.
- The application of the method depends on the characteristics of the company. Currently, Machine-builder X is growing rapidly. As Machine-builder X is growing, more opportunities will arise as more buying power will enable better relationships with suppliers. This might mean that lower lead times can be agreed upon, possibly changing the most effective approach for an order group. Further research can be conducted when new opportunities arise for Machine-builder X, for example for outsourcing more sub-assemblies to highly rated suppliers.
- A lot of information in this thesis, for example the information on the KPIs of suppliers, can be used as a baseline for further research on these topics. Where currently almost all KPIs must be measured qualitatively, quantitative analysis would be possible if data of suppliers is tracked in the future. Furthermore, the visualization of the phases might become useful for identifying more possibilities for improvement within the processes happening at Machine-builder X.

6.3 Conclusion

To decrease the negative effect that certain suppliers have on the throughput time, a method needed to be designed specifically for Machine-builder X. Three methods for supply base reduction were found in literature. These methods were focused on reducing the supplier base for one purchasing decision and included a detailed process for applying different methods to achieve a more consolidated supply base. As the goal in this thesis required an analysis on all the purchasing decisions, the methods needed to be transformed or redesigned into a method specific for the situation at Machine-builder X. The selection of the relevant steps taken in the supply base reduction methods studied in literature, together with the lead time estimation tool made it possible to design a method applicable for the entire supply base of Machine-builder X. Applying this designed method to the supply base of Machine-builder X resulted in several evaluated suggestions that can be followed to achieve a throughput time of four months. With the use of the lead time estimation tool, the lead times of the order groups could be analysed. Each order group or sub-assembly present in machines 11 and 15 is analysed, where a maximum estimated lead time over twelve weeks is considered as a purchasing decision that endangers the desired throughput time of four months.

1. Multiple order groups (Order groups 2, 9, 10, 13) do not endanger a desired throughput time of four months. The maximum lead time of the materials within these order groups is estimated lower than twelve weeks. These materials can be ordered after the design phase is concluded.
2. Other order groups (Order groups 3, 6, 8, 12) contain materials that have a maximum estimated lead time slightly above the twelve weeks. To achieve a throughput time of four months, these materials must be ordered within the design phase. Machine-builder X must focus on designing these products on time, such that the order can be released to the supplier on time as well.
3. Several materials, part of Order groups 4, 6, 7, 8, 11, and 14, have an estimated lead time higher than eighteen weeks. These materials cannot be ordered after the PO is released, because of their immediate risk on the timeline. Capital investments are an alternative approach, resulting from ordering the materials before the PO is intended to be released and/or hold inventory. The risk that the supply of these materials has on the throughput time can be resolved by holding inventory, with an inventory cost of 10 percent of the component costs.
4. The laser, part of Order group 5, has an estimated lead time of 21.19 weeks which endangers the timeline of four months. The laser is a special component as it is not essential to have it delivered simultaneously with the rest of the machine. Because of the high investments, no financial risk is taken with capital investments. The laser can be ordered on the day PO is released, where on average this component would arrive on time at the customer or at Machine-builder X.
5. Outsourcing the ‘Gas Panel’ (part of Order group 11) is a possible approach to limit the risk of delays in the timeline. The ‘Gas Panel’ can be outsourced to supplier ‘M-114’ for an additional cost of €1,364.51.
6. Multiple purchasing decisions (in Order groups 6 and 11) could be sourced at alternative suppliers. These alternative suppliers have a higher overall KPI score and could therefore have a beneficial impact on the throughput time based on agreements that would have to be made.

Summarized, different approaches are identified and analysed for all order groups within the Machine X, machines 11 and 15. The costs and benefits of the alternative approaches are evaluated, where the optimal approach at this moment in time is resulted. The alternative approaches include outsourcing sub-assemblies, ordering before intended release and holding stock, and sourcing at alternative suppliers.

6.4 Recommendations

Recommendations can be made to Machine-builder X based on the conclusions from the results. The recommendations relate to the numbered conclusions given in the previous section.

1. For the order groups that have a maximum estimated lead time lower than twelve weeks, using the lead time estimation tool is sufficient. The lead time estimation tool allows the purchaser of the materials to estimate the maximum delivery date, which makes it possible to plan the purchase. Apart from this, no additional focus is required on these order groups.

