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Rough-cut Capacity Planning for a Supplier and Supplier Network

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Department of Industrial Engineering & Innovation Sciences
Eindhoven University of Technology

Rough-cut Capacity Planning for a Supplier and Supplier Network

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Master's Thesis

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Abstract

The research is executed at ASML, the world's leading manufacturer of photolithographic machines used to produce semiconductor chips. ASML wants to increase its capacity because the demand for lithography machines has risen, but currently, ASML experiences an undesirably high increase in delivery delays from their suppliers resulting in production stops at ASML and increased workload for the Supply Chain department. One of the strategies to act more proactively and prevent delivery delays instead of mitigating them is to map and track the capability of the suppliers. Even though ASML proactively assesses supplier capabilities, the number of material escalations is growing, indicating that the 4M-analysis currently being used might not be reliable with the growth of ASML.

This research develops a model and standardized method for Rough-Cut Capacity Planning on men and machines for a supplier and a supply chain. This model will provide transparency and visibility in terms of available options to increase/decrease capacity and trigger the discussions and scenarios to be evaluated every quarter. The model incorporates lead time offsetting, hiring and firing capacity, safety stock, and work control to obtain a capacity plan. A method for including capacity as a norm capacity is introduced to include fluctuations in capacity (scheduled downtime, holidays, etc.), something that to the best of our knowledge we currently do not see in the literature. The model is tested on different scenarios with a synthetic data set on supplier and supply chain structures.

Management summary

This master thesis project is executed at ASML, the world's leading manufacturer of photolithographic machines used to produce semiconductor chips. 85% of the parts in ASML's machines are produced by their suppliers. The Sourcing & Supply Chain department is responsible for guiding this complex network. The department monitors and maintains this network to ensure the right materials are delivered at the right time. ASML wants to increase its capacity because the demand for lithography machines has risen. The steep demand growth poses a challenge not only to their factory but to their entire N-tier supplier landscape on their capability. Insufficiencies in ASML's supply chain will significantly impact output and customer service levels, affecting both financial results and customer satisfaction. Currently, ASML experiences an undesirably high increase in delivery delays from their suppliers resulting in production stops at ASML and increased workload for the Supply Chain department.

One of the strategies to act more proactively and prevent delivery delays instead of mitigating them is to map and track the capability of the suppliers. On a quarterly basis, ASML conducts a Capacity Investigation of a selection of suppliers called the 4M-analysis. In the Capacity Investigation, suppliers are asked, to assess capacity on Men/Machines/Methods/Materials on a four year outlook. Even though ASML proactively assesses supplier capabilities, the number of material escalations is growing, indicating that the 4M-analysis that is currently used might not be reliable with the growth of ASML. One of the problems is that the response that ASML receives on the 4M-analysis varies widely. Some suppliers deliver an in-depth analysis of their machine availability, while other suppliers only confirm without any research backing their claim.

The main objective of this research is to develop a model and standardized method for rough-cut capacity planning. The focus will be on 2 of the 4M's, namely, men and machines. The main research question is formulated as follows:

How to design a standardized method for suppliers to perform their Rough-Cut Capacity Planning of their Men and Machines?

The thesis is divided into three parts. **Part I** describes the current way of working on the 4M-analysis at the supplier of ASML. In **part II** we propose a model to assess the internal capacity of a supplier and a supply chain. **Part III** is devoted to testing the model on various situations and to gaining feedback on the proposed model.

Part I focuses on gaining insight into the current way of working on the 4M method. The information is gathered by interviews with suppliers of ASML and Logistics Supplier Manager (LSM)ers. We got an understanding of who performed the analysis and what the processes are that the supplier uses to get their information. We observed that every supplier had their own way of working on the 4M-analysis. We found some insights for ASML around the 4M-analysis, like the Where-Used and Enriched Demand is often missing or incomplete. The qualitative aspects of the supplier interviews were used to support the development of the model in part II. The quantitative aspects were used to determine reasonable values for the cost parameters such as holding cost.

In **part II** we propose a model for aggregate capacity planning in the context of S&OP. We made use of linear programming because it is a time-efficient way of obtaining results. We use a rolling schedule as a method to incorporate the impact of stochastic end item demand and stochastic capacity. In the model, we include item lead times, hiring and firing capacity, safety stock, resource lead time, and workload control. We included capacity slack in the model to cope with uncertainty. A method for including capacity as a norm capacity is introduced to include fluctuations in capacity (scheduled downtime, holidays, etc.), something that to the best of our knowledge we currently do not see in the literature. We also included an extension to the

model where a supply chain could be modeled. The goal of the output model is twofold. The first goal is to check whether the supplier has enough capacity to produce the items from the forecast that is given. The second goal is to give suppliers insight into their capacity planning.

The interface of the model is a spreadsheet, as it is the industry standard and most known. The input of the model will be split into three categories: input men, input machines, and input items. (see figure 0.1) The inputs will then be loaded into a Python-based model, and the output will be shown in a spreadsheet. The in- and output files will be separate files because the input file contains sensitive information about the supplier that they do not want to share with ASML. The output of the model will show the capacity plan per resource. This capacity plan will provide transparency and visibility in terms of available options to increase/decrease capacity and trigger the discussions and scenarios to be evaluated in every quarter.

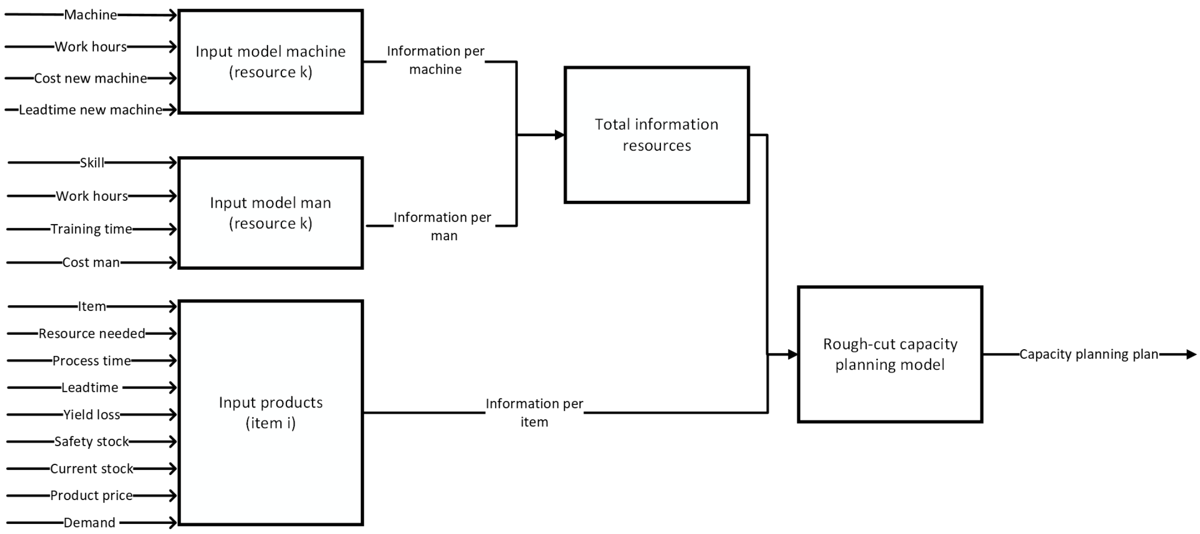

Figure 0.1: Schemes of input model

In **Part III** we discuss the results of implementing the model discussed in part II. We used a synthetic data set to test different scenarios. The different scenarios are used to verify the proper functioning of the model. The model can incorporate lead time offsetting and can deal with seasonality in demand and capacity. We applied the model to different supply chain structures and we saw that the model works for series systems, parallel systems, and multi-tier systems.

We did a second round of interviews with suppliers and from that concluded that the model adds value. The model provides value for the supplier as well as ASML with transparency and visibility in terms of where the capacity plan is based upon, due to the standardization. Next to that, the method is standardized which gives the suppliers a frame of reference for what ASML wants to see in their analysis, which is something that we identified as a problem in the first interviews. It also gives ASML the information if a supplier is able to comply with their forecasted demand. The model takes into account lead time offsetting of items, making it easy to implement into a supply chain. Suppliers that are nested in the supply chain could benefit from this as they have difficulties as multi-tier suppliers to get information about the forecasted demand from ASML. Improvements to ASML's and the supplier's IT infrastructure are required to make the model more user-friendly and ready for implementation.

Preface

I proudly present my graduation project, which is the last step in completing my Master's Degree in Operations Management and Logistics at the Eindhoven University of Technology (TU/e). This thesis marks an end to my eight years of studying, where I have come from a bachelor's degree in applied physics to a master's degree in industrial engineering. It does not only mark the end of my time at TU/e, but also my time at the ASML. Therefore I would like to express my appreciation to those who assisted me during my master's thesis.

First of all, I would like to express my gratitude to my mentor and first supervisor Ton de Kok. I enjoyed our biweekly meetings, your knowledge, and positivism really inspired me. After our meetings, I would always leave with more energy than I came in with.

My graduation project would not have been possible without ASML. Therefore I would like to thank ASML for the opportunity to be a small part of the company these past months.

I would like to thank my family and friends for supporting me in pursuing a Master's Degree. Furthermore, I would like to thank my boyfriend for his unwavering support and encouragement. Finally, I would like to thank Vera, I am glad we got to do the Master's together, and I am proud of us for both making it.

Maureen van Kempen

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List of Abbreviations

12NC 12 digit Numerical Code

BOM Bill of Materials

CME Critical Material Escalation

COPD Customer Order Decoupling Point

CRP Capacity Requirement Planning

CSC Critical Supply Chain

DUV Deep Ultra Violet

ERP Enterprise Resource Planning

EUV Extreme Ultra Violet

FCFS First come first serve

IBP Integrated Business Planning

ISCP Integral Supply Chain Plan

LSM Logistics Supplier Manager

MES Manufacturing Execution System

MLCLSP Multi-item Multi-level Capacitated Lot Sizing Problem

MPS Master Production Schedule

MRP Material Requirements Planning

OEE Overall Equipment Effectiveness

QLTCS Quality, Logistics, Technology, Cost and Sustainability

RCCP Rough-Cut Capacity Planning

SAT Supplier Account Team

SCM Supply Chain Management

SCOP Supply Chain Operations Planning

WIP Work in Progress

1 Introduction

This research project has been executed at ASML. Therefore, a summary of the company and relevant context will be given. The Supply Chain Model of ASML will be given. After that, an introduction to ASML's Supply Chain Management (SCM) and the strategy to asses their suppliers on their long-term capability will be given.

1.1 Company description

ASML is the world's leading manufacturer of photolithographic machines used to produce semiconductor chips. The company was founded in 1984 as a joint venture between Philips and ASM International. ASML currently has more than 39000 employees and had net sales of 21.2 billion euros in 2022 (ASML, 2023). Its headquarters are located in Veldhoven, and its operations are spread across Europe, Asia, and the US.

ASML develops, manufactures, and services lithography machines. The machines work by printing several layers of patterns on a wafer of semiconductor material. Together, these printed layers form a network of transistors that results in a chip. The smaller these transistors can be made, the more structures can be printed on a surface, thus making the chip more powerful.

The company produces two main types of machines: Twinscan (N)XT and Twinscan NXE. Twinscan (N)XT uses a Deep Ultra Violet (DUV) light source and has a resolution down to 38 nanometers, and a maximum throughput of 300 wafers per hour. Twinscan NXE uses new Extreme Ultra Violet (EUV) light source technology. The NXE machines have a resolution of just 13 nanometers and process up to 160 wafers per hour. Additionally, ASML offers metrology inspection systems as well as refurbished systems.

85% of the parts in ASML's machines are produced by their suppliers, such as Carl Zeiss and VDL. Their supply chain is a complex multi-tier network with over 5000 suppliers. The Sourcing & Supply Chain department is responsible for guiding this complex network. The department monitors and maintains this network to ensure the right materials are delivered at the right time.

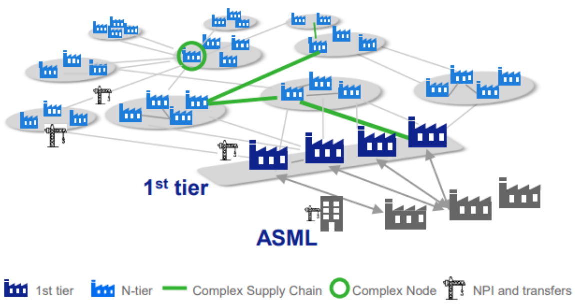


Figure 1.1: Supply chain of ASML

1.2 Supply chain ASML

As mentioned previously, ASML has a complex network of suppliers. ASML has multiple suppliers (1^{st} tier suppliers), suppliers also have their suppliers (2^{nd} tier suppliers), with that logic 3^{th} and 4^{th} tier suppliers exist as well, creating an entire N-tier network. The 1^{st} tier suppliers have a direct influence on material availability, while the 2^{nd} (and higher) tier suppliers have an indirect impact on material availability. Figure 1.1 gives an illustrative example of such a network. Because ASML purchases the majority of its components rather than manufacturing them in-house, it has a diverse network of suppliers. The diversity in the ASML network comes from the different kinds of suppliers in terms of the company's size and their various products, like mechanical and electrical products.

The supply chain planning of ASML can be divided into three levels: Strategic, Tactical, and Operational. Operational planning focus on scheduling prioritization, WIP tracking, and escalation planning and is done based on a weekly Material Requirements Planning (MRP) run. The tactical level focuses on the forecast; the demand plan is updated monthly based on the latest customers' orders book and factory loading. The tactical planning is done on a 12 to 18 months time horizon. The last layer is strategic planning, done quarterly to assess long-term capacity planning. The strategic planning is done on a time horizon of 0.5 to 3 years. An overview of planning levels within ASML can be found in table 1.1. This research will focus primarily on strategic planning, where comprehensive term capability management takes place.

Table 1.1: Overview planning levels

Planning level	Focus	Review time	Planning horizon	Activities
Strategic	Capability	Quarterly	0.5 - 3 years	Lead time assessment and capability management
Tactical	Forecasts	Monthly	12 - 18 months	Supply capacity loading and decoupling
Operational	Orders	Weekly	0 - 4 weeks	Order and demand and supply management

1.3 Supply chain management

ASML recognizes Critical Supply Chain (CSC) and Complex Nodes in their supply chain to improve and monitor together with their suppliers. Currently, the number of CSC is more than 100 suppliers, including Carl Zeiss, Prodrive Technologies, KMWE, and Neways. ASML describes their collaborations as: *'Leveraging ASML's and suppliers' competencies to optimize performance, flexibility, and risk exposure through seamless, open, and trusted collaboration, ultimately working as if it were one enterprise.'*. As part of the mission to 'guarantee material availability at the right quality and cost for our customers, today and for the future', the objective of the Complex Supply Chain process is to prepare suppliers by securing module supply chain capacity for mid- and long-term integral demand.

To become a CSC for ASML the supplier has to have the following characteristics:

- Long lead time item (> 26 weeks)
- High cost price (> 200 k€)
- Low/unstable yield
- Complex part (Complex process flow/multiple outsourced steps)
- Major new product introduction/ramp coming up
- Complex demand drivers
- Historical escalations

When a supplier becomes a CSC, a Supplier Account Team (SAT) is formed to improve supplier performance in the five leading business aspects: Quality, Logistics, Technology, Cost and Sustainability (QLTCS). The SAT then reviews default targets, decides whether a need exists to propose custom targets, and reviews this with the Category Manager. The next step is to send a capability self-assessment survey to the supplier, which can be used to resolve a difference in the supplier and SAT perception of process maturity. Based on the self-assessment survey, the SAT determines and prioritizes the gaps. ASML then comes up with an agreement on actions and the timing of the activities, which is discussed with the supplier to form cooperation. The joint account team of ASML and the Supplier formally accept the action plans, and the actions will be reviewed periodically (at least quarterly). During the year, SAT receives improvement plan updates and requests to close improvement plans. ASML expects the supplier to update the sourcing lead if an improvement plan can be closed. The ASML lead auditor verifies the gap closure and, if agreed, closes the improvement plan and updates the supplier capability assessment score. The SAT will share the successful closing with the supplier.

Suppliers can transfer from a CSC to a normal supplier if they meet the following requirements:

- Lead time Capability ok and no open actions on mid- and long-term
- Stable part: On time in full > 85% and no structural vendor undesired schedule out
- No open items on technologies or major redesigns foreseen
- Correct SAP demand and forecast and a clear insight at supplier mid- and long-term required capability

1.4 Capacity management suppliers process

Every CSC is assessed quarterly on their capabilities. This quarterly analysis aims to have a 3-year horizon maximum move rate for capacity planning/investigation. The process for capacity management is given in figure 1.2.

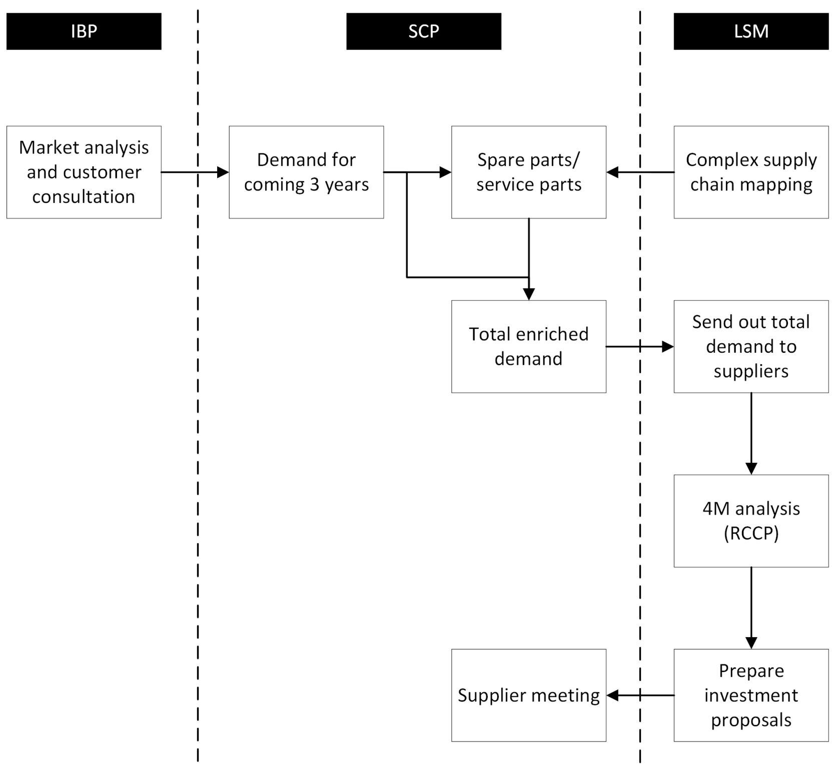


Figure 1.2: Standard quarterly process to share infrastructure capability and receive formal feedback on feasibility capability request

The process begins with market analysis and customer consultation on demand for the upcoming 4 years from Integrated Business Planning (IBP). With that, the so-called 'Red table' is formed. This is an overview of the estimated maximum demand per 12 digit Numerical Code (12NC). The Red table and the enriched demand will be sent to the supplier, who is asked to perform a 4M analysis. 4M stands for men, machine, Methods, and Material. ASML asks to confirm that the supplier can follow their maximum demand in these 4 regions to confirm their Rough-Cut Capacity Planning (RCCP). Figure 1.3 presents a more detailed flowchart with swim lanes.