2. Materials with a maximum estimated lead time slightly (i.e., one to two weeks) above twelve weeks do require some additional attention. When the PO is released by the customer, it is recommended to focus on making the design ready to order the customized parts that have a maximum estimated lead time slightly above the twelve weeks. The buy-parts do not require additional attention for the design, but also must be ordered before finishing the design phase.
3. For materials with a maximum estimated lead time over eighteen weeks, it can be suggested to hold inventory for Category 1 and Category 2 (i.e., Consumables and Spare items). The materials from Category 1 and Category 3 (i.e., Consumables and Large customized parts), will also have to be ordered before the intended release of PO. The capital investments of €17,587.00 are suggested to be made to achieve a throughput time of four months. All ordered items are held on stock when the PO is cancelled by the customer. The expected inventory costs are €1,758.70, as 10 percent of the capital investment is assumed as inventory costs. These are the components part of Order groups 4, 6, 7, 8, 11, and 14, where possible alternative approaches are more expensive.
4. When Machine-builder X notices problems with the delivery of the laser component (Order group 5) in the future, it is suggested to negotiate with the supplier to be able to consistently achieve a throughput time of four months. Currently, capital investments are not recommended because of the financial risk and the possible delay in the delivery not being critical for the customer of Machine-builder X.
5. For the 'Gas Panel', it is suggested to outsource this sub-module to supplier 'M-114'. For an additional cost of €1,364.51, a full sub-assembly can be delivered within the timeframe of twelve weeks.
6. It is recommended to further evaluate alternative suppliers for multiple purchasing decisions (in Order groups 6 and 11). Costs and agreed lead time need to be evaluated to find out if alternative suppliers would have a beneficial impact on the throughput time.

In conclusion, when the recommendations outlined above are followed by Machine-builder X, the desired throughput time of four months can be achieved. Following these suggestions would result in additional direct costs of €3,123.21 (including inventory costs and costs for outsourcing the 'Gas Panel') and a total capital investment of €17,587.00. For order groups 4, 7 and 14, outsourcing was a possibility. This approach, however, is currently more expensive than ordering before intended release of PO and holding inventory. When these sub-assemblies are further standardized, and the amount of orders are increased, it is possible that outsourcing the sub-assemblies at supplier 'M-144' is more beneficial than what is currently the case. As discussed with supplier 'M-144', this could go hand in hand with keeping an LLI kit (long lead-time item kit). This makes it possible to have the items within the sub-assembly that have a long lead time, on inventory, allowing supplier 'M-144' to deliver the assembled sub-assembly in time. For now, as Machine-builder X is growing, ordering before the intended release of PO is sufficient and less expensive.

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Appendices

Appendix 1: Do-discover-decide

This appendix follows the do-discover-decide format to find all necessary actions to systematically find solutions to the core problem and progress throughout the thesis assignment.

Do

Defining the problem

- Draft inventory of problems
- Make problem cluster identifying core problem
- Investigating characteristics and context of the company

Problem-solving method

- Draft problem-solving approach
- Make stakeholder analysis
- Enlist colleagues that have knowledge on plan of attack stages for help
- Plan interviews with colleagues that have relevant information/opinions
- Plan weekly reflection on project with supervisor
- Provide a theoretical framework on the research
- Make research design
- Get opinions and information from colleagues on supply chain and suppliers
- Get the data from the lead times of the last years (and more data if available)

Analysing the problem

- Transform data in a useable and easy overview
- Make a visual representation of the current supply chain (timeline)
- Make a visual representation of the supply chain that is the norm (timeline)
- Literature study for applicable methods
- Analyse data gathered on suppliers agreed and true lead time

Formulating solutions

- Provide main solution to the core problem
- Provide and evaluate alternative solutions to the core problem

Choosing a solution

- Let the company choose a solution

Implementing the solution

- Make implementation plan (step-by-step) for the solution
- Make a cost-benefit analysis on the method for implementation

Evaluating the solution and report writing

- Analyse and evaluate solution implementation
- Write and combine results into a clear overview in the report

Discover

Defining the problem

- What are causes for a long throughput time?

Problem-solving method

- Who in the company deal with the problems in the supply chain (who has information about suppliers) and can inform me to help answer knowledge problems?

- What are limitations in my research and how can this be expressed in a theoretical framework?

Analysing the problem

- How can the current throughput time of six months at the company be visually represented and how can this be squeezed towards four months?
- What are reasons for late deliveries from the supplier to the company?
- Which suppliers generally have a higher lead time than agreed (negatively inconsistent)?
- What are the key performance indicators to be used for suppliers of Machine-builder X?
- What framework can be used to decrease the negative effect from inconsistent suppliers on the throughput time?

Formulating solutions

- What are the relevant methods for reducing the supplier base?
- How can supplier lead times be estimated more accurately?

Choosing a solution

Implementing the solution

- How can a method be designed, based on the literature, for implementation at Machine-builder X?
- What are the costs and benefits of the methods to be implemented at Machine-builder X?
- How does the implementation affect the throughput time?

Evaluating the solution and report writing

- What suggestions or conclusions can be made from conducting the thesis at Machine-builder X?

Decide

Defining the problem

- Choose the core problem
- What do you consider and what do you ignore within the project?

Problem-solving method

- Who do I involve in the investigation?
- Select data that is relevant for the project.
- Risk assessment: what to do when solving the core problem does not achieve the norm?

Analysing the problem

Formulating solutions

Choosing a solution

- Choose best solution with company (based on criteria and interpretation from stakeholders)

Implementing the solution

- Does the company agree with the implementation plan? Plan implementation and evaluation.

Evaluating the solution and report writing

- Suggest and/or decide with the company which problem to work on next.

Appendix 2: Stakeholder analysis

The following stakeholders are identified within the company:

- COO of the company, supervisor for this project. The COO is responsible for operations in the company, this includes development, production, and service. In the project, the COO has a lot of information and will provide me with a lot of data to answer the knowledge problems and come to results for the project's purpose. He will be the talking point for me and guide me through necessary points in the project cycle. The COO has the most knowledge on the topics I will be working with and will be the most powerful and have the most interest in the project. The priority in communication during this project will be with the COO of Machine-builder X.
- The senior mechanical engineer (SME) has information on material parts made by the company or for example sub-assemblies. This will be important in identifying opportunities for clustering certain materials to one supplier as an example. This stakeholder has mostly interest in the project with the overlap of his functionalities and the desired results of the project.
- The service manager (SM) has a lot of information about the procurement process. This will be important for information about procurement of materials such as materials that have a long lead time. This stakeholder has his influence on the knowledge necessary on the procurement level and will be relatively influential on that aspect.
- The technical account manager (TAM) has information on the total supply chain. This will be important for identifying the whole supply chain and providing a visual representation. The basis of the project is to provide an overview on the process (between customer order and delivery) and this stakeholder has a lot of knowledge on this topic.
- Head of production (HoP) has knowledge of the suppliers. This will be important for identifying opportunities for reducing the supplier base. This will also link with opportunities for outsourcing sub-assemblies for example. The final goal of the project is to reduce the negative effect that inconsistent suppliers have on the throughput time. The idea to cluster suppliers is heavily linked with the functionalities of this stakeholder, meaning high overlap of interests.

The different stakeholders are measured on their power and interest levels as shown in Figure 10.