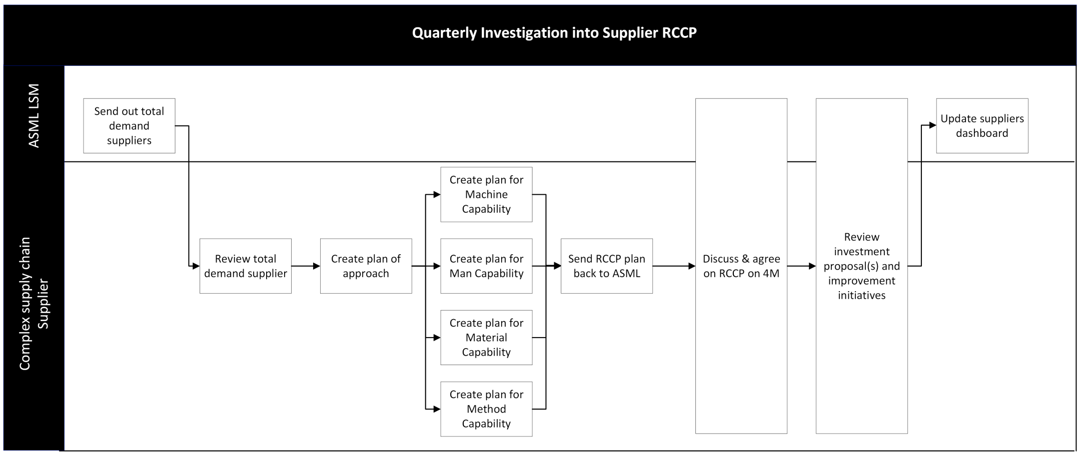


Figure 1.3: Swim lane diagram of quarterly 4M analysis process

We looked at medium-sized to large-sized companies to determine how their process on the 4M analysis is performed. The size of the company in this context matters because smaller companies might not have separate roles, for example, demand planner and production planner. The demand planner at the supplier is usually in the lead of the 4M analysis and, depending on the analysis consults with the production planner, supply chain planner, quality engineer, or operations engineer. Inputs of the 4M method also depend on the analysis. For example, machine inputs could include tooling, equipment, machine capacity, and other customer demands. The men analysis's input might include holiday profile, total demand, and available resources. Machine and men have similar inputs and resources needed to perform the analysis. The material analysis is about material availability in the supply chain of the supplier inputs can be other customer demand and material availability. In material analysis, controls such as lead times, inventory levels, and planning methodology are essential to have a complete analysis. Methods focus more on resources to support the making of the product inputs of this analysis, such as test strategy, production methods, and quality performance.

The analysis intends to detect future problems resulting in supply chain abruption. Then, capacity details will be shared with LSM via 4M assessment. Based on the assessment outcomes, an Integral Supply Chain Plan (ISCP) meeting will be initiated to check whether follow-up tasks or proposals need to be made to ensure the supplier can fulfill the maximum demand. The quarterly results will then be put into a dashboard to track the progress of the 4M analysis and the lead time capability.

According to the 4M analysis, the supplier's risk will be determined. This is done by assigning a color code to each of the 4M's. Four colors, each with increasing risk: Green, Light Green, Yellow, and Red. More information about the definitions of the colors is given in appendix A. Based on the 4M's colors, the supplier gets an overall color. For example, if a supplier scores yellow on 2 of the 4M's and two light green, the supplier's color will be yellow and thus will be monitored more closely compared to when it has a green color. If, after a 4M analysis, a supplier has a light green, yellow or red color, the assessment of the supplier will be monthly.

The monthly process is in place to monitor the supplier more closely. Suppose a supplier has a red and/or yellow color. In that case, the SAT will work closely with the supplier to investigate opportunities to get to a state where the supplier is confident that they can deliver the product in the future. This can mean that ASML looks at the investment of new machines at their supplier or reviews design changes that can improve the lead time of a product.

1.5 Outline

The remainder of this thesis is structured according to the methodology proposed in section 2.6. The thesis will consist of three parts, part I is the analysis and diagnostics, part II contains the modeling, and part III contains the learning and evaluation. In section 2 we will discuss the problem context and solution direction. Section 3 discusses the current way of working on the 4M analysis at suppliers. A theoretical background on the problem will be discussed in section 4 and with the input from the supplier interviews and the theoretical background a model will be proposed in section 5. The model will be tested on different scenarios in section 6 and the evaluation of the model by sensitivity analysis and feedback from the supplier will be given in section 7. The final conclusions and recommendations are discussed in section 8. Finally, in section 9 we will reflect on this thesis including its academic implications, limitations, and recommendations for future research.

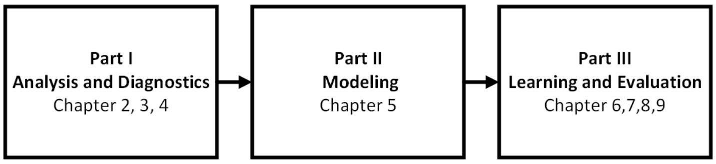


Figure 1.4: Outline of this thesis combined with research approach

PART I

ANALYSIS AND DIAGNOSTICS

2 Problem context

In this section, the problem context is elaborated on and discussed. The problem context will be divided into three parts: problem description, problem analysis and problem diagnostics. Consequently, the research questions are will serve as a basis structure of the thesis. Finally, the scope of the research will be given.

2.1 Problem description

ASML wants to increase its capacity because the demand for lithography machines is risen. The steep demand growth poses a challenge not only to their factory but to their entire N-tier supplier landscape on their capability. Insufficiencies in ASML's supply chain will significantly impact output and customer service levels, affecting both financial results and customer satisfaction. Currently, the Supplier Operations Department sees an increase in delivery delays caused by N-tier material availability imposed by the direct suppliers. If production output might be at risk, a Critical Material Escalation (CME) process is initiated. The CME process knows three levels, with increasing urgency, as shown in figure 2.1.

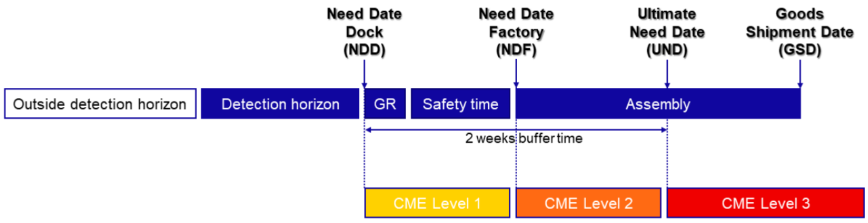


Figure 2.1: Critical Material Escalation (CME) process

The number of CMEs has increased by a factor of eight in the first half of 2022, affecting logistical performance and requiring significant management attention over all sectors within ASML. CMEs are requiring a lot of time and thus are expensive, some supplier deliveries even led to a production stop at ASML. ASML foresees that the trend of supplier issues is only going to grow ASML want to increase their demand.

To summarize, the problem statement is formulated as follows:

Problem statement: *'ASML experiences an undesirably high increase in delivery delays from their suppliers resulting in production stops at ASML and increased workload from the Supply Chain department.'*

2.2 Problem analysis

The increase of supplier delays does not only happen to the CSC but the recent past has shown that even simple parts like screws can cause huge issues. As a result of these supply chain developments, ASML wants to investigate how to coordinate or manage N-tier suppliers more centrally and proactively. One of the strategies to behave more proactively and prevent CMEs instead of mitigating them is to map and track the capability of the suppliers.

On quarterly basis, ASML conducts a Capacity Investigation and shares a 'Move-rate Letter' with their 1st tier suppliers that are CSCs, containing a 3 to 4-year outlook on machine build starts per platform and more extensive field upgrades. Suppliers are requested to confirm their capacity outlook and advised to use 4M-Methodology to assess capacity on men/machines/methods/materials. The supplier provides proof of its capabilities or an improvement plan to close an existing gap, in consultation with the Logistic Supplier Manager (LSM) of ASML. This process is explained in more detail in section 1.4. Even though ASML proactively assesses supplier capabilities, the number of escalations is growing, indicating that the 4M-analysis might not be reliable.

Problem analysis: *'Even though ASML proactively assesses supplier capabilities, the number of escalations is growing, indicating that the 4M-analysis might not be reliable.'*

2.3 Problem diagnostics

To indicate the causes of the unreliable 4M-analysis, a cause and effect diagram is made, which can be found in figure 2.2. From the cause and effect diagram, two main causes are identified from ASML's perspective.

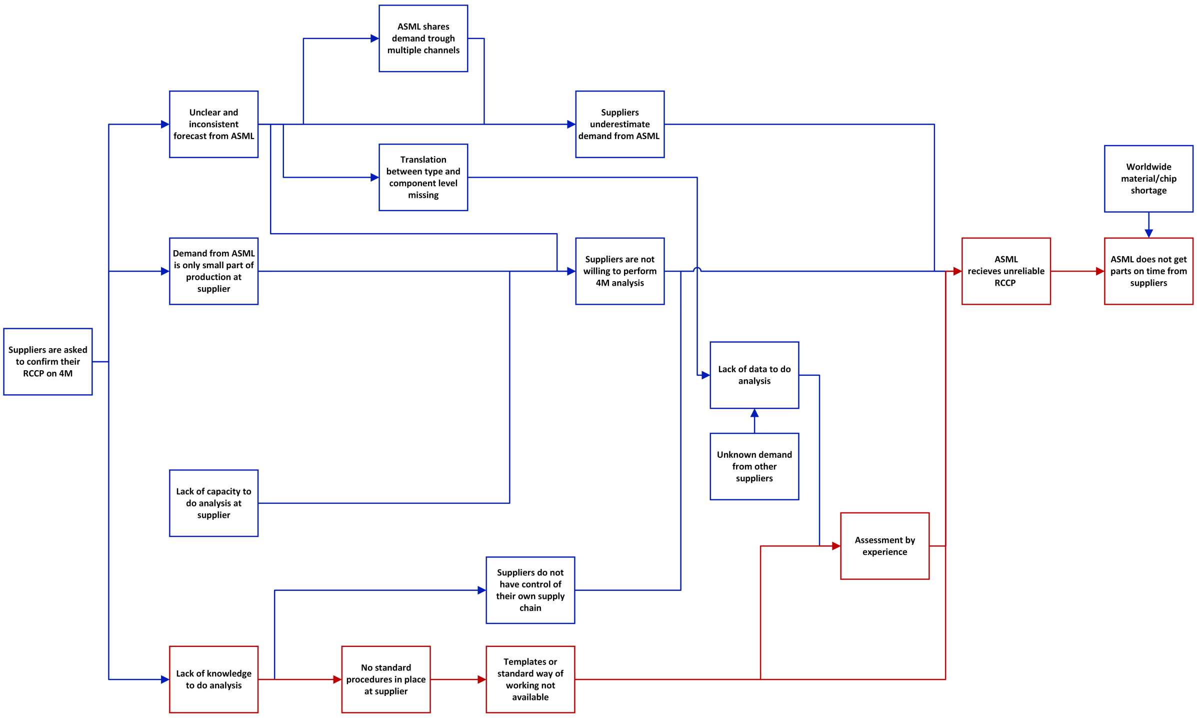


Figure 2.2: Cause and effect diagram

The first main cause of suppliers' unreliable RCCP is that the forecast of ASML is often unclear and inconsistent. ASML shares its forecast on a strategic level and its demand planning on the tactical and operational levels. The strategic demand is the maximum capacity ASML wants to reserve, so suppliers expect it to be lower than the actual demand. This also happens in reality because the tactical demand tends to be lower than the strategic forecast.

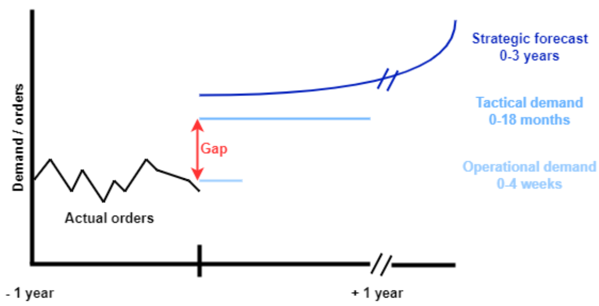


Figure 2.3: Forecast versus actual demand

However, the problem shows when the operational demand is shared; here, the demand in extreme cases is 50% of the tactical demand. A visual representation of this problem is shown in figure 2.3. Suppliers underestimate the demand from ASML because they notice this trend and do not want to reserve capacity if it is unused. The problem with this is if one supplier underestimates the demand and thus, in the future, does not deliver on time, ASML cannot achieve the planned growth.

The second main cause of the unreliable RCCP is the lack of knowledge to do the analysis. This second main cause, as indicated in red in figure 2.2, will be the focus of this research. One of the problems related to this cause is that the response received by ASML on the 4M-analysis varies widely. Some suppliers, for example, deliver an in-depth analysis of their machine availability, while other suppliers only confirm without any research backing their claim. This can be because suppliers, especially small businesses, do not have procedures to check their capacity periodically. These procedures can be an ERP system, general information about machine utilization or material availability. Suppliers also lack the methodology to translate the demand into capacity requirements and are therefore not rigorous in their analysis of the 4Ms. Suppliers do not have a standard way of working and, therefore, therefore may not know where to start on an investigation resulting in a wide variety of responses.

Problem diagnostics: *'Suppliers do not have a standard way of working and, therefore, may not know where to start on an investigation resulting in a wide variety of responses.'*

This research will focus on providing the supplier with a standard way of working to asses their 4M-analysis. The goal of this is to prevent assessment by only experience (without data) and having an unreliable RCCP, as indicated in red in figure 2.2. From the cause and effect diagram, it can be seen that 'no standard procedures in place at supplier' is also an input for assessment by experience, but this is out of scope since we are working from ASML's perspective and not the supplier's. The same holds for the 'lack of data to do analysis', ASML can provide the correct information but cannot make sure that other customers of that supplier do the same, and thus it is out of scope.

2.4 Research questions

The main objective of this research is to develop a model and a standardized method for rough-cut capacity planning. The focus will be on two of the 4Ms, namely, men and machines. To address the problem statement, the main research question is formulated as follows:

How to design a standardized method for suppliers to perform their Rough-Cut Capacity Planning of their Men and Machines?

To answer the research question, the research has three main parts. The analysis and diagnostics are partly done in this proposal but will be investigated further in the project. The research questions relating to those three main parts are formulated as follows:

1. Analysis and diagnostics
   - 1.1 *How do suppliers of ASML currently determine their capacity on men and machines?*
   - 1.2 *What methods exist in the literature for assessing the capacity of suppliers and their network?*
2. Modeling
   - 2.1 *How can a framework be made where suppliers can be standardized on their rough-cut capacity plan?*
   - 2.2 *How is a standardized framework, where suppliers' rough-cut capacity plan can be checked, structured?*
   - 2.3 *How can a rough-cut capacity plan be made for a supply chain?*

3. Learning and Evaluation

    3.1 *What are the results of using a rough-cut capacity model on synthetic data?*

    3.2 *What are the results of implementing a standardized rough-cut capacity plan at a supplier?*

2.5 Scope

This project should focus on Rough-cut capacity planning, which includes two of the 4M components: men & machines. The focus is on the 2Ms because the two are linked together in the analysis and for the project's scope. This research will focus on high-level capacity assessment (strategic planning) with a time frame of one to four years, where the Red Table will act as a starting point. The method should be reviewed by at least two suppliers, preferably one 1^{th} tier supplier and one 2^{nd} tier supplier.

2.6 Project approach

Developing a quantitative model to solve an operations management problem is central to this project. Bertrand and Fransoo (2002) have an overview of quantitative model-based operations research. They discuss a model introduced by Mitroff et al. (1974), which they describe as a seminal article on methodology in operations management research. This methodology will be used because it focuses on the solution design process, which is central to this research. Unlike more generic methods, such as the problem-solving cycle from Aken van and Berends (2018), the problem definition and diagnosis are not part of the research cycle. Therefore the problem-solving cycle (Aken van and Berends, 2018) will be implemented with the operations management research model Mitroff et al. (1974), which is given in figure 2.4.

The problem-solving cycle consists of five steps: problem definition (I), analysis and diagnosis (II), solution design (III), intervention and evaluation (IV), and learning (V). In the research model used in this project, the solution design and intervention step will be substituted for the Mitroff et al. (1974) model. The model of Mitroff et al. (1974) consists of six phases: conceptualization, modeling, model solving, implementation, feedback, and validation. The problem-solving cycle starts with a problem definition found in section 2.1. The next step of the cycle is analysis and diagnostics, which can be partly seen in this research proposal but will be mainly covered in the thesis. After a diagnosis has been made, a conceptual model will be made based on the problem situation. The conceptual model will include variables, but their relationship will be determined in the scientific model. The scientific model will be validated with the problem using a synthetic data set. Feedback on the model will be obtained. At least two suppliers will be asked to provide feedback: a 1^{th} tier supplier and one 2^{nd} tier supplier. When returning to the problem-solving cycle, results will be reflected. The problem-solving cycle and the operations management research model are considered iterative processes; thus, the cycles can be executed multiple times.

The research will consist of three parts: analysis and diagnostics (I), building modeling (II), and learning and evaluation (III). Figure 2.4 will guide how to go through these steps. First, a framework will be determined: analysis and diagnostics in figure 2.4. This will be done by assessing how suppliers currently determine their capacity on men and machines. The information will be retrieved by interviews with LSMers and suppliers and will guide the modeling. Next, to determine the current state of the way of working, a literature review will determine the critical characteristics of RCCP on men and machines. Research into planning models will also be done, which will be input for the next phase.