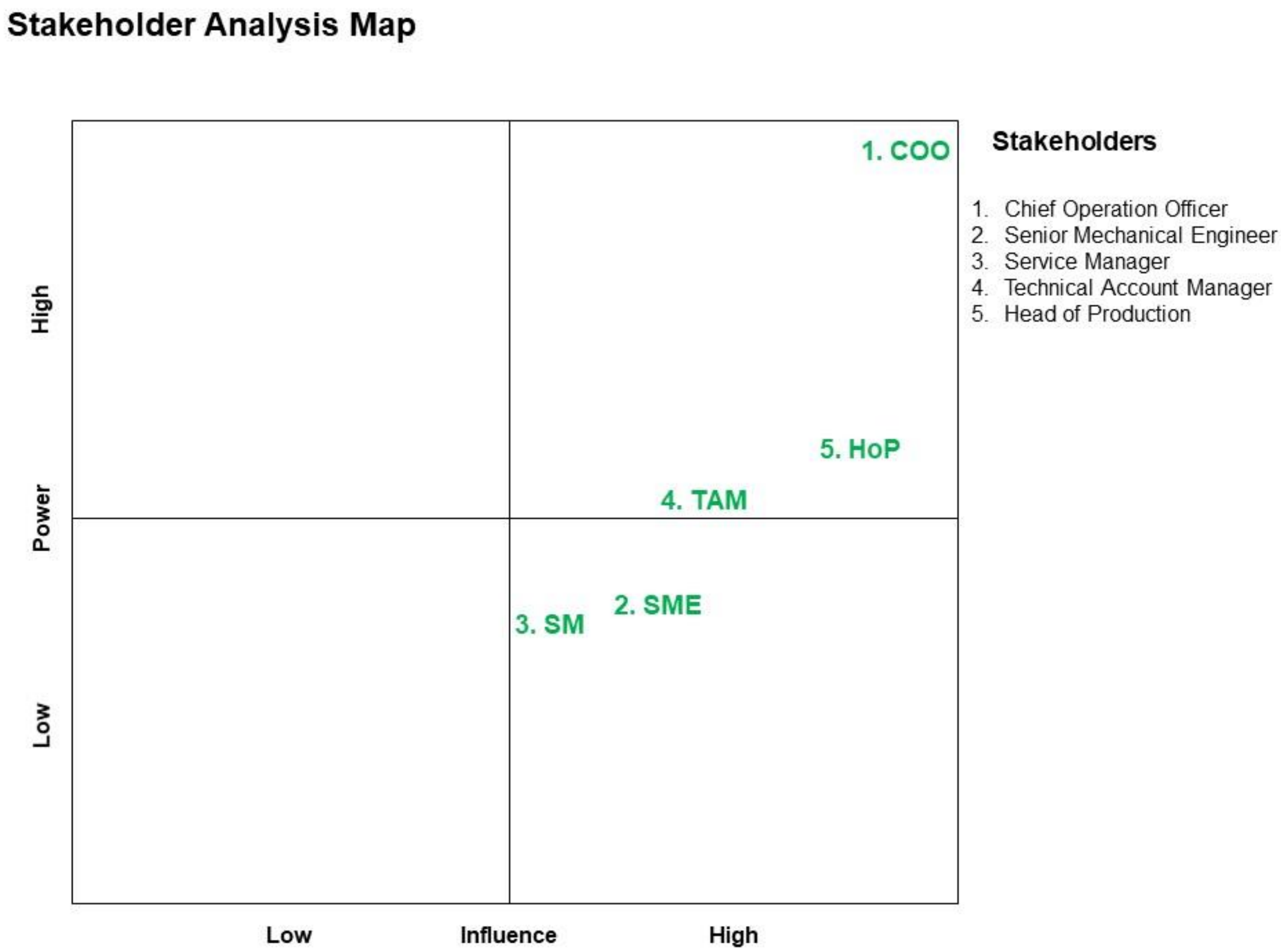

Figure 10: Stakeholder analysis within Machine-builder X ("Stakeholder analysis template," n.d.)

Appendix 3: Order and delivery information

In Tables 20 and 21, order information is given for both machine 11 and machine 15. Here it can be seen that for machine 11, the first materials were ordered 10-05-19 which is around two weeks after PO. The materials are ordered until 30-09-19 which is four months later, even though these particular products did not endanger the timeline, it can be seen that the 'Mirror box' materials were ordered from 22-07-19 and fully delivered at 10-10-19. This is two weeks before the shipment of the machine. The sub-order groups are groups of materials that are similar. The materials are not necessarily ordered simultaneously or from the same supplier, because some of the materials in the component group have to be engineered and some products have a high lead time and need to be ordered as soon as possible.

The 'Mirror box' components are critical parts of the assembly and was one of the component groups that was not fully delivered early. Because of component groups like the 'Mirror box', the assembly is finished late and the shipment date is endangered. Even though the 'Quartz Group' and the 'Laser' were only fully delivered at 18-11-19 and 24-10-19 respectively, these component groups were not critical for the shipment of the machine. When the lead time can be estimated more efficiently for component groups like the 'Mirror box', Machine-builder X might be able to order these products earlier and accelerate the shipment of the machine.

The critical materials necessary before the machine can be shipped, are all delivered before the shipment date. Non-critical materials might be delivered after the shipment, straight to the customer. For finding value in the lead time estimation, it is important to focus on the critical materials, such that the shipment date of the machine can be accelerated.

Machine 11:

Table 20: material order information for machine 11.

Row Labels	# of materials	Earliest order date	Latest order date	Latest delivery date	Max agreed delivery date
"Issues"	**4**	**1-Jul-19**	**22-Jul-19**	**1-Aug-19**	**19-Aug-19**
Sub-modules	**93**	**10-May-19**	**29-Aug-19**	**18-Nov-19**	**25-Sep-19**
Quartz Group	6	29-May-19	2-Jul-19	18-Nov-19	25-Sep-19
Foreline	22	10-May-19	5-Jul-19	9-Oct-19	16-Aug-19
Cooling water	14	6-Jun-19	29-Aug-19	12-Sep-19	19-Sep-19
Miscellaenous	7	5-Jul-19	8-Aug-19	4-Sep-19	29-Aug-19
O-rings	18	2-Aug-19	2-Aug-19	27-Aug-19	30-Aug-19
Baratron tree	5	23-May-19	8-Aug-19	16-Aug-19	29-Aug-19
Gas Panel	19	15-May-19	8-Aug-19	16-Aug-19	29-Aug-19
Pneumatics	2	23-May-19	23-May-19	1-Jul-19	11-Jul-19
Laser	**1**	**6-Jun-19**	**6-Jun-19**	**24-Oct-19**	**12-Sep-19**
OSS & BDM	**65**	**28-May-19**	**10-Sep-19**	**10-Oct-19**	**22-Oct-19**
Mirror box	30	22-Jul-19	10-Sep-19	10-Oct-19	22-Oct-19
General components	35	28-May-19	2-Aug-19	10-Sep-19	6-Sep-19
Tooling	**37**	**1-Jan-19**	**29-Aug-19**	**10-Oct-19**	**26-Sep-19**
Others	**4**	**2-Sep-19**	**30-Sep-19**	**4-Oct-19**	**7-Oct-19**
Droplet Trap Module	**6**	**28-May-19**	**24-Jul-19**	**27-Sep-19**	**30-Aug-19**
Wafer Stage	**40**	**22-May-19**	**6-Aug-19**	**23-Sep-19**	**20-Sep-19**
LEW base w/ gatevalve	26	22-May-19	6-Aug-19	23-Sep-19	20-Sep-19
General components	14	23-May-19	24-Jul-19	10-Sep-19	29-Aug-19
Loadlock	**132**	**22-May-19**	**18-Sep-19**	**20-Sep-19**	**2-Oct-19**
Main loadlock chamber	43	22-May-19	18-Sep-19	20-Sep-19	2-Oct-19
Scara & gripper assy	20	22-May-19	28-Jun-19	16-Sep-19	23-Aug-19
Manual drawer	6	11-Jun-19	9-Aug-19	16-Sep-19	30-Aug-19
Drive assy	32	1-Jun-19	2-Aug-19	10-Sep-19	30-Aug-19

Foreline Loadlock	18	22-May-19	5-Jul-19	4-Sep-19	16-Aug-19
Motion & control	13	28-May-19	28-May-19	4-Jul-19	9-Jul-19
Heater	**21**	**23-May-19**	**5-Jul-19**	**16-Sep-19**	**25-Sep-19**
Frame & Covering	**3**	**31-Jul-19**	**9-Aug-19**	**10-Sep-19**	**9-Sep-19**
Power & Control Cabin.	**15**	**28-May-19**	**30-Aug-19**	**7-Sep-19**	**13-Sep-19**
Main Chamber	**13**	**23-May-19**	**5-Jul-19**	**5-Sep-19**	**29-Aug-19**
Target Module	**20**	**22-May-19**	**6-Aug-19**	**12-Sep-19**	**27-Aug-19**

Machine 15:

Table 21: material order information for machine 15.