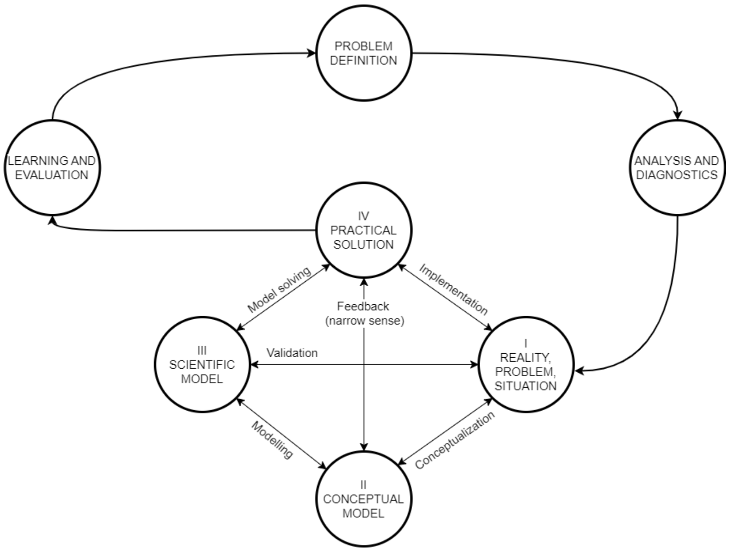


Figure 2.4: Problem solving cycle by Aken van and Berends (2018) and the operations management research model by Mitroff et al. (1974)

The next phase is building a quantitative model, where the operations management cycle by Mitroff et al. (1974) will be used as a guideline. The first step will be conceptualizing a model and choosing to include or exclude variables. In the conceptualizing phase, a framework will be made to standardize suppliers. Then, a scientific model will be built by determining the relationship between variables. This scientific model will then be validated by taking applying the model to a synthetic data set. After the model is validated, the next phase will be to build a standard method with that model, for example in, Excel or Python.

The last phase is learning and evaluation. Here we aim to prove that the model can be used in the 4M method. This will be done by creating synthetic data and evaluating the model. Next to that, feedback will be obtained from the supplier and the LSMer on the user-friendliness and applicability.

Finally, we will summarize the findings, remark on them, and provide suggestions to ASML.

3 4M-analysis at suppliers

In this section, we aim to answer the research question *1.1: How do suppliers of ASML currently determine their capacity on Men and Machines?*. The goal of the supplier interviews is threefold. First, we aim to determine the current status of how suppliers perform the 4M-analysis. This input will guide modeling as we establish a base of what suppliers are capable of in the 4M-analysis. Second, in the interviews, the supplier will be asked what inputs and outputs they currently have to perform a 4M-analysis. These will serve as an assumption on the model parameters we will describe in section 5.2. Finally, we want to make the model suitable for the suppliers' capabilities in order to boost their willingness and precision of the 4M-analysis, as the suppliers perform the analysis.

3.1 Supplier selection

Four variables influenced the selection of suppliers to participate in the interview process: readiness to collaborate, geographic proximity, they are in the supplier cluster 'Mechatronics and electronics', and they have done the 4M-analysis at least once. The readiness to collaborate has resulted in selecting suppliers with whom ASML has well-evaluated, long-term partnerships, or suppliers participating in LCB's High-Tech Supply Chain Excellence Program. A face-to-face interview was recommended to encourage open and informal information exchange, driving the second criterion. Vendors with a long-term relationship with ASML are predicted to be more eager to discuss how they proceed with the 4M-analysis. However, this could introduce bias. Due to confidentiality, the suppliers that were interviewed will not be named in this thesis.

3.2 Interview outcomes

In this section, we will discuss the outcomes of the supplier interviews. First, a general remark on the execution of the 4M-analysis will be given. Next, the in- and outputs that the suppliers use to execute the 4M-analysis will be explained. Lastly, a few general remarks are given that results of the interviews.

3.2.1 Execution of 4M-analysis

Out of the four suppliers that were interviewed, three sent their analysis. The three 4M analyses were all different in how they were performed and the data they showed. In this section, the differences and similarities in execution will be summarized.

Determining a capacity is dependent on the production plan. A distributor's capacity, for example, is restricted mainly by the delivery performance of its suppliers, as well as warehouse and storage space. An integrator is someone who, unlike a component manufacturer, is more likely to be bound by (specialized) human resources. In contrast, a component maker is first constrained by capital goods and raw material availability. The three companies interviewed were capital goods companies, which are also the main focus of the 4M-analysis for ASML. The findings about the way companies execute and present their analysis are summarized below:

- All three the 4M analyses were presented in a PowerPoint format.
- Only one of the three gave details about their calculations and how they performed the analysis. The other two only showed the end result of their calculations.
- Two suppliers choose to use a graphical way of showing their capacity. They did this with figures of capacity versus demand with bar charts or graphs.
- There were two suppliers that had sister companies, so treated their sister companies as their own suppliers and did a separate capacity analysis on each of them.
- Two suppliers used their own calculations in Excel, and the other supplier calculations in their own PowerBi.
- One supplier showed the capabilities of their capacity on the component level and resource level. Two suppliers showed the capabilities of their capacity only on their resources.

The suppliers indicated that there was no single way of working that ASML requested, and that the direction of the analysis was also dependent on the LSMer that was currently working with the supplier. From the analysis shared with the input of LSMers, the best practices of these outcomes will be used to create the model, interface, and output later.

3.2.2 Input and output variables of Men and Machines

In the interviews, the suppliers were asked to give their inputs on which they based the analysis. This was done to assume the supplier and the supply chain characteristics. These characteristics will be used to determine the model parameters in chapter 5.2. The same holds for the output, but this will later be used to form the model's output using best practices. In this section, the findings of the input and output variables will be summarized.

During the interviews, the suppliers were questioned about the inputs they utilized, who helped them with the analysis and the systems they depended on to obtain the required data. To gain a comprehensive understanding of the analysis, the providers were requested to give details not only on the tools and technology used but also on the techniques and resources applied.

In the analysis, most of the time, the Demand Planner or Integrated Business planner is in the lead. They make sure that on all the 4Ms, there is an analysis performed and a coherent story between the 4Ms. Strategic objectives from the supplier are also an essential input for the analysis of the 4M because it gives direction as to which solution may be chosen. A summary of the finding from the interviews is given in figure 3.1. The figure is in the format of the IDEF0 scheme. This means that the arrows coming in from the left side of each block are the inputs, and the arrows going out on the right side are the outputs. The arrows coming into the block from above are the controls, and the arrows coming in from below are the resources needed for each of the 4M analyses.

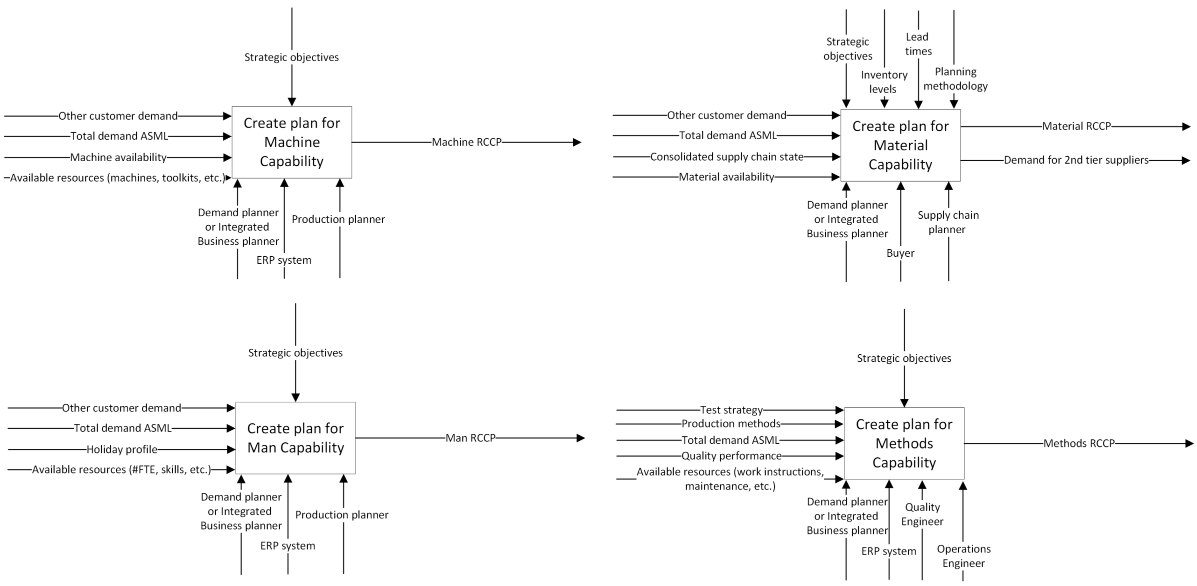


Figure 3.1: IDEF0 schemes of 4M method

The capacity analysis on machines is mainly done by the Demand Planner or Integrated Business Planner but with the support of the Production Planner. The Production planner provides input on the current state of the capability and availability of the machine. From the Enterprise Resource Planning (ERP) system, the planners collect data on the throughput and availability of the machines. The machines throughput was mainly derived from real-time data collected in the Manufacturing Execution System (MES) linked with the ERP system. Other data collected from the ERP system is the forecast of other customers; in some situations, the forecast of other customers was not provided within the time frame that ASML requires the supplier to complete their analysis, so the forecast data was extrapolated. The strategic objectives on machines provided an input expansion for the factory, outsourcing, and obtaining new machines.

The investigation into material availability in the supply chain is mainly done by Demand Planner or Integrated Business planner, Buyer, and Supply Chain planner. The supplier consolidates their supply chain by sending out a letter to their suppliers so they can confirm that they can deliver the volumes that result from ASML's Red Table demand. Some suppliers that are critical might even ask to do a small 4M-analysis.

The capacity analysis on manpower shares some similarities with the analysis of the machines. The main difference lies within the calculation of the availability of manpower. On the manpower, suppliers consider parameters like holiday profile and sick leave.

The capacity analysis on methods is more abstract than the rest of the 4M-analysis. Suppliers, therefore, also give feedback that they found this analysis the most difficult because they do not always know what to cover in the analysis. The output of the capacity analysis could be the digitization of systems, improvements in the escalation process, or quality process improvements. This analysis is mainly done together with the Quality Engineer and Operations Engineer.

Since we want to create a model that focuses solely on men and machines, we will delve more into the methods that a supplier used to obtain their capacity study. A general overview of the steps needed to perform the analysis, as well as detailed inputs, are given in figure 3.2. This figure is a general way of working. It may differ slightly from supplier to supplier. For example, for the supplier with sister companies, this process would be executed for each company.

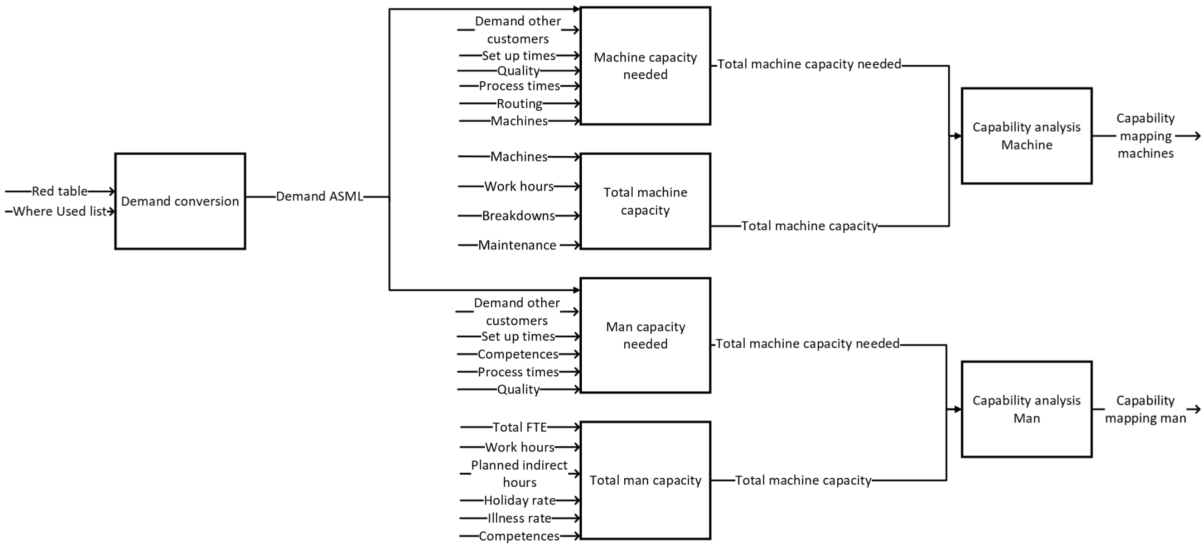


Figure 3.2: IDEF0 schemes of process 4M method

Suppliers generally start by converting the Red Table demand to the demand for the components they need to deliver. They do this with the so-called Where Used List and the Bill of Materials (BOM). The Where Used List is provided by ASML to the supplier. The output is created from the Red Table and the Where Used List server as input into the total time needed for the men and machine and the demand of the other customers that use the same resources. As stated before, the demand of other customers is either a forecast given by the customer or an extrapolation of the demand from the last years.

The analysis of the machine capacity is split into two parts: the machine time needed and the total machine capacity. The machine time depends on set-up times, process times, quality rate, routing, and the machine they need to be performed on. This information is retrieved from the ERP systems, which record real-time data from the MES system. The total machine capacity depends on the number of machines, total working hours, breakdowns, and scheduled maintenance. When the suppliers have the machine time and the total machine time, they can perform the analysis by comparing the two. If the total machine time needed exceeds the total machine capacity, the supplier must devise a plan to close this gap. This can be done, for example, by buying a new machine, improving the existing cycle time, outsourcing, improving quality, or expanding the factory.

The analysis on the men capacity is split into two parts as well. First, the capacity on men needed to comply with the demand of ASML and other customers will be calculated with the set-up times, process times, competence needed, and quality rate. The calculation on men capacity needed is similar to that of the machine capacity needed. The total capacity on men is calculated with the following parameters: total FTE, work hours, planned indirect hours, holiday rate, illness rate, and available competencies. When the suppliers have the capacity demand and available capacity, they can compare the two, as done for the machine capability analysis. If the total demand for capacity exceeds the total available capacity, the supplier must devise a plan to close this gap. For capacity on men, this can be done, for example, by hiring new people, training already existing employees, introducing more working hours by adding an extra shift, or outsourcing.

3.2.3 General remarks

In addition to the 4M-analysis and internal capacity analysis insights, the supplier interviews revealed additional insights into the overall process. These broad findings are not integrated into the model but can help ASML enhance its supplier collaboration. The main additional findings are listed below.

Wide variety in analysis

Within the 4M-analysis, there is much variation in how the analysis is conducted. In combination with a different LSMer, every supplier conducts their analysis in a different way. For example, one supplier had a more proactive way of sharing their capabilities. This supplier shares their move rate with ASML and lets ASML know that they need to give them a certain amount of time when they want to increase their move rate. Other suppliers give only their analysis on the Red Table and only show what they need to reach the demand of the Red Table.

Where Used list

The Red Table shows IBP's forecast for the next four years. The maximum projection for each ASML machine type is shown in this overview. The supplier is then asked to convert the forecast on machine type to the forecast on products that must be delivered. They transform the forecast using the Where Used list, a word for the BOM. According to suppliers, the Where Used list is not always up to date. Sometimes products are listed with incorrect units, or the Where Used list indicates that they must use an obsolete product. As a result, suppliers cannot correctly convert ASML forecasts to their own.

Commitment & Risk

Most suppliers indicated that ASML is one of the only suppliers that deliver their forecast in this format and four years ahead. ASML uses the Red Table to develop trust and illustrate potential growth in the upstream supply chain. In previous years ASML could not fulfill the demand for the Red Table, which caused suppliers to take the demand for the Red Table with a grain of salt. The problem with ASML being unable to fulfill the demand is depicted in figure 2.3. Suppliers do not want to reserve or buy capacity when it is not needed, but when suppliers underestimate the demand from the Red Table, it can happen that they will not be able to deliver in the future.

Dynamic demand

Suppliers indicate that the demand they get from ASML is typically very dynamic. The demand that they receive from day to day has a lot of rescheduled messages. Reschedule messages indicate that an order's due date has been changed forwards or backward in time. Suppliers report that they occasionally receive a last-minute communication that the order has been pushed forward, but it also happens the other way around that orders are pushed backwards. This causes much frustration on the supplier's side as prioritizing en reordering production orders is not cost- and time effective.

Bull-whip effect

One of the suppliers said that they fear that if ASML suddenly increases their demand, a Bullwip effect will occur, mainly because the network of suppliers is complex. One supplier can act as a first-tier and a third-tier, meaning they do not consistently see the increase in demand as a third-tier supplier. The supplier indicated that they are especially afraid that suppliers will hoard materials. This bull-whip effect, which is visualized for a three-echelon supply chain in figure 3.3, is caused by delays in passing on information upstream into the supply chain and delays in acting upon this information at every level in the chain. Forrester, 1997 Supplier collaboration planning reduces these delays by making information regarding the entire chain available to every decision-maker. Therefore, ASML must keep trying to share its demand information with its supply chain.

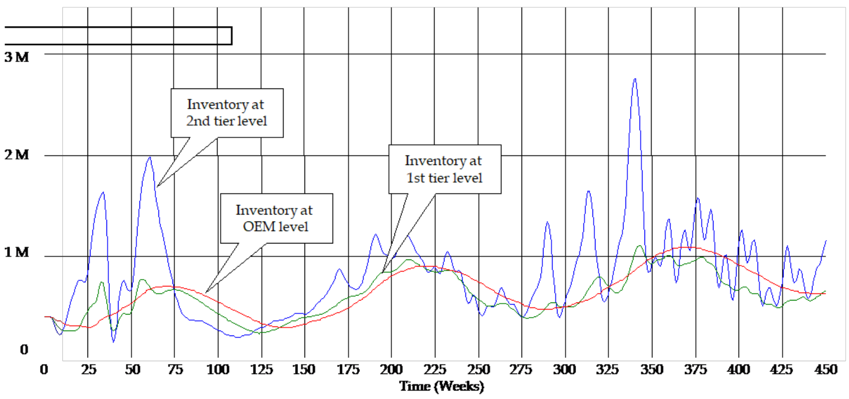


Figure 3.3: Bull-whip effects in a 3-echelon supply chain Forrester, 1997

Enriched demand

The enriched demand is additional demand for service parts or parts needed if a machine is upgrading. The enriched demand is usually sent with the Red Table for a complete overview of future demand. Suppliers have indicated that this list is not always complete or sometimes not sent. If the list is incomplete or missing, the supplier does not have the total demand and, therefore, cannot estimate their capacity well.

3.3 Conclusion

This section was aimed to gain insight into how suppliers currently determine their capacity. The interviews were conducted to gain insight into the status of how the suppliers perform the 4M-analysis, the in- and outputs that they use to perform the analysis, and the capabilities of the suppliers in the analysis. With this, we have aimed to answer the following sub-question:

1.1: How do suppliers of ASML currently determine their capacity on men and machines?

The 4M-analysis is presented in a PowerPoint format, where the results are shown graphically. Two suppliers performed their calculations in Excel and one in PowerBi. Suppliers indicated that there was no single way of working and that the results they needed to show were also dependent on the LSMer who was working with them on the analysis.

We got an understanding of who performed the analysis and what the processes are that the supplier uses to get their information. We observed that every supplier had their own way of working on the 4M-analysis. We found some insights for ASML around the 4M-analysis, like the Where-Used and enriched demand is often missing or incomplete. The in- and outputs the suppliers use for the capacity analysis on the men and machines are also known. The in- and outputs will later be used as a guide to make a model to determine the capabilities of the men and machines.

4 Theoretical background

This section discusses various methods for tactical capacity planning in a manufacturing and supply chain setting. We will first discuss capacity planning in a manufacturing firm and propose a model that will be the foundation of the model developed in section 5. Then we review the literature on supply chain models and propose a model that will also serve as a foundation for the model that will be developed. Lastly, we will elaborate on uncertainty's role in capacity planning and propose methods to deal with them. In this section, we aim to answer the following research question: *1.3 What methods exist in the literature for assessing suppliers' capacity and their network?*.

4.1 Capacity planning

Capacity planning ensures that the production department's future flow of work orders are aligned with available production capacity. Capacity planning does not usually refer to concrete production orders which are about to be released in the department but to the flow of expected production orders, a portion of which may already be known. (Bertrand et al., 1990) The goal of capacity planning is to ensure that the expected utilization of the department's available or soon-to-be-available capacity does not exceed the rate specified in the department's logistics parameters. The expected batch sizes and lead times must also meet these parameters.

Capacity planning is a complex issue (Nahmias and Cheng, 2009). When considering an expansion of existing capacity, a company must go through countless possibilities. First, it must be decided whether to increase capacity by changing the existing infrastructure. This is a viable option because expanding capacity in an existing plant is less expensive than building a new facility. However, ultimately capacity will exceed the plant room for further expansion. When a company decides to build a new facility, it faces decisions like: when, where, and how much.

In most capacity expansion problems, the objective is to minimize the discounted costs associated with the expansion process. Costs for expansions, shortages, congestion, idle capacity, maintenance, and inventory are all included. The decision maker frequently imposes constraints. These are examples of budget constraints or restrictions on acceptable policies, such as upper limits on expansion sizes, excess capacity, and capacity shortages.

There are three levels of capacity planning: strategic, tactical, and operational (Chien et al., 2018; Martínez-Costa et al., 2014). The main difference between different strategies is the time frame in which the decisions are made. Tactical capacity planning, or aggregate planning, deals with medium-term planning, typically one year. Strategic planning is concerned with changes in the medium to long term, typically several years. The terms medium and long term is relative to the pace of changes in technology and demand (Martínez-Costa et al., 2014). In the case of the 4M-analysis, the decisions are based on: the expansion of capacity in the bottleneck resource to increase overall capacity and workforce levels to overcome seasonal demand and facility modifications. All these decisions belong to the tactical capacity planning categorization. Furthermore, the 4M-analysis is done quarterly, which some authors classify as the mid-term planning process (Chen et al., 2009; Wu and Chang, 2007). Therefore the capacity planning in the 4M-analysis can be identified as tactical.

According to Martínez-Costa et al. (2014), quantitative procedures are typically used to guide tactical decisions. Thus, attention is drawn to the various capacity planning methods available in the literature and their alignment with the described characteristics.

4.1.1 Aggregate planning of capacity

To understand aggregated planning of capacity, the Aggregated Production Planning (APP) concept will first be described. APP refers to the mid-to-long-term period for planning decisions (Baykasoglu and Gocken, 2010). APP transforms the forecasted demand into resource plans for a specific planning horizon. (Nam and Logendran, 1992b) APP works as a constraint on the Master Production Schedule (MPS), and the objective is to create resource strategies from the anticipated demand for a specific planned period. This is accomplished by ensuring that the various product categories' varying needs are met while considering the manufacturing resources and constraints. The method also guarantees the desired outcomes through policies such as overtime, subcontracting, workforce levels, and so forth (Zhang et al., 2012).

Aggregate planning is done on a high and less detailed level compared to lower levels (Zhang et al., 2012). Therefore, it plays a base-line role for disaggregated plans such as MPS, Capacity Requirement Planning (CRP) and MRP (Mirzapour Al-E-Hashem et al., 2011). Nam and Logendran (1992a) proposes a different approach to solve aggregate production planning and identifies that products are grouped in families or a surrogate product is selected; from this gross level, sufficient resources and capacity can be determined to satisfy the demand of the planning horizon. A hierarchical decision process is used in this way, in which aggregated decisions yield global constraints that are applied to more detailed decisions (Bitran and Hax, 1977). The aggregated planning process aims to weigh the benefits of matching forecasted demand against the effects of changing available capacity (Nahmias and Cheng, 2009). As production plans are translated into capacity requirements for aggregated resources, capacity shortage and abundance are identified. To achieve balance, decisions about output rates, backlogs, employment levels, inventory levels, and subcontracting must be made.

Nahmias and Cheng (2009) propose a model for aggregate capacity planning with a linear cost structure. This allows the use of linear programming to solve the problem. Table 4.1 and 4.2 give the parameters and decision variables used in the aggregate planning problem. The objective of this model is to minimize the related cost 4.1, subject to different constraint 4.2 - 4.5.

The objective function (4.1) is the sum of all the production costs. The objective of this model is to reduce the cost of hiring, firing, producing on time, producing on overtime, subcontracting, and idle production. The first constraint (4.2) is the conversion of the workforce. The second constraint (4.3) is the production and workforce definition, and the last constraint (4.4) is the inventory balance equation. For all decision variables, it holds that they need to be greater or equal to zero (4.5). However, this model has a some limitations as it does not buffer against the impact of uncertainty, does not include lead time, and does not provide the means to scale this into supply chain modeling.

Table 4.1: Parameters of the Aggregated Planning linear model

Parameters	Detail
c_H	Cost of hiring one worker
c_F	Cost of firing one worker
c_I	Cost of holding one unit of stock for one period
c_R	Cost of producing one unit on regular time
c_O	Incremental cost of producing one unit on overtime
c_U	Idle cost per unit of production
c_S	Cost to subcontract one unit of production
n_t	Number of production days in period t
K	Number of aggregate units produced by one worker in one day
I_0	Initial inventory on hand at the start of the planning horizon
W_0	Initial workforce at the start of the planning horizon
D_t	Forecast of demand in period t

Table 4.2: Decision variables of the Aggregated planning linear model

Problem variables	Detail
W_t	Workforce level in period t
P_t	Production level in period t
I_t	Inventory level in period t
H_t	Number of workers hired in period t
F_t	Number of workers fired in period t
O_t	Overtime production in units
U_t	Worker idle time in units (”undertime”)
S_t	Number of units subcontracted from outside

$$\text{Minimize} \sum_{t=1}^{T} (c_H H_t + c_F F_t + c_I I_t + c_R P_t + c_O O_t + c_U U_t + c_S S_t) \tag{4.1}$$

Subject to:

$$W_t = W_{t-1} + H_t - F_t \quad \text{for } 1 \leq t \leq T \tag{4.2}$$

$$P_t = K n_t W_t + O_t - U_t \quad \text{for } 1 \leq t \leq T \tag{4.3}$$

$$I_t = I_{t-1} + P_t + S_t - D_t \quad \text{for } 1 \leq t \leq T \tag{4.4}$$

$$H_t, F_t, I_t, O_t, U_t, S_t, W_t, P_t \geq 0 \tag{4.5}$$

4.2 Supply chain capacity planning

'A supply chain is a network of facilities that performs the procurement of material, the transformation of material to intermediate and finished products, and distribution of finished products to customers' (Lee and Billington, 1995). A supply chain is simply a network of material processing cells having supply, transformation, and demand characteristics. Figure 4.1 illustrates an example of a supply chain network. There are various causes of uncertainty along every supply chain, including demand, process, and supply. Inventories are often used to buffer against the chain from these uncertainties. Supply chain management manages material and information flows inside and between facilities such as vendors, manufacturing and assembly plants, and distribution centers.

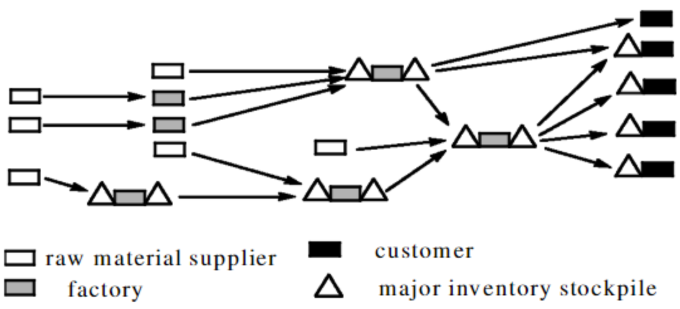


Figure 4.1: Typical supply chain (Rota et al., 2002)

Since the 1960s, operation researchers have been studying supply chain management. They have traditionally modeled supply chains as multi-echelon inventory networks with uncertain demand focusing on determining optimal purchasing quantities across the complete network. (Clark and Scarf, 2004)

Finding the most efficient and cost-effective approach to satisfy a company's production demands while considering the capacity of suppliers, manufacturers, and logistics providers is known as Supply Chain Capacity Planning (Lee and Billington, 1995). It entails anticipating future demand and coordinating the operations of various supply chain partners to ensure that the necessary resources are available at the right time.

Managing the supply-demand balance is an integral part of Supply Chain Capacity Planning. For example, ASML anticipates a rise in demand; therefore, their suppliers may need to increase manufacturing capacity or find new suppliers to match that need. However, if demand drops, a company may need to reduce capacity or negotiate with suppliers to reduce its inventory.

A supply chain problem modeled as a Multi-item Multi-level Capacitated Lot Sizing Problem (MLCLSP). We want to use a capacitated supply chain problem because we want to be able to calculate capacity planning. Shapiro (1993), Baker (1993) and Erengüç et al. (1999) provide literature assessments of mathematical programming methodologies for production planning and supply chain planning. Billington et al. (1983) developed the first approach for formulating an Linear Programming problem. Chung and Krajewski (1984) and Hopp and Spearman (2011) provide similar models. These models plan in a precise amount at distinct points in time. A recognized capacity measure acts as an upper bound on production for each time bucket, i.e., the time between two successive decision points. As they develop due to the limiting capacity, the actual production lead times are outputs of the model and depend only on the size of the order and the available capacity.

Belvaux and Wolsey (2001) makes use of mixed integer programming to formulate the MLCLSP. They derive problem-specific required inequalities that increase MIP solver performance. Furthermore, they distinguish between situations where planning occurs frequently and infrequently: small-time bucket problems versus big-time bucket problems. Özdamar and Barbarosoglu (2000) proposes a heuristic approach for the solution of the MLCLSP. The suggested technique aims to tackle this issue by combining the power of Lagrangian relaxation to divide difficult-to-solve issues into smaller sub-problems with the intensive search capability of simulated annealing. The Lagrangean relaxation is applied to the capacity constraint and the inventory balance equation. Erengüç et al. (1999) studies MP models that contain the concept of scheduled lead times. They discuss various issues by distinguishing between supplier stage problems, plant stage problems, and distribution state problems. However, none of these formulations distinguishes between planned order and capacity utilization, which is critical for modeling manufacturing flexibility by avoiding inefficient use of available resources in accordance with the planned lead time idea.

State-of-the-art research focuses on tractable uncapacitated stochastic models with low structural complexity for convergent and divergent structures and a mathematical programming technique for solving deterministic cases (Belvaux and Wolsey, 2001; Billington et al., 1983; Hopp and Spearman, 2011).

4.2.1 Supply chain operations planning

This section will give an example of a supply chain capacity planning model by de Kok and Fransoo (2003). This model develops a SCOP model in the context of Supply Chain Management. The model does not use lot-sizing, making the problem easier since it becomes a linear programming model instead of a mixed integer program. The objective of this model is to coordinate the release of materials and resources in the supply network under consideration such that customer service constraints are met at a minimal cost. The SCOP problem thus refers to the integration of the well-known MRP-II framework's Master Production Schedule (MPS), Rough Cut Capacity Planning (RCCP), Material Requirements Planning (MRP-I), and Capacity Requirements Planning (CRP) components. The SCOP function coordinates activities throughout the supply chain by deciding on the quantity and timing of material and resource releases. The model combines three important supply chain activities: manufacturing, transportation, and planning.

As stated before, a supply chain can be seen as a network, with suppliers delivering raw materials and customers buying the produced costs (Spitter, 2005). To create an end product, raw materials must undergo numerous transformation activities. These transformation processes can be physical, like manufacturing or assembly, or nonphysical, such as transportation from one site to another. The model assumes a make-to-stock environment that allows the suppliers to produce without knowing the exact demand.

We assume that products in the supply chain can be created on several resources, each producing various items. These resources have a limited capacity. Backorders are only permitted for end items, and we assume planned lead times with multi-period capacity use. The main challenge with SCOP is to ensure that, given the system restrictions, such as resource and material availability constraints, the best possible quantity of the item is released at the best possible time to achieve the lowest costs. Because demand is stochastic, the SCOP problem is tackled by forecasting end-item demand over the planning horizon. Seasonal influences are included if the planning horizon is sufficiently long.

Table 4.3: Parameters of the SCOP model

Problem variables	Detail
h_i	holding cost on item i
c_i	time required to process one unit of item i on its resource
$C_{k,t}$	Amount of capacity available in units of time of resource k in period t, $k1, \ldots, K, t \geq 1$
$\hat{D}_i(t, t+s)$	exogenous demand for item i in period $t+s$ as determined at the start of period t, $t \geq 1, s \geq -t, \forall i$

Table 4.4: Decision variables of the SCOP model

Problem variables	Detail
$\hat{G}_i(t, t+s)$	endogenous demand for item i in period $t+s$ as determined at the start of period t, $t \geq 1, s \geq -t, \forall i$
$\hat{B}_i(t, t+s)$	backlog of item i at the start of period $t+s$ as determined at the start of period t, $t \geq 1, s \geq -t, \forall i$
$\hat{I}_i(t, t+s)$	inventory of item i at the start of period $t+s$ as determined at the start of period t, $t \geq 1, s \geq -t, \forall i$
$\hat{r}_i(t, t+s)$	quantity of item i released at the start of period $t+s$ as determined at the start of period t, $t \geq 1, s \geq -t, \forall i$
$\hat{q}_i(t, t+s)$	quantity of item i processed in period $t+s$ as determined at the start of period t, $t \geq 1, s \geq -t, \forall i$

The linear programming model is given below:

$$\text{Minimize} \sum_{i=1}^{N} \left(\sum_{s=1}^{T} h_i \hat{I}_i(t, t+s) + \sum_{s \in E} \theta h_i \hat{B}_i(t, t+s) \right) \tag{4.6}$$

Subject to:

$$\begin{aligned} \hat{I}_i(t, t+s+1) - \hat{B}_i(t, t+s+1) = \hat{I}_i(t, t+s) - \hat{B}_i(t, t+s) - \hat{G}_i(t, t+s) - \hat{D}_i(t, t+s) \\ + \hat{r}_i\left(t, t+s-L_i\right), \forall i, s = 0, \ldots, T-1 \end{aligned} \tag{4.7}$$

$$\hat{B}_i(t, t+s+1) - \hat{B}_i(t, t+s) \leq \hat{D}_i(t, t+s), \quad \forall i, s = 0, \ldots, T-1 \tag{4.8}$$

$$\sum_{w=1-t}^{s} \hat{r}_i(t, t+w) \geq \sum_{w=1-t}^{s} \hat{q}_i(t, t+w), \quad \forall i, s = 0, \ldots, T-1 \tag{4.9}$$

$$\sum_{w=1-t}^{s} \hat{r}_i(t, t+w) \leq \sum_{w=1-t}^{s+L_i-1} \hat{q}_i(t, t+w), \quad \forall i, s = 0, \ldots, T-1 \tag{4.10}$$

$$\sum_{i \in U_k} c_i \hat{q}_i(t, t+s) \leq C_{k,L+s}, \quad k = 1, \ldots, K, \quad s = 0, \ldots, T-1 \tag{4.11}$$

$$\hat{r}_i(t, t+s), \hat{q}_i(t, t+s), \hat{I}_i(t, t+s), \hat{B}_i(t, t+s) \geq 0 \tag{4.12}$$

The goal of the model is to minimize the cost of inventory and back-ordering (4.6). The first constraint (4.7) describes the definition of the inventory position. The second constraint (4.8) defines back-ordering. The third and fourth constraints (4.9, 4.10) describes the order in which items are released, and the last constraint is the capacity constraint (4.11). Lastly, all the decision variables are greater or equal to zero (4.12). The model introduces safety stock to cope with short-term demand uncertainty but does not include ways to deal with other types of uncertainties.

4.3 Rolling schedule context

The performance of each SCOP problem is measured using a rolling schedule to incorporate the impact of stochastic end item demand, see figure 4.2.

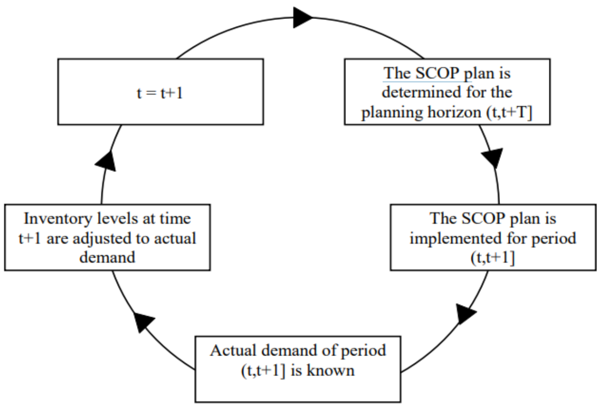


Figure 4.2: Rolling schedule concept (Spitter, 2005)

Decisions in the SCOP model are based upon demand forecast. For the successive periods, $(t, t+1], (t+1, t+2], \ldots, (t+T-1, t+T]$ the SCOP is determined based on a forecast of the demand, whereby t is the current time, and T is the planning horizon (Spitter, 2005). Then, just the first phase of the production plan is implemented by releasing both materials and resources scheduled to be released within that first period. Following the first period, actual customer demand is known, and a new production plan for the next planning horizon is created based on actual net inventory levels, a possibly updated prediction of future demand, and outstanding orders generated by prior plans. By implementing the rolling schedule, we can shift the planning horizon after each period after, say, three periods. In this situation, the three periods of the decided production plan are implemented, and only after the third period is a new production plan computed based on the actual demand of the previous three periods and the demand prediction for the next time horizon. This most likely minimizes the system's nervousness but also shortens the reaction time to deviations from the client demand prediction.

We limit ourselves in this thesis by adjusting the planned horizon after each phase. In this case, this will be a quarter since the 4M-analysis is done quarterly.

4.4 Role of uncertainty

The SCOP assists decision-making under uncertainty by accounting for processing delays and limits imposed by previous decisions. As a result, uncertainties, delays, and limits must be explicitly included in SCOP design. When working with deterministic models, you ignore the stochastic nature in reality. Most processes in real life are stochastic, and therefore ignoring that could have a significant impact. Uncertainty in this context can be defined as unpredictable situations that occur in production contexts and cause disruptions in the operations and performance of organizations (Koh and Gunasekaran, 2006). Uncertainty can be categorized into different variations. Koh et al. (2002) categorize uncertainty between input (uncertainty that comes from outside the system, such as demand variation) and process (uncertainty within the system, such as demand uncertainties). Internal demand uncertainty includes conditions that could reduce the volume output after production, such as quality variations, yield, etc. In contrast, internal supply uncertainty includes all production-specific conditions that could lead to uncertainty in the production itself, such as queues, lead times, unavailability of tools or materials, operator absence, and breakdowns.