Order groups	# of materials	Earliest order date	Latest order date	Latest delivery date	Max agreed delivery date
Sub-modules	**88**	**3-Sep-19**	**7-Nov-19**	**12-Feb-20**	**13-Feb-20**
Quartz Group	5	3-Sep-19	22-Oct-19	12-Feb-20	13-Feb-20
Baratron tree	6	3-Sep-19	29-Oct-19	31-Jan-20	24-Jan-20
Foreline	22	3-Oct-19	29-Oct-19	7-Jan-20	20-Dec-19
Gas Panel	20	3-Sep-19	29-Oct-19	19-Dec-19	16-Dec-19
Cooling water	15	3-Oct-19	29-Oct-19	4-Dec-19	13-Dec-19
O-rings	18	22-Oct-19	25-Oct-19	27-Nov-19	29-Nov-19
Pneumatics	2	7-Nov-19	7-Nov-19	27-Nov-19	5-Dec-19
Laser	**1**	**7-Oct-19**	**7-Oct-19**	**27-Jan-20**	**27-Jan-20**
OSS & BDM	**83**	**1-Jan-19**	**14-Jan-20**	**20-Feb-20**	**17-Feb-20**
Mirror box	47	1-Jan-19	14-Jan-20	20-Feb-20	17-Feb-20
General components	36	1-Oct-19	7-Nov-19	18-Dec-19	17-Dec-19
Tooling	**34**	**18-Oct-19**	**20-Jan-20**	**21-Feb-20**	**9-Mar-20**
Others	**4**	**16-Jan-20**	**17-Jan-20**	**2-Feb-20**	**31-Jan-20**
Droplet Trap Module	**6**	**9-Oct-19**	**29-Oct-19**	**16-Dec-19**	**17-Dec-19**
Wafer Stage	**40**	**30-Aug-19**	**28-Nov-19**	**20-Dec-19**	**19-Dec-19**
LEW base w/ Gatevalve	26	3-Sep-19	28-Nov-19	20-Dec-19	19-Dec-19
General components	14	30-Aug-19	29-Oct-19	16-Dec-19	17-Dec-19
Loadlock	**128**	**3-Oct-19**	**30-Oct-19**	**31-Jan-20**	**24-Jan-20**
Main loadlock chamber	42	8-Oct-19	30-Oct-19	31-Jan-20	24-Jan-20
Scara & gripper assy	21	3-Oct-19	28-Oct-19	23-Jan-20	20-Jan-20
Drive assy	28	8-Oct-19	28-Oct-19	20-Dec-19	17-Dec-19
Foreline Loadlock	19	3-Oct-19	29-Oct-19	12-Dec-19	17-Dec-19
Manual drawer	8	8-Oct-19	30-Oct-19	11-Dec-19	17-Dec-19
Motion & control	10	25-Oct-19	25-Oct-19	5-Dec-19	6-Dec-19
Heater	**26**	**30-Aug-19**	**23-Oct-19**	**12-Dec-19**	**19-Dec-19**
Frame & Covering	**10**	**3-Oct-19**	**26-Nov-19**	**12-Dec-19**	**17-Dec-19**
Power & Control Cabin.	**16**	**25-Oct-19**	**26-Nov-19**	**17-Dec-19**	**24-Dec-19**
Main Chamber	**15**	**30-Aug-19**	**30-Oct-19**	**12-Dec-19**	**17-Dec-19**
Target Module	**17**	**2-Oct-19**	**25-Oct-19**	**12-Dec-19**	**18-Dec-19**

Appendix 4: Applying the method on the order groups

Confidential information

Appendix 5: Supplier ID

Confidential information

Appendix 6: Ranking of suppliers

Confidential information

Appendix 7: Evaluation of thesis results

The aim of this questionnaire is to get feedback on the resulting deliverables and suggestions from this thesis. Statements are formulated based on this goal and are answered by the COO of Machine-builder X, with additional feedback. The feedback is extended by results from a presentation given to all stakeholders. Answers range from 1 to 5 as follows:

1 = Strongly disagree
2 = Disagree
3 = Neutral
4 = Agree
5 = Strongly agree

Additional feedback can be given per statement.

Statement 1:
I intend to make use of the suggestions and recommendations resulted from this thesis.

Answer: 4.5

Additional feedback: The assignment was done for a reason for Machine-builder X as well. The suggestions resulted from this thesis will be used to improve the throughput time.

Statement 2:
This research gave me a better view of the suppliers of Machine-builder X.

Answer: 4

Additional feedback: The COO himself already had quite a good understanding of the suppliers. When new employees will be hired for example for sourcing activities, a lot of information from this thesis can be easily used for knowledge transfer. When more strategical decisions will be made in the purchasing department, the results from the thesis can be used to get a good overview of the suppliers.

Statement 3:
This research will help to achieve the norm (throughput time of four months).

Answer: 3.5

Additional feedback: The results from this thesis will help to achieve the norm, however Machine-builder X is still very dependent on ‘M-144. When agreements are made with ‘M-144’, the throughput time will still depend a lot on the supply performance of ‘M-144’. Further research will be necessary, including for example a focus on the design phase.

Statement 4:
I intend to make use of the lead time estimation tool resulting from this project.

Answer: 4

Additional feedback: The goal is that other employees will make use of this tool when this job is given to (new) employees. It will be used, maybe with some additions or changes.

Statement 5:
This research gave me a better insight into the process of building a machine, in terms of the phases and influences of different factors on the throughput time.

Answer: 3

Additional feedback: Will be a good use as a reference document. Some insights of this thesis were some confirmations or reminders for Machine-builder X.

Statement 6:
The designed method was an effective approach for achieving the goal of this thesis.

Answer: 3

Additional feedback: Solutions were found for a lot of different possible problems. The deep research of the construction of the machine made it possible to be creative in different kinds of solution strategies, which is what Machine-builder X is looking for. Where this thesis was focused on the suppliers and the lead times, it would also be beneficial to focus on the design phase. Here it would be possible to improve the efficiency to start ordering even earlier for example.