Several buffering and dampening approaches are employed to mitigate the effect of uncertainty. Buffering is related to physical conditions. An example of buffering is defining safety stocks. Dampening refers to intangible conditions, and an example of this is making use of safety lead time (Koh et al., 2002). Since we decided to use a deterministic model, we must include slack to hedge against uncertainty. Galbraith (1973) argues that the complexity/uncertainty of a problem, in general, can be dealt with by three alternative options:

- Information and communication technology
- Decomposition of the problem in smaller sub-problems
- Slack in time, material, and resource

Finding the best combination of solutions for a given situation is an art, not a science (Wiers and de Kok, 2017). Information and communication systems are the means to capture large amounts of input data and store them. To deal with uncertainty in these systems, many people ignore it and rely on frequently updating information about task and work order completions, forecasts, and customer orders. In such cases, we solve problems without uncertainty over and over again (Wiers and de Kok, 2017). In the proposed model (section 5.2), we use a deterministic mathematical programming model in a rolling schedule context which will allow us to use information and communication technology to deal with uncertainty. The second method is a decomposition of the problem into smaller sub-problems. We will use this method by not planning for the whole supply chain but planning capacity for each supplier. The third method is using slack in time, material, and resources. Queueing theory investigates the behavior of a system composed of resources confronted with an exogenous stream of jobs with variable arrival times and uncertain processing requirements, regarding which resources must process the jobs and how much processing time is required. The examination of such systems reveals slack due to uncertainty (Wiers and de Kok, 2017). Safety time, capacity slack, and safety stock are forms of slack against uncertainty and will be implemented into the model.

4.5 Conclusion

The proposal is to combine the base models provided by Nahmias and Cheng (2009) and de Kok and Fransoo (2003) and include uncertainty through slack variables. With this section, we answered the following research question:

1.3 What methods exist in the literature for assessing suppliers' capacity and their network?

We have identified the following levels of capacity planning: strategic, tactical, and operational. We found that the 4M method is used on a tactical level. With that, mathematical programming, specifically linear programming, appears as a typical solution for aggregation planning type problems. Its benefits include solving the problem quickly, especially when what-if analysis is required. We discussed models in MLCLSP. We saw that current research focuses on tractable uncapacitated stochastic models with low structural complexity for convergent and divergent structures and a mathematical programming technique for solving deterministic cases. Lastly, we discussed the role of uncertainty in capacity planning and how to cope with the uncertainty in modeling.

PART II

MODELING

5 Model design

This section describes the development process and mathematical formulation of the model used to assess the internal capacity of the supplier. This section will answer three research questions: *2.1 How can a framework be made where suppliers can be standardized on their rough-cut capacity plan?*, *2.2 How to build a reliable rough-cut capacity plan?* and *2.3 How can a rough-cut capacity plan be made for a supply chain?*.

We will develop a model for aggregate capacity planning in the context of S&OP (Sales and Operations Planning). The goal of the output model is twofold. The first goal is to check whether the supplier has enough capacity to produce the items from the given forecast. The second goal is to provide suppliers insight into their capacity planning.

We will start by addressing the model assumptions derived from interviews in section 5.1. In section 5.2, a model will be proposed for analyzing a supplier's capacity. We will then discuss the model's interface choices in section 5.6. Next, we discuss the data transformation process (section 5.7) and how the inputs for the model are practically structured in section 5.8. The output will briefly be discussed in section 5.9. Lastly, we will discuss the approach to verify and validate the model in section 5.10.

5.1 Model assumptions

This section provides the most key modeling assumptions used in the model described in section 5.2. The first part will consist of model assumptions that reflect the information gathered with the interviews with the suppliers and LSMers. Therefore, the assumptions used in the model reflect what suppliers are currently assuming in their analysis. The second part of this section will be assumptions for the model. The assumptions serve to simplify to get a feasible model. First assumptions based on interviews:

- **Time buckets: month** - In the 4M-analysis, providers are asked to affirm their capabilities for each quarter. However, based on the 4M analyses that have been conducted, it appears that suppliers prefer a monthly analysis.
- **Demand fixed and known** - In the 4M-analysis the Red Table is leading. The Red Table contains the demand for the coming 3-4 years. This demand is given as deterministic but, in reality, is stochastic in nature. The model will not deal with the stochastic nature of the demand and will assume that all inputs are deterministic.
- **Translation Red Table** - One of the problems that suppliers indicated (also stated in section 3.2.3) is that they have trouble with translating the Red Table demand to products that they need to deliver. The problem with the translation lies in the Where Used list (BOM) from ASML, which is often incomplete or not up to date. The problems with the were-used list are out of scope, and we assume that the supplier can translate the demand in the Red Table into their demand.
- **Uncapacitated external supply of materials** - The model focuses on a supplier's internal capacity (man and machine capacity). Therefore we assume that materials are always available for production and that they will not restrict output. Thus, this aspect is addressed in the Material analysis of the 4M-analysis and is out of scope.
- **Unused capacity is penalized** - As stated in section 3.2.3, suppliers are afraid to commit because they do not want under-utilized machinery or employees. Therefore we incorporate a variable in the model that gives a penalty cost for capacity that is not used. This provides the supplier insight into what happens if they commit to the high demand for ASML and what it would mean if ASML does not keep the promise of a high demand.
- **Overall capacity increases** - ASML expects that their overall sales and demand will

increase in the coming years. However, this does not hold for every machine type that they sell. Some machines will be phased out in the coming years. Therefore, it is essential to show what additional capacity is needed to keep up with the demand and the capacity that will be redundant once specific machines will phase out.

- **Penalty cost** - During the interviews, the suppliers and the LSMers were asked what the penalty cost was for being unable to deliver. In reality, no penalty cost is requested from the supplier when they cannot deliver, other than not being paid for the products they do not deliver. However, we still choose to include penalty cost to make a trade-off between inventory, capacity investment, and having items short.

- **Forecast known for each month** - The forecast for each item is known per month. In the Red Table, the forecast is given per year, but the supplier is asked in the input to provide the demand per month. This is because the demand will not be the same every month.

- **Capacity known for each month** - In the input, the suppliers will be asked to give their capacity on each resource per month. Capacity is also non homogeneous throughout the year because, for example, planned maintenance and holiday patterns.

- **Forecast extrapolation** - In the model, the forecast for the last year is extrapolated. This is needed because otherwise, the model would stop releasing orders near the end of year four, which in practice will not be the case. When the forecast is extrapolated, the model will release orders until the end of the fourth year. The 'extra' year that is extrapolated will not be shown in the output. We chose to replicate year four in year five as an extrapolation.

The second set of assumptions serves to simplify to get a feasible model. These assumptions may not reflect reality. The main limitations of this model, as well as some of the primary modeling assumptions, are highlighted in section 9.

- **Engineering changes** - In the model, we assume that items do not change over time, e.g., due to engineering changes. This can be done because the 4M-analysis is done regularly (every quarter), and with every quarter, the engineer changes will be included in the change in demand.

- **First-come-first serve** - Orders are fullfiled with First come first serve (FCFS) principle. The oldest back-order demand is always fulfilled first. In practice, allocation issues are frequently resolved in collaboration with ASML to improve supply chain performance.

- **Lead times** - Lead times in this model are constant and known. This holds the lead time in obtaining capacity and the lead time for the material to become available for production. Lead times are not consistent and, according to suppliers, are not reliable. The lead time of obtaining capacity is especially unreliable, as historical data from the past last years show. Last year's Corona and the conflict in Ukraine had a big impact on lead times of materials. We still choose to exclude the uncertainty of lead times in the model mainly because the lead times will be revised every quarter when the 4M-analysis is done.

- **End items are special** - End items are different from intermediate items. Penalty cost only occurs on end items because they are the ones that ASML needs. Holding cost only occurs for end items because intermediate items are WIP and do not have a stock location; this holds the same for safety stock.

- **Removing capacity** - Obtaining capacity has a lead time, but we do not use a lead time for removing capacity. In practice, there might be a lead time for removing the capacity.

For example, a supplier needs to give an employee a notice period.

5.2 Model formulation

In this section, we develop an approach for mathematical programming in a rolling schedule setting to compute the long-run average cost of maintaining customer service level constraints. All the variables used in the model can be found in table 5.1 and 5.2. The model structure and constraints are derived from de Kok and Fransoo (2003) and Selçuk et al. (2008). In this model, we use a deterministic model in a rolling schedule framework. The problem is stochastic because reality is not deterministic, and the model is aimed to mirror reality. Therefore we address safety stocks; the buffer stocks required to cope with end-item uncertainty. In a planning framework, decisions are made immediately and provide information about the future. These future release decisions are preliminary since future unknown circumstances will influence them. (de Kok and Fransoo, 2003) To deal with this, we need to estimate future demand; ASML does this in their IBP process and translates this into the Red Table.

We consider a manufacturer with operational uncertainty and a downstream deterministic demand for a set of items. The set of items is called N, where one item is indicated by i in the model. Within the set of items exist a subset of end items E indicated by index m. End items are special because they only have safety stock (v_m), holding cost (hf_m), and penalty cost (p_m). Penalty cost in this context is the customer's pain because their supplier cannot deliver. In this case, the customer is ASML. We introduce period $t + s$ in the variables to indicate that we are making decisions now and with future knowledge.

Table 5.1: Input variables model

Variable	Description
Input	
N	Set of items intermediate items and end items i, $i = 1, 2, \ldots, N$
E	Set of end items $\{i \mid a_{ij} = 0, i = 1, 2, \ldots, N, j = 1, 2, \ldots, N\}$
U_k	Set of items that can be processed on resource k, $k = 1, 2, \ldots, K$
γ_k	Cost of obtaining extra capacity on resource k, $k = 1, 2, \ldots, K$
τ_k	Leadtime capacity on resource k, $k = 1, 2, \ldots, K$
δ_k	Cost of idle capacity on resource k, $k = 1, 2, \ldots, K$
ρ_k	Cost of idle capacity on resource k, $k = 1, 2, \ldots, K$
c_{ik}	Time required to process one unit of item i on resource k, $i = 1, 2, \ldots, N$,
hf_m	Holding cost for finished end item m at the start of the period, $m \in E$
hw_i	Holding cost for WIP item i at the start of the period, $i = 1, 2, \ldots, N$
L_i	Throughput time between release and availability items i, $i = 1, 2, \ldots, N$
ε_i	Yield loss for item i, $i = 1, 2, \ldots, N$
p_m	Penalty cost incurred for each unit short for end item k and the end of a period, $m \in E$
v_m	Safety stock for end item m , $m \in E$
$\hat{d}_m(t, t+s)$	Forecast ASML for end item m in period t+s, $m \in E,\ t = 1, 2, \ldots, T,$ $s = 0, 1, \ldots, T-1$
$\hat{o}_m(t, t+s)$	Forecast other customers for end item m in period t+s, $m \in E,$ $t = 1, 2, \ldots, T,\ s = 0, 1, \ldots, T-1$
$\hat{F}_m(t, t+s)$	Forecast made at the beginning of period t of the exogenous demand for end item m in period t+s, $m \in E$, $t = 1, 2, \ldots, T,\ s = 0, 1, \ldots, T-1$

The demand is known and deterministic for each end. For ease of use, the demand on the end items is divided into two parameters: the demand from the customer who requests the capacity analysis ($\hat{d}_m(t, t+s)$) (in this case ASML) and the demand from the other customers ($\hat{o}_m(t, t+s)$). We split the forecasted demand because ASML delivers the forecasted demand from their Red Table, while the demand from other suppliers might be an estimation. Since the demand is known ahead of time, it is also referred to as a forecast ($\hat{F}_m(t, t+s)$) and is the sum of the demand from ASML ($\hat{d}_m(t, t+s)$) and the other customers ($\hat{o}_m(t, t+s)$). Backorders are used to fill unmet demand. In this model, time is aggregated into periods, and the planned lead time is given as an integer number of periods, suggesting that an order released at the beginning of a period is expected to be available after a duration equal to the planned lead time.

Every item i has a process time on resource k (c_{ik}). One item can require more than one resource to be processed. The items have a lead time (L_i), and yield loss (ε_i) is also defined for every item i.

One of the set decisions from solving the model is the material release decision. The material available on the end item is the physical stock ($X_i(t, t+s)$). We also define the WIP ($W_i(t, t+s)$) of item i with related holding cost (hw_i). The release of item i that becomes available at the start of period t is ($\hat{r}_i(t, t+s)$). As a result of releasing the item i, it becomes available as processed item ($\hat{p}_i(t, t+s)$).

Items can be processed on resource k. A resource can be either men or a machines; the model does not distinguish the resource type. We define U_k as a set of items that can be processed on resource k. The capacity available at period t on resource k is $\hat{C}_k(t, t+s)$. The amount of items i that is processed on resource k is $\hat{q}_{ik}(t, t+s)$. Capacity in this model is not static but can be changed by obtaining and removing capacity. Capacity can be obtained ($\theta_k(t, t+s)$) with cost (γ_k) and leadtime (τ_k). Capacity can also be removed ($\Phi_k(t, t+s)$) with cost (δ_k). Removing capacity does not have a lead time. Underutilized capacity ($I_k(t, t+s)$) will also be penalized with cost (ρ_k).

Table 5.2: Output variables model

Variable	Description
Output	
$X_i(t, t+s)$	Physical net inventory of item i at the end of period t, $i = 1, 2, \ldots, N$, $t = 1, 2, \ldots, T,\ s = 0, 1, \ldots, T-1$
$\hat{r}_i(t, t+s)$	Quantity of item i released at the start of period t immediately after receipt of $p_i(t)$, $i = 1, 2, \ldots, N,\ t = 1, 2, \ldots, T,\ s = 0, 1, \ldots, T-1$
$\hat{p}_i(t, t+s)$	Quantity of item i that becomes available at the start of period t from the transformation activity generating item i, $i = 1, 2, \ldots, N$, $t = 1, 2, \ldots, T,\ s = 0, 1, \ldots, T-1$
$W_i(t, t+s)$	WIP level at the start of period t+s, just before the release of additional WIP into the shop, $i = 1, 2, \ldots, N,\ t = 1, 2, \ldots, T,\ s = 0, 1, \ldots, T-1$
$\hat{q}_{ik}(t, t+s)$	Amount of item i processed on resource k in period t, $i = 1, 2, \ldots, N$, $t = 1, 2, \ldots, T,\ s = 0, 1, \ldots, T-1$
$\theta_k(t, t+s)$	Capacity obtained in period t on resource k, $k = 1, 2, \ldots, K$, $t = 1, 2, \ldots, T,\ s = 0, 1, \ldots, T-1$
$\Phi_k(t, t+s)$	Capacity removed at time t on resource k, $k = 1, 2, \ldots, K,\ t = 1, 2, \ldots, T$, $s = 0, 1, \ldots, T-1$
$\hat{C}_k(t, t+s)$	Capacity at time period t on resource k, $k = 1, 2, \ldots, K,\ t = 1, 2, \ldots, T$, $s = 0, 1, \ldots, T-1$
$I_k(t, t+s)$	Idle capacity at time t on resource k, $k = 1, 2, \ldots, K,\ t = 1, 2, \ldots, T$, $s = 0, 1, \ldots, T-1$

The objective of the model is to minimize the sum of cost over a finite time horizon (T). The costs consist of holding cost (hf_m) back ordering cost (p_k) of not being able to deliver, cost of obtaining capacity (γ_k), cost of removing capacity (δ_k), holding cost over the WIP (hw_i) and cost of unused capacity (ρ_k). Therefore the objective function is:

$$\begin{aligned} \min_{\{1\leq i\leq N, 1\leq t\leq T, 0\leq s\leq T-1\}} & \sum_{s=0}^{T-1}\sum_{m\in E} hf_m\left(X_i(t,t+s)-v_i\right)^+ + \sum_{s=1}^{T-1}\sum_{m\in E} p_m\left(X_m(t,t+s)-v_m\right)^- \\ & + \sum_{s=1}^{T-1}\sum_{k=0}^{K}\gamma_k\theta_k(t,t+s) + \sum_{s=1}^{T-1}\sum_{k=0}^{K}\delta_k\Phi_k(t,t+s) \\ & + \sum_{s=1}^{T-1}\sum_{k=0}^{K}\rho_k I_k(t,t+s) + \sum_{s=0}^{T-1}\sum_{i=1}^{N} hw_i W_i(t,t+s) \end{aligned} \tag{5.1}$$

To make the model input easier for the supplier, the total independent demand is split into demand from ASML and demand from other customers.

$$\hat{F}_m(t,t+s) = \hat{d}_m(t,t+s) + \hat{o}_m(t,t+s), \quad m\in E,\ t=1,2,\ldots,T,\ s=0,1,\ldots,T-1 \tag{5.2}$$

The concept of planned lead times is a method of ensuring future material availability. The restrictions should be written so that they mirror the conceptual principles underlying the planned lead times notion. We introduce yield loss (ε_i) on item (i) as a variable in 5.3. Therefore, the ratio between released and available items is given in equation 5.3.

$$\hat{r}_i(t,t+s)(1-\varepsilon_i) = \hat{p}_i(t,t+s-L_i), \quad \forall i,\ \forall k,\ t=1,2,\ldots,T,\ s=0,1,\ldots,T-1 \tag{5.3}$$

The net inventory depends on the inventory in the previous period, the forecasted demand, the items that become available resulting from production, and the dependent demand. Therefore the inventory balance equation is as follows:

$$\begin{aligned} X_i(t,t+s+1) = X_i(t,t+s) - \hat{F}_i(t,t+s) + \hat{r}_i\left(t,t+s-L_i\right), \quad \forall i,\ t=1,2,\ldots,T, \\ s=0,1,\ldots,T-1 \end{aligned} \tag{5.4}$$

Orders must be released before they can be processed on a resource. Here the assumption is that at the start of period 1, the system is empty. Therefore the following constraint is used:

$$\sum_{w=1-t}^{s}\hat{r}_i(t,t+w) \geq \sum_{k=0}^{K}\sum_{w=1-t}^{s}\hat{q}_{ik}(t,t+w), \quad \forall i,\ \forall k,\ t=1,2,\ldots,T,\ s=0,1,\ldots,T-1 \tag{5.5}$$

We want to ensure that the order released at the start of the period t is available for usage in period $t+L_i$. From this, it follows that:

$$\sum_{w=1-t}^{s}\hat{r}_i(t,t+w) \leq \sum_{k=0}^{K}\sum_{w=1-t}^{s+L_i-1}\hat{q}_{ik}(t,t+w), \quad \forall i,\ \forall k,\ t=1,2,\ldots,T,\ s=0,1,\ldots,T-1 \tag{5.6}$$

When an item is released, we want to ensure enough capacity is available. We do this by formulating the following constraint:

$$\hat{r}_i(t,t+s) = \sum_{k=0}^{K} \hat{q}_{ik}(t,t+s) \quad \forall i,\ t=1,2,\ldots,T,\ s=1,2,\ldots,T-1 \tag{5.7}$$

Since capacity is limited in this model, capacity requirements need to make sure that the model does not exceed the available capacity. Constraint 5.9 ensures that the production capacity over all produced items cannot exceed the total capacity in a time period:

$$\sum_{i\in U_k} c_{ik} q_{ik}(t,t+s) \leq \ \hat{C}_k(t,t+s), \qquad \forall k,\ t=1,2,\ldots,T, s=0,1,\ldots,T-1 \tag{5.8}$$

We want to create capacity as a dynamic concept. We use the hiring and firing concept from Nahmias and Cheng (2009). The full model from Nahmias and Cheng (2009) can be found in section 4.1.1. In order to do that, we have to introduce two new variables namely, $\theta_k(t,t+s)$ the capacity obtained (hiring) and $\Phi_k(t,t+s)$ the capacity removed (firing). Obtaining capacity has a lead time, this can be in the form of training or lead times of equipment. The variable τ_k is the lead time of obtaining extra capacity on a resource, with that it follows:

$$\begin{aligned}\hat{C}_k(t,t+s+1) = \hat{C}_k(t,t+s) + \theta_k(t,t+s-\tau_k+1) - \Phi_k(t,t+s), \quad k=1,2,\ldots,K,\\ t=1,2,\ldots,T, s=0,1,\ldots,T-1\end{aligned} \tag{5.9}$$

The WIP balance equation is given in 5.10. Here the WIP is increased by the amount of work loaded and decreased by the order that is completed.

$$\begin{aligned}W_i(t,t+s+1) = W_i(t,t+s) + \hat{r}_i(t,t+s) - \hat{p}_i(t,t+s+1), \quad \forall i,\ t=1,2,\ldots,T,\\ s=0,1,\ldots,T-1\end{aligned} \tag{5.10}$$

The definition of unused capacity is given in constraint 5.11. The unused capacity is the total capacity at moment t+s minus the total capacity needed in time t+s.

$$\hat{C}_k(t,t+s) - \sum_{i\in U_k} c_{ik} q_{ik}(t,t+s) = I_k(t,t+s), \qquad \forall k,\ t=1,2,\ldots,T, s=0,1,\ldots,T-1 \tag{5.11}$$

Release quantity, product quantity, work in progress, process quantity, capacity obtained, capacity, and idle capacity have to be greater than zero. Therefore, we describe the following constraints:

$$\hat{r}_i(t,t+s) \geq 0, \quad \forall i,\ t=1,2,\ldots,T,\ s=1,2,\ldots,T-1 \tag{5.12}$$

$$\hat{p}_i(t,t+s) \geq 0, \quad \forall i,\ t=1,2,\ldots,T,\ s=1,2,\ldots,T-1 \tag{5.13}$$

$$W_i(t,t+s) \geq 0, \quad \forall i,\ t=1,2,\ldots,T,\ s=1,2,\ldots,T-1 \tag{5.14}$$

$$\hat{q}_{ik}(t,t+s) \geq 0, \quad \forall i,\ \forall k,\ t=1,2,\ldots,T,\ s=1,2,\ldots,T-1 \tag{5.15}$$

$$\theta_k(t,t+s) \geq 0, \quad \forall k,\ t=1,2,\ldots,T,\ s=1,2,\ldots,T-1 \tag{5.16}$$

$$\Phi_k(t,t+s) \geq 0, \quad \forall k,\ t=1,2,\ldots,T,\ s=1,2,\ldots,T-1 \tag{5.17}$$

$$\hat{C}_k(t,t+s) \geq 0, \quad \forall k,\ t=1,2,\ldots,T,\ s=1,2,\ldots,T-1 \tag{5.18}$$

$$I_k(t,t+s) \geq 0, \quad \forall k,\ t=1,2,\ldots,T,\ s=1,2,\ldots,T-1 \tag{5.19}$$

5.3 Capacity slack

In section 4.4, we discussed the different kinds of uncertainty in the context of production planning; input and process uncertainty. We have introduced safety stocks to hedge for input uncertainty. Input uncertainty may contain uncertainty outside of the manufacturing plant, such as demand variation. In section 4.4, we also discussed a method to cope with process uncertainty; capacity slack. We want to include capacity slack to cope with unforeseen breakdowns of machines or sickness of employees. A manufacturing firm might also want to be careful with planning on 100% utilization of a resource because this will increase the lead time and work in progress due to queuing orders (Hopp and Spearman, 2011). Therefore we introduce the capacity slack variable, ψ_k, to hedge for uncertainty in the manufacturing process. ψ_k is a variable that indicates the maximum utilization of a resource and lies between 0% and 100%. The new capacity constraint replaces 5.9 in the model stated above. The new capacity constraint will therefore be:

$$\sum_{i \in U_k} c_{ik} q_{ik}(t, t+s) \leq \psi_k \hat{C}_k(t, t+s), \quad \forall k, \ t = 1, 2, \ldots, T, s = 0, 1, \ldots, T-1 \tag{5.20}$$

Because we do not want to penalize the slack parameter we also adjust constraint 5.11. We formulate a new constraint for the unused capacity:

$$\hat{C}_k(t, t+s) - \sum_{i \in U_k} c_{ik} q_{ik}(t, t+s) = \psi_k I_k(t, t+s), \quad \forall k, \ t = 1, 2, \ldots, T, s = 0, 1, \ldots, T-1 \tag{5.21}$$

5.4 Norm capacity concept

The initial thought for the model was to use the average capacity as input for $\hat{C}_k(0, 0)$. The capacity would be planned according to the demand from that starting point. If the demand were higher than the capacity, the model would 'hire' capacity, and if the demand were lower than the capacity, it would be 'fired'. In reality, capacity varies from period to period; for example, man's capacity will be lower in the summer months because of holidays. For machine capacity, it holds as well; for example, scheduled maintenance for machines is known. Therefore use a norm capacity as an input per month. Norm capacity is the average production expected over a number of periods or seasons under normal conditions, considering capacity loss due to planned maintenance or planned holidays.

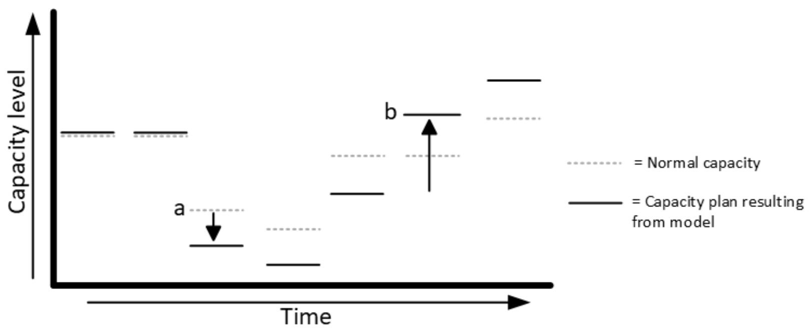


Figure 5.1: Capacity level over time with norm capacity and capacity resulting from model

Constraint 5.9 no longer holds when using the norm capacity as input. The fluctuations in the capacity that occur due to, for example, holidayss do not mean that a penalty cost for removing or obtaining that capacity should be assigned. In addition, the rule that the capacity solely depends on the capacity in the previous period, the capacity obtained, and the capacity removed is not valid anymore. The capacity in the next period is not dependent on the previous period because the capacity is already known for the next period.

To deal with the capacity being an output, we introduce two different capacity variables: $\bar{C}_k(t, t+s)$ the norm capacity and $\hat{C}_k(t, t+s)$ the capacity plan resulting from the model. When the capacity parameters are split, we can use the relative fluctuations in the norm capacity to adjust the capacity. This relative change in capacity is shown in figure 5.1. The demand for that period is lower than the capacity needed (situation a), so the model will adjust and remove the capacity. In the next period, the capacity will move with the norm capacity. In situation b, the opposite of the situation is happening; the demand is higher than the capacity available, so capacity needs to be obtained.

Because constraint 5.9 does not hold, we formulate a new constraint that will replace 5.9. In the new constraint, we will use the split definitions of capacity. The capacity on time 0 is the norm capacity on time 0 ($\hat{C}_k(0) = \bar{C}_k(0)$). This constraint solves a practical problem but has not been found in the literature.

$$\begin{aligned}\hat{C}_k(t, t+s+1) = \hat{C}_k(t, t+s) + (\bar{C}_k(t, t+s+1) - \bar{C}_k(t, t+s)) + \theta_k(t, t+s-\tau_k) \\ - \Phi_k(t, t+s), \quad k = 1, 2, \ldots, K,\ t = 1, 2, \ldots, T, s = 0, 1, \ldots, T-1\end{aligned} \tag{5.22}$$

5.5 Supply chain modeling extension

The model of de Kok and Fransoo (2003) is a multi-level model. The formulation in section 5.2 does not allow for multi-level modeling. To solve this, we propose two solutions: one focuses on first-tier supply chain modeling, and the second focuses on N-tier supply chain modeling. In section 6, we will discuss the results of both methods.

5.5.1 First-tier supply chain modeling

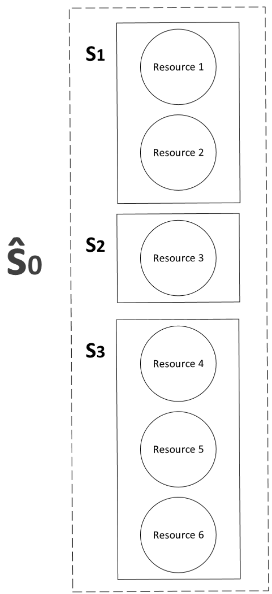


Figure 5.2: Structure first-tier supply chain model

We also want to see how first-tier suppliers would perform in the model. This is especially important for ASML as they need all the components to finish their machines. If one supplier does not have enough capacity and thus cannot deliver the parts, ASML is likely to tell their other suppliers that they do not have to deliver to prevent stock buildup. Therefore we would like to see the influence of long lead times in a supply network. To use the model from 5.2 for supply chain planning, we must define how to put multiple suppliers in one model. In the model, all the suppliers are used as input for the model. The model here does not distinguish between, for example, a resource from a suppliers. This is graphically shown in figure 5.2.

In the model, we do not have to distinguish suppliers because they need to deliver together; if one of the suppliers cannot deliver, ASML cannot produce their machines. In the output, we can show which supplier can deliver because we know the index in which they are placed in the model.

5.5.2 N-tier supply chain modeling

To define a N-tier supply chain, we must define Customer Order Decoupling Point (COPD). The COPD indicates how deeply the customer order penetrates the supply chain. (de Kok and Fransoo, 2003) It is the distinction between the order-driven and forecast-driven supply chain segments for a specific product-market combination. All releases downstream of the COPD are based on actual client orders and are not planned under demand uncertainty. This is also called exogenous demand, which we called $F_i(t, t+s)$ in section 5.2. Dependent demands are planned based on all releases upstream of the COPD. The dependent demand will be called $D_i(t, t+s)$. Because we are talking about supply chains, the COPD will be seen as end items in the supply chain.

The dependent demand ($G_i(t, t+s)$) for items i is generated by producing items before the COPD. We introduce variable a_{ij} as the number of items i required to produce one item j. Therefore we define the dependent demand as the sum of the intermediate items from all suppliers (J) in the supply chain.

$$G_i(t, t+s) = \sum_{j=1}^{N} a_{ij} \hat{r}_j(t, t+s), \quad \forall i \in I \tag{5.23}$$

The dependent demand can then be introduced in constraint 5.4. We formulate the new constraint as follows:

$$\begin{aligned} X_i(t, t+s+1) = X_i(t, t+s) - \hat{F}_i(t, t+s) + \hat{r}_i\left(t, t+s-L_i\right) - \sum_{j=1}^{N} a_{ij} \hat{r}_j(t, t+s), \\ \forall i,\ t = 1, 2, \ldots, T,\ s = 0, 1, \ldots, T-1 \end{aligned} \tag{5.24}$$

5.6 Interface

In the interviews, the suppliers and LSMers were asked to describe a tool they would like to use to determine if the supplier has enough internal capacity to fill the forecast for the coming four years fully. Most suppliers and LSMers indicated that they would like to use spreadsheets as most people are already familiar with them. Many companies also consider spreadsheets as the industry standard way of working.

The goal of the output of the model is twofold. On the one side, we want ASML to check whether the supplier can confirm the demand that has been requested, but on the other hand, we also want suppliers to get more insight into their capacity planning. The interface of the model plays an essential role in achieving both goals. The inputs will serve as insight into what parameters are essential for capacity planning for the supplier. The model output will confirm if the suppliers can fully fill the demand of ASML. Still, we also want to make the output interactive for suppliers to tweak the output to their capacity expansion plan that they might already have in place.

The in- and output of the model will be two different spreadsheets as suppliers have indicated in the second interview that they want to keep the data that is asked in the model private from ASML. In this way, the supplier only has to share the outcomes of the model and not the sensitive data behind it. The transformation of data will be explained in section 5.7.

The model does not distinguish between a resource as man or machine. They are both called resources (k). This was a conscious model choice because if we made a distinction between men and machines, we would add complexion into the model by adding a binary variable. This would make the model a mixed-integer linear programming model, which is generally harder to solve and would add a lot of computing time. However, calculating the net capacity of a man and a machine requires different parameters (see section 5.8). Therefore we choose to have two different tabs in the spreadsheet to calculate the net available capacity of men and machines.

5.7 Data transformation

As stated in section 5.6, the goal is to keep the tool in spreadsheets as much as possible. We asked the supplier to fill in all the information about their resources and items into a spreadsheet. Information on resources and items will be discussed in section 5.8. The spreadsheet is then loaded into a Python file. Initially, we wanted to execute the model with the built-in Excel solver, but this could not be used because the model uses multiple indices. The model will produce the output parameters that are then transformed into a spreadsheet. Figure 5.3 shows the data translation process.

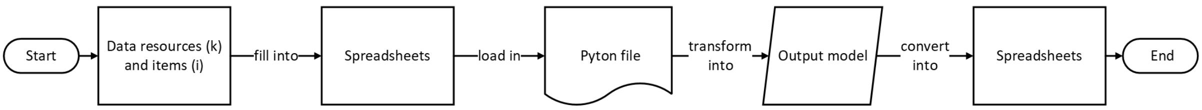


Figure 5.3: Process of translating data on resources and items to capacity planning output

5.8 Input model

In this section, we will discuss the outline of the input file needed to run the model. The model's input is a spreadsheet with four different tabs: input man, input machine, input items, and forecast on items. We will discuss the choices of the different spreadsheets in this section. In the spreadsheet file, the choice has been made to separate the dynamic and static data. Dynamic data in this context is, for example, the capacity pattern and is dynamic because every iteration needs to be reviewed since time has passed. Static data such as process times are not time-dependent and only need to filled in once. As discussed before, the input for the men and machine will be translated into the model as one variable: resource k. All items needed to run the model are asked directly in the spreadsheet except for the penalty cost of being unable to deliver, penalty cost of unused capacity, holding cost, and holing cost for WIP which are calculated indirectly. The parameterization of cost variables will be discussed in section 6.1.

5.8.1 Input Man

The first sheet that we are going to discuss is the sheet that is used to calculate the total men capacity. The supplier is asked to fill in the sheet of men skills needed for their production. In figure 5.4, the inputs requested in the sheets are given. The capacity of each month is asked for each skill. In the model, the start capacity will be the capacity of the resource on time 0 ($\hat{C}_k(0)$). The training time needed will serve as the lead time of a resource (τ_k). The cost of an employee (cost man) will be a penalty for hiring a new person (γ_k).

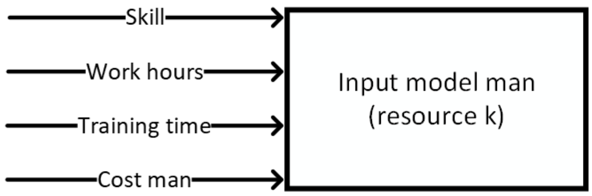


Figure 5.4: Schemes of input man

5.8.2 Input machine

The second sheet that we ask suppliers to fill out is the capabilities of their machines. The capacity per machine per month is given in the sheet. The machine capacity at time 0 will serve as input for the model as the start capacity of a resource on time 0 ($\hat{C}_k(0)$). We have also seen suppliers use Overall Equipment Effectiveness (OEE) to calculate their net capacity per machine. We choose not to include this because we express the available capacity per month, which provides for maintenance, and the quality rate is given on the item level, not on the resource level. The cost of the new machine will serve as the penalty cost on obtaining a new resource (γ_k), and the lead time new machine will serve as the lead time on resource (τ_k).

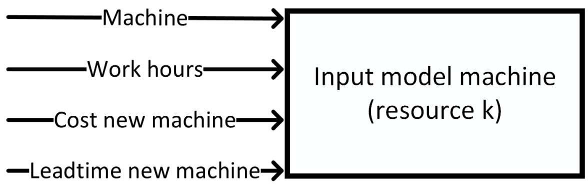


Figure 5.5: Schemes of input machine

5.8.3 Input item parameters

After the man and machine sheet, the supplier is asked to fill out the items sheet, which is the final step in completing all information needed to run the model. In the last sheet, the supplier is asked about the items (i) that a supplier needs to deliver. If an item is a sub-process, the supplier is asked not to include the safety stock or the current stock. The resource needed and the processing time will be the time required to process one unit of item i on resource k (c_{ik}). The lead time is the time between the release of an order for an item and when the ordered items are available for usage in other items (L_i). The safety stock (v_m), the current stock ($X_i(0)$), and the holding cost only have to be filled in for end items. Yield loss (ε_i), product price, and forecast are asked for every item.

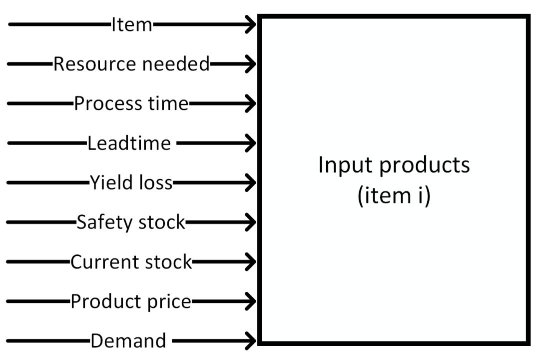


Figure 5.6: Schemes of input items

The forecast on each item is given in a different tab in the spreadsheet because we want to separate the dynamic data from the static data. The forecast is provided per month for the coming four years. The last year of the forecast will be extrapolated to ensure that the model does not cut off at the end of year four.

5.8.4 Combined input

When all sheets are correctly filled in, python can translate the data from the sheets to arrays in the model. This process is shown in figure 5.6. The model will combine the input from men and machines into input for resources. As stated before, the model does not differentiate between the resource as man or machine for model simplification. In the model's output, every resource will be shown so that the person analyzing it can see the difference between men and machines again. The parameters of the items will go directly into the model and will not be translated.

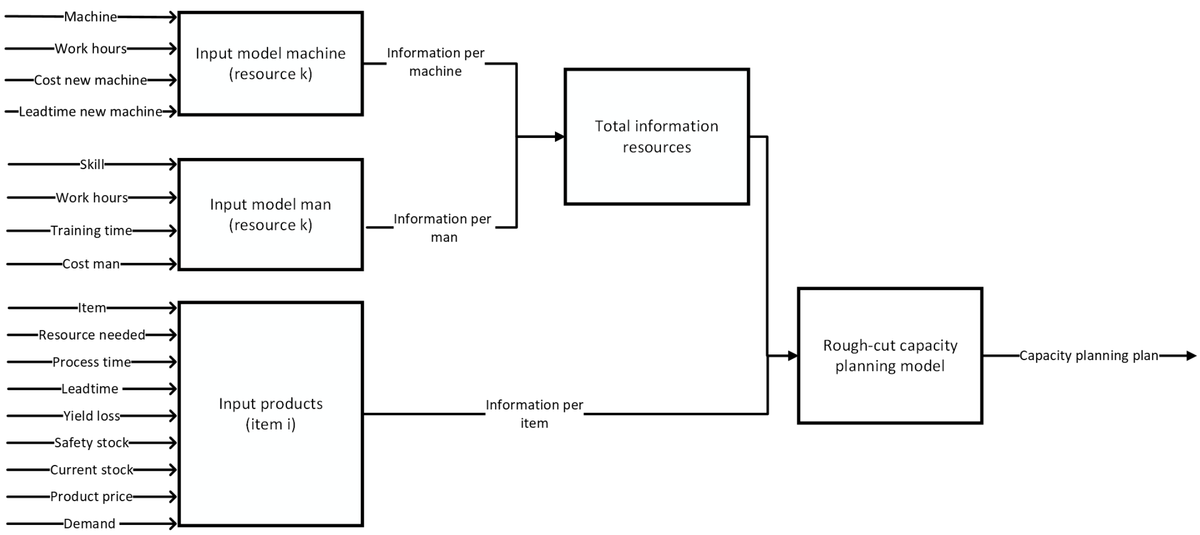


Figure 5.7: Schemes of input model

5.9 Output model

As discussed in section 5.6, the output file is separate from the input file. The output file shows the model's outcomes so that both of the model's goals are met. The first goal was to check whether the supplier could produce the items given the demand. From the output, the supplier can see how much additional capacity is needed over time to keep up with the demand of ASML. The first spreadsheet will show a list of the resources and if the cumulative capacity is enough to cover the demand. A proposal for a dashboard of the first sheet is given in appendix B in figure B.2. When a supplier is not ready or at risk, the supplier is then asked to develop a structured plan to show that they will have this capacity. This plan can be a facility expansion, hiring, or a capacity implementation plan. The plan that the suppliers are asked to make after the model's output is out of scope because it can be different for every supplier.

The second goal of the model was for the supplier to get insight into their capacity planning. This goal is achieved by letting the output be more interactive. The supplier can still change output when they want to add or remove capacity. In the output, we show the cumulative capacity of each resource; this is done because we do not want to know the capacity on a certain period (such as a day), but we want to know if the capacity over four years will be enough to fulfill the demand of ASML. A proposal for a dashboard for the second sheet is given in appendix B in figure B.3. More details on the visuals of the output will be discussed in section 6.

5.10 Model verification and validation

The fundamental procedures for assessing and building confidence in numerical models are model verification and validation. The process of establishing whether a model implementation effectively represents the developer's conceptual definition of the model and its solution is known as verification. Validation is determining the degree to which a model accurately represents the real world from the model's intended usage standpoint. Verification and validation are both processes that collect evidence of a model's correctness or accuracy for a specific scenario; thus, verification and validation cannot prove that a model is correct and accurate for all possible scenarios, but they can provide evidence that the model is sufficiently accurate for its intended use. This section will explain how the model will be verified and how the validation will take place.

5.10.1 Verification

It is crucial to verify the correctness of the model. In this section, we will focus on the verification of the model. The verification's main goal is to estimate the numerical accuracy of a given solution to the governing equations and check if the coding is done right. The errors identified and removed by calculation verification may include code errors, incorrect input options, and model errors. The verification is done using a synthetic data set to run the model. We validate the model by using various input combinations and looking at the output data. In our case, we will look at the impact of lead time, seasonality, and different supply chain structures. If the output data changes as we expect it to, then the model will most likely be implemented correctly. An example of a check could be if the demand for an item is increased significantly, the resource would require more capacity, and more capacity would be obtained in the output.

5.10.2 Validation

Modeling and validation processes cannot be separated because building a model requires a constant validation process (Landry et al., 1983). In between the modeling, a few steps toward the validation of the model are implicitly included. We zoom in on the modeling part of the research method given in figure 2.4. Figure 5.8 shows the modeling validation process. This figure is inspired by Mitroff et al. (1974) and gives the validation steps between the four stages in modeling. This section will discuss the five kinds of validation that can be used to validate the model. A few validation steps are done simultaneously with the modeling, but they will be briefly discussed.

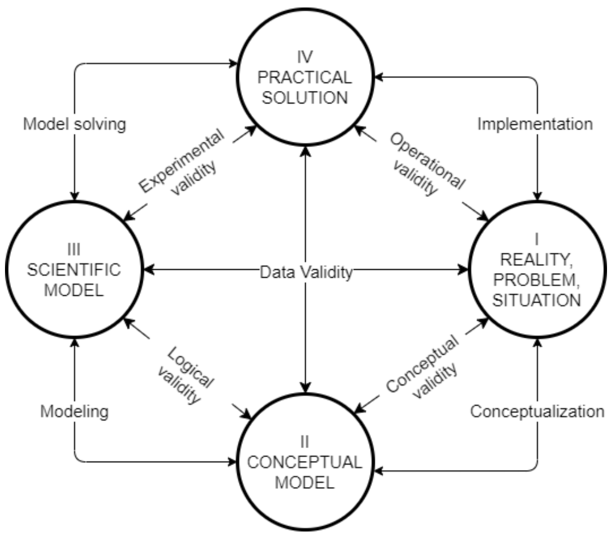


Figure 5.8: Modeling validation process (Landry et al., 1983)

Conceptual validation

The main concern of conceptual validation is the degree of relevance of the assumptions and theories underlying the conceptual model of the problem situation for the intended users and the use of the model. Conceptual validity answers questions like, "Are we viewing the problem situation from the correct perspective?" and "To what extent do the constructs reflect the situation?" (Landry et al., 1983). We have implemented this by using the supplier interviews and interviews with LSMers to check what suppliers are capable of and what the problem is from their perspective. We also looked at how the inputs are related to each other to make a capacity plan. The conceptual validation therefore mainly be found in section 3.

Logical validation

Logical validation is a type of validity concerned with the scientific model's ability to describe the problem situation as defined in the conceptual model correctly and accurately. Logical validation entails checking to see if any relevant variable or relationship has been left out of the formal model: it seeks to assess internal coherence as well as the impact of the modeling language on the formalization process. (Landry et al., 1983) The validation is done by transforming the model into a scientific model (section 5.2) where the assumptions of the conversion from model to scientific model are discussed in section 5.1.

Experimental validation

The scientific model is built to get capacity planning on each resource; the practical solution is how the capacity planning is represented. Experimental validation refers to the quality and efficiency of the solution mechanism. During the model design, this has already been addressed. The choice for the type of modeling is discussed in section 4, and the option for the solution mechanism is briefly discussed in section 5.7. In appendix C, we will confirm that the choices made during the model's development will lead to a reasonable computing time. This is done by implementing different-sized data sets into the model.

Operational validation

Operation validation generates information that assists decision-makers in accepting or rejecting the solutions and recommendations of the formal models to be adopted. It also reveals whether the model has the potential to justify the investment of time, effort, and money. In our case, this means that we want to get feedback on the model's testing method, interface, and output. This feedback is requested from suppliers and from LSMers. The feedback is quantitative and is sometimes also referred to as face validation. The operational validation will be discussed in section 7.2.

Data validation

Data validation concerns the data's sufficiency, accuracy, appropriateness, and availability. Because demand and supply are stochastic in nature, a single experiment concerns a single item's process over a period of time, typically at least half a year. (de Kok, 2018) During this time, data is collected to generate probability distributions that describe the demand and supply processes. In this research, due to time constraints, we do not have the time to collect data over such a time span and, therefore, cannot check if the data used represent a supplier's production process. We make use of synthetic data to run the model. In the review of the model, we ask the supplier if the synthetic data could reflect reality. This method of data validation is far from airtight, but the goal of the synthetic data is to show that the model could work if a supplier uses it.

5.11 Conclusion

The goal of this section was to describe the development process and mathematical formation of the model used to assess the internal capacity of a supplier. A model has been formulated, and the in- and outputs of the model have been discussed. Next to that, we also formulated an extension of the model to be used in supply chain planning. Lastly, we discussed the verification and validation process of the model. With this, we aimed to answer the following sub-questions:

2.1 How can a framework be made where suppliers can be standardized on their rough-cut capacity plan?

We developed a model for aggregate capacity planning in the context of S&OP. We used linear programming because it is a quick way of obtaining results. The model includes item lead times, hiring and firing capacity, safety stock, and workload control. We included capacity slack in the model to cope with uncertainty, and we developed a method to include norm capacity, something that to the best of our knowledge we currently do not see in the literature. The goal of the output model is twofold. The first goal is to check whether the supplier has enough capacity to produce the items from the forecast that is given. The second goal is to provide suppliers insight into their capacity planning.

2.2 How is a standardized framework, where suppliers' rough-cut capacity plan can be checked, structured?

The interface of the model is a spreadsheet, as it is the industry standard and most known. The model's input will be split into three categories: input men, input machines, and input items. The inputs will then be loaded into a Python-based model, and the output will be again shown in a spreadsheet. The in- and output files will be separate files because the input file contains sensitive information about the supplier that they do not want to share with ASML. The output of the model will show the capacity plan per resource. This capacity plan will provide transparency and visibility in terms of available options to increase/decrease capacity and trigger the discussions and scenarios to be evaluated in every quarter.

2.3 How can a rough-cut capacity plan be made for a supply chain?

We use the model to calculate suppliers' internal capacity plan and extend the resources. Supply chain planning is the same as production planning, but with more resources. We propose two extensions to the model for first-tier and N-tier capacity planning. The difference between first-tier capacity planing and N-tier capacity planning is the linkage between the suppliers. First-tier supply chain planning will provide ASML with an overview to which suppliers propose a risk to their forecasted demand. Whereas N-tier capacity planning provides suppliers with insight into where demand is coming from and the capabilities of other suppliers.

PART III

LEARNING AND EVALUATION

6 Results

In this section, we discuss the results of implementing the model discussed in section 5. The parameterization of cost variables will be looked into first. The findings of the syntactic data set will be shown next, where we apply the model to different structures of supply chains. In this section, we aim to answer the following research question: *3.1 What are the results of using a rough-cut capacity model on synthetic data?*.

6.1 Cost parameters

As discussed in section 5.8.3, the penalty cost, cost of unused capacity, holding cost, and the holding cost of WIP are not inputs. They will be calculated indirectly from the other inputs that have been given. This section will explain the motivation of the parameter values chosen. In section 7.1, we will discuss the impact of the parameters on the optimal objective and the impact on the capacity plan resulting from the model.

6.1.1 Holding cost (hf_m)

Holding costs are costs associated with storing unsold goods. Holding costs include storage space, labor, insurance, the price of damaged goods, and depreciation. Storing products also brings risk with it because engineering changes can occur, making the stock obsolete. We estimate the holding cost at 25% of the product price.

6.1.2 Back ordering cost (p_m)

In this model, we want to check if the supplier can supply their product given the demand of ASML, but in reality, back-ordering can occur. Backorders are undesired by ASML because they can cause a production stop. Back orders could result in the generation of discrete and implicit costs by the supplier. The various types of indirect costs incurred by a supplier owing to back ordering include extra material handling administration and transportation costs required to expedite the delivery of the back ordered items of the customer, profit loss owing to customer order cancellation, profit loss cost owing to the sales of the back ordering items at discounted selling prices, cost of additional resource capacity required to meet the back ordered items, workers or machine idleness cost owing to stock-outs of the raw materials, rescheduling cost owing to change in production schedule (Makinde and Munyai, 2020). As the workers or machine idleness cost owing to stock-outs of the raw materials is high from ASML's point of view, we estimate the back ordering cost (p_m) to be four times the product price.

6.1.3 Cost of removing capacity (δ_k)

When a supplier has a lot of unused capacity on one machine, they might want to sell the resource. When a company decides to remove that capacity, it will not get the original value back but rather a salvage value. This is because the resource will have gone through depreciation over time. For example, companies can use discounted cash flow to determine what a machine is worth at a given time (Hilton et al., 2006). Therefore it is hard to put a specific cost on the unused machine capacity because each company will make a different calculation. Another difficulty of having a varying cost of removing capacity is that it will add unnecessary complexity. In the model, the cost of removing capacity will, therefore, be estimated at the price of buying a new machine.

As opposed to a machine, which depreciates over time, a resource increase in value due to training. But employee firing could have far-reaching implications. Firms that recruit and fire regularly have a negative public image. This could hurt sales and deter potential employees from joining the organization. Employee morale may suffer as a result. Furthermore, fired workers may not wait for business to pick up again. Firing workers can have a negative impact on the labor force's future size if those workers find work in other industries. Finally, most businesses are not free to recruit and fire at will. Labor agreements limit management's ability to change staff levels at will (Nahmias and Cheng, 2009). The consequences of 'firing' a machine are different. Based on parameter tuning, we will estimate the cost of firing men's capacity at two times the cost of obtaining capacity.

6.1.4 Cost of idle capacity (ρ_k)

In section 5.2, we introduced idle capacity (ρ_k). From a supplier point of view, you want to maximize your capacity to lower costs. The goal of the cost of unused capacity is to make sure that the model does not 'fire' unnecessary capacity. Based on parameter tuning, we will estimate the cost of unused capacity at two times the cost of obtaining capacity.

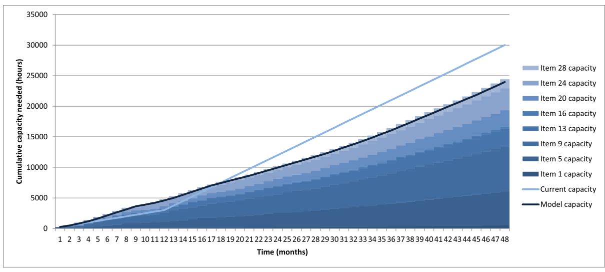
6.1.5 Holding cost WIP (hw_i)

The cost of unfinished products in the production process is referred to as WIP cost. In this scenario, the cost is holding raw materials or intermediary products on the work floor. Some suppliers have indicated that their production plan does not calculate the holding cost of WIP. Therefore we choose to make the holding cost WIP as a percentage of the product price. This is done because the product price includes total overhead, labor, and material costs incurred by the company, which is based on where WIP is based. The cost of WIP is set to 20% of the total cost.

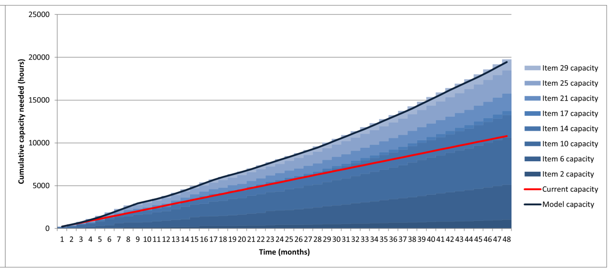
6.2 Results one supplier

In the output of the model, there will be one sheet that gives an overview of all the resources and if they have sufficient capacity to cover the forecasted demand (see appendix B figure B.2). A supplier or LSMer then has the choice to have more detailed information on each resource by selecting the resource (see appendix B figure B.3). The information shown in this tab is when suppliers need to 'order' a new machine or when the capacity can be removed. Based on the data shown in the output, the supplier can, for example, do a scenario analysis by changing the capacity per month in the input file. Next to the results on when to buy or remove a resource, the output also shows a graph with the cumulative monthly demand. In this graph, the cumulative demand is split into the items so that a supplier can also see which items contribute the most to the total capacity needed.

Figure 6.1 shows an example of an output from the model. The two figures show two possible outcomes, the current capacity is enough to fulfill the forecasted demand (figure 6.1a), and the capacity is not enough to fulfill the forecasted demand (figure 6.1b). The results are obtained from a synthetic data set with 30 items and 7 resources. Note that utilization of 100% is used in this example i.e. no slack on capacity.



(a) resource with sufficient capacity



(b) resource with insufficient capacity

Figure 6.1: Results of the model with one supplier, 30 items, and 7 resources

In figure 6.1, it can be seen that the model capacity follows the forecasted capacity needed for the items produced on that resource. If the capacity needed is more than the current capacity, the model will obtain capacity τ_k time before it is needed. A supplier can, therefore, see in one glance when they should order new equipment or hire more personnel. But the model also works the other way around. If the current capacity exceeds the needed capacity, the model removes the excess capacity. The supplier can use this information to see how much excess capacity they have and plan to utilize it.

6.2.1 Influence of lead time

Next, we want to see the influence of a long lead time on items on the capacity plan that the model calculates. We compare three scenarios, one where all the items have a lead time of one month, one where all the items have a lead time of three months, and one where all the items have a lead time of eight months. We use a steady forecasted demand pattern where demand increases by 30% each year. In figure 6.2, the three scenarios are plotted together.

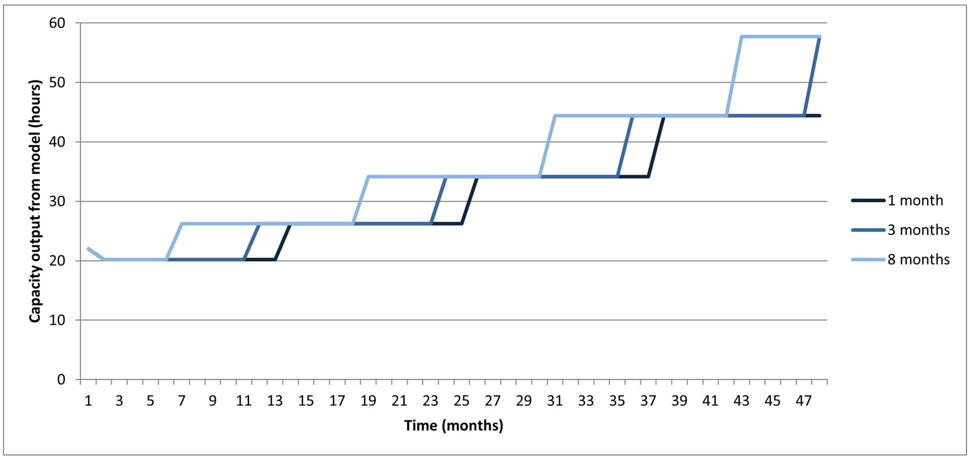
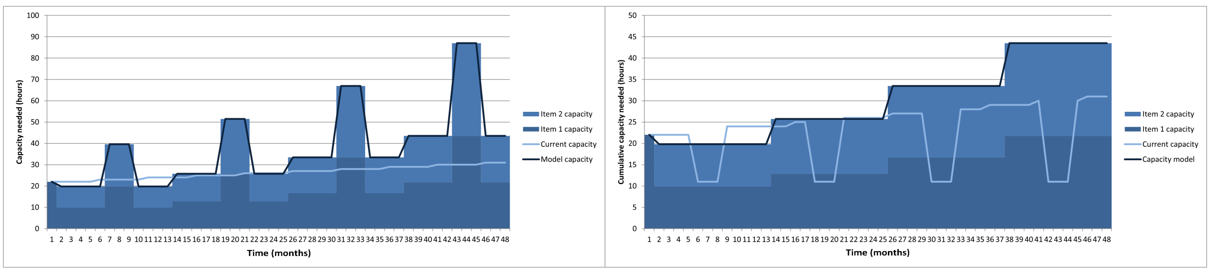


Figure 6.2: Capacity plan with lead time offsetting, one supplier with 4 items

We can see from figure 6.2 that the capacity shifts to the left when the lead time increases. When the lead time of an item increases, the capacity is needed earlier. This stresses the importance of including lead time in the model. If items have a big lead time, it is important to look at when the capacity is needed instead of only considering when a product needs to be delivered.

6.2.2 Influence of seasonality

In figure 6.3, we see the results of seasonality on demand (figure 6.3a) and on capacity (figure 6.3b). The figure plots the capacity plan against the time in months.



(a) Effect of seasonality on demand in the capacity plan (b) Effect of seasonality on capacity in the capacity plan

Figure 6.3: Effect of seasonality on the capacity plan

We see that for fluctuations in the demand, the model will adjust its capacity; because we set the cost of idle capacity to two times the cost of obtaining capacity, the model will remove the capacity after each demand spike. The fluctuations in capacity influence the hiring and firing of capacity, but we see in the model that the capacity plan of the model will still cover the forecasted demand.

6.2.3 Handling of back orders

To see how the supplier will react to back orders, we create a scenario where at time 0, we will have backorders (i.e., negative stock). In figure 6.4, we show the result of this scenario.

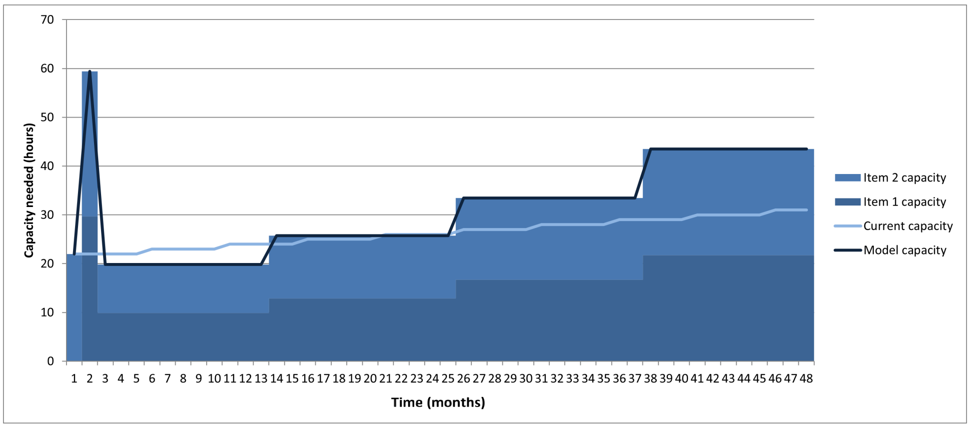


Figure 6.4: Capacity plan with initial back orders, one supplier with 2 items

Since the inventory is negative, the model will buy a resource to close this gap. In this case, the model will ensure that the back orders are covered as soon as possible since we set the cost for back ordering high.

6.3 First-tier supplier network

The first-tier network will have the same results as one supplier because the model is structured the same. The benefit of having a first-tier network analysis is for ASML to instantly see which suppliers can deliver and which can not immediately. A proposal for a dashboard where ASML will have this overview is given in appendix B in figure B.1. Suppose one of the suppliers cannot follow the forecasted demand. In that case, it does not make sense for the other supplier to comply with the forecasted demand because ASML will not order the forecasted materials because they want to avoid having a lot of items in stock.

6.4 N-tier supplier network

In this section, we will evaluate the n-tier supplier network extension of the model. We do this by looking at three different supply chain structures: a series supplier network, a parallel supply network, and a mixed supply chain model.

6.4.1 Series supplier network

The first supply chain we are going to discuss is a series supplier network. Figure 6.5 gives a schematic view of this supply chain.

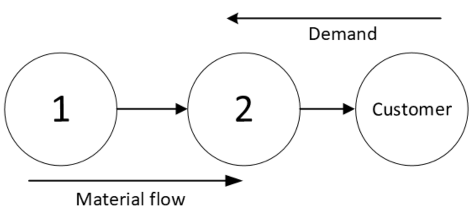


Figure 6.5: Series supplier network example

The supplier network consists of two suppliers and one customer. Demand is generated from the customer to supplier 2, from supplier 2, demand is generated to supplier 1. The lead time of suppliers 1 and 2 are both one month. In figure 6.6, the results of the capacity plan are given.

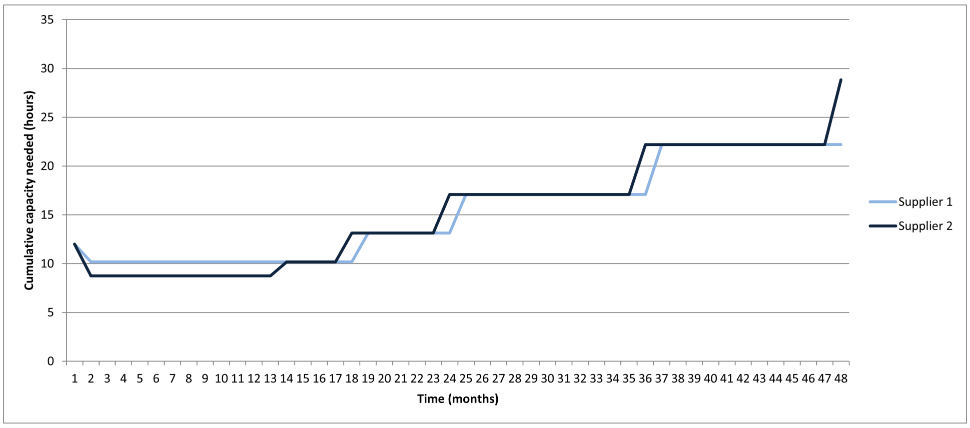


Figure 6.6: Series supplier network output on capacity, time against capacity plan model

We see that, because of the lead time from supplier 2, supplier 1 needs to make sure that they need to raise their capacity one period before supplier 2. From a capacity planning point of view, being a second-tier supplier has the same effect as increasing lead time in a series system.

6.4.2 Parallel supply network

Next, we discuss the model's results on a parallel supply network. The parallel network is given in figure 6.7.

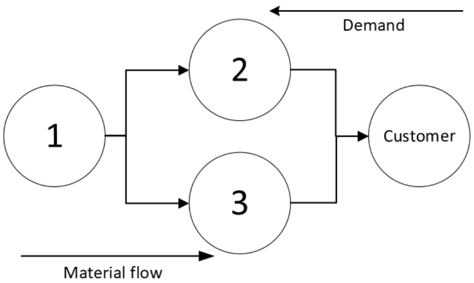


Figure 6.7: Parallel supplier network example

The customer again generates demand for suppliers 2 and 3. Supplier 1 receives demand from suppliers 2 and 3. The lead time for suppliers 1, 2, and 3 are 1, 3, and 1 month, respectively. The results on the parallel supply chain and their capacity planning are given in figure 6.8.

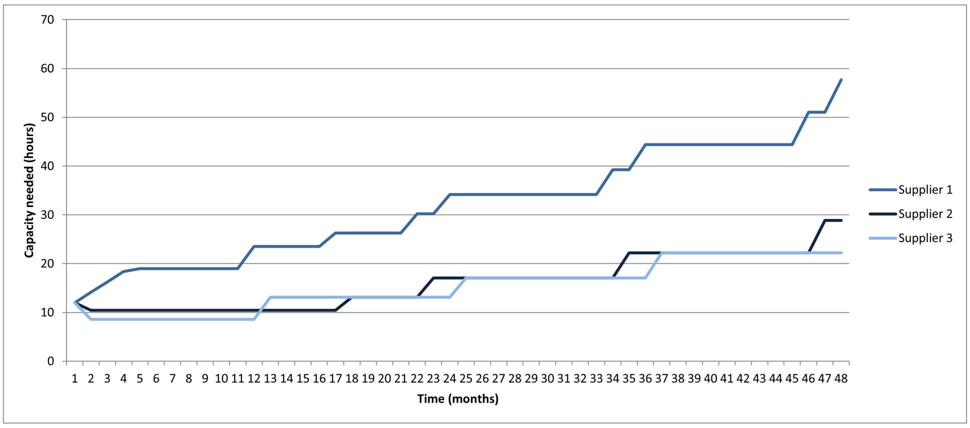


Figure 6.8: Parallel supplier network output on capacity, time against capacity plan model

We can see in the figure that because supplier 2 has a longer lead time the capacity plan shifts 3 periods back. We see that if we add the capacity plan of suppliers 2 and 3, we get the capacity plan for supplier 1.

6.4.3 Mixed supply network

To model a N-tier supply chain, we first need to define one. As stated in section 1.2, a supplier could be a direct or indirect supplier in the network of suppliers. A direct supplier delivers directly to ASML, and an indirect supplier delivers through suppliers to ASML. We want to model a supply chain with both a divergent and convergent structure, as these are also elements in the supply chain of ASML. We want to model a supply chain that has at least three layers. We took an example of Beeks et al. (2023), which analyzed a prescribed N-tier supply network from ASML. The supply chain that identified Beeks et al. (2023) can be found in appendix D, and the simplified version can be found in figure 6.9.

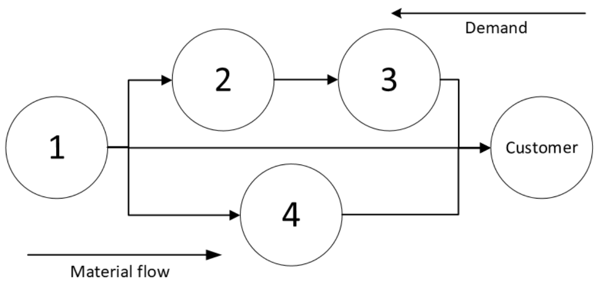


Figure 6.9: N-tier supplier network example

We construct a supply chain that consists of 4 suppliers and one customer. Supplier 1 is a 1^{th}-, 2^{nd}-, 3^{th}-tier supplier, supplier 2 2^{nd}-, 3^{th}-tier supplier and supplier 3 and 4 are 1^{th}-tier suppliers. We have a divergent aspect from supplier one to suppliers 2 en 4 and a convergent aspect from suppliers 3 and 4 to customer 5. Demand comes from customers, and demand for suppliers 2 and 3 is generated through the other suppliers. For simplification, we assume that each supplier only makes one product. The lead time of suppliers 1, 2, 3, and 4 are one month, three months, one month, and two months respectively. In figure 6.10, the capacity plan for each supplier is given.

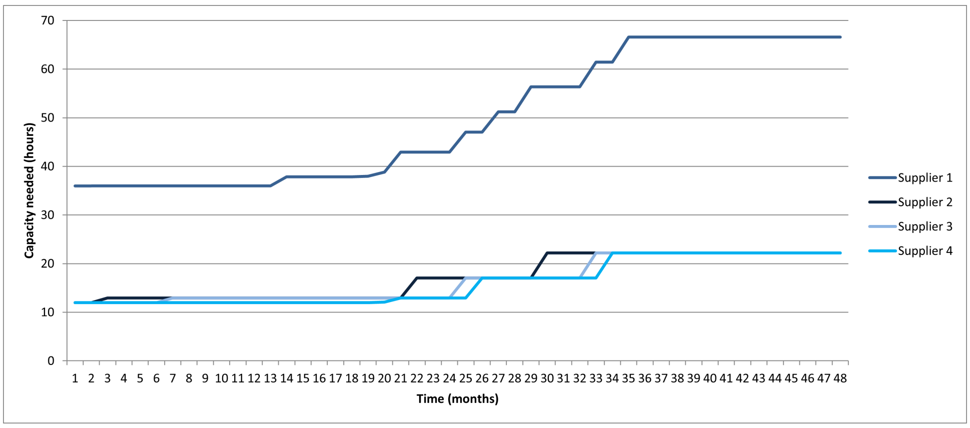
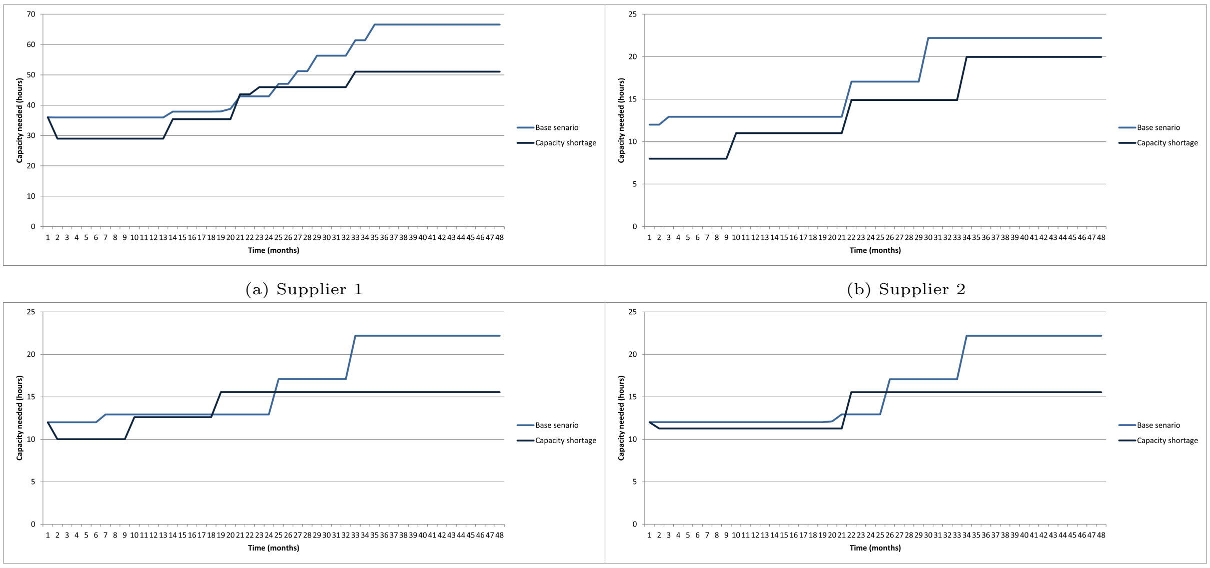


Figure 6.10: N-tier supplier network output on capacity, time against capacity plan model

In figure 6.10, it can be seen that due to lead time offsetting, suppliers 2, 3, and 4 do not need the same capacity at the same time. Supplier 1 has a steep demand increase due to the rise in demand coming from 3 different sources: directly from the customer, indirectly via supplier 4, and indirectly via suppliers 2 and 3. Therefore it is crucial that supplier 1 knows in advance what suppliers 3 and 4 need to deliver as the lead time from supplier 1 to the customer is longer. For example, the lead time between supplier 1 through suppliers 2 and 3 is five months, meaning supplier 1 has to increase their capacity five months earlier.

We want to see what the effect are if one of the suppliers in the supply chain does not have sufficient capacity. We create this scenario by setting the capacity of supplier 2, so that it can not cover the forecasted demand and is not able to obtain capacity. In figure 6.11, the capacity plan on each supplier is given.



(a) Supplier 1

(b) Supplier 2

(c) Supplier 3

(d) Supplier 4

Figure 6.11: Effect of one supplier in the supply chain not having enough capacity

In figure 6.11 we see that the shortage of capacity at supplier 2 does impact the capacity plan of all suppliers. As a consequence of the shortage at supplier 2, supplier 3 (figure 6.11c) does not have the necessary materials to produce their products and thus cannot increase their capacity. Since supplier 3 can not deliver the forecasted demand the customer will ask supplier 4 (figure 6.11d) to deliver the same quantities as supplier 3. The customer does this to avoid unnecessary stock. The capacity at supplier 1 (figure 6.11a) will therefore also be lower since suppliers 2 and 4 will lower their demand. The scenario that one supplier will not be able to confirm to the demand of ASML is likely to happen. As supplier 2 is in direct contact with supplier 1 and 3 they will receive information about the capacity shortage and thus can alter their capacity plan and lower it. Supplier 4 is not in direct contact with supplier 2 and if ASML does not communicate the capacity shortage, it will not receive this information and will have excess capacity and stock. This stresses the importance of applying this model to a supply chain as the information sharing about capacity decisions for suppliers is dependent on the bottle neck supplier in the supply chain.

6.5 Conclusion

In this chapter, we discuss the choices for the cost parameters and apply the synthetic data set to one supplier, first-tier supplier network, and n-tier supplier network. With this, we aimed to answer the following sub-question:

3.1 What are the results of using a rough-cut capacity model on synthetic data?

The proposed model is used to analyze different supply (chain) structures. We made simplified cases where we looked at lead time offsetting, material flow and demand flow. We have seen that the model can incorporate capacity and demand lead time offsetting. The model can cope with demand and capacity variation and will hire and fire capacity according to the forecasted demand. We have seen that the model can make capacity planning for different supply chain structures.

7 Model evaluation

In this section, we will evaluate the robustness of the model with a sensitivity analysis of several parameters. Next, we will discuss the feedback obtained by interviews on the model developed. In this section, we aim to answer the following research question: *3.2 What are the results of implementing a standardized rough-cut capacity plan at a supplier?*.

7.1 Sensitivity analysis

The cost parameters defined in section 6.1 are estimations and are not known with absolute certainty. Sensitivity analysis studies the effects of parameter changes on a given optimal solution of a model. Changing the value of a parameter is called a perturbation of that parameter (Sierksma and Zwols, 2015). In this section, we will look at perturbations of cost parameters in the objective function. A perturbation on the cost parameters of the model parameter will, in general, influence the optimal solution and objective value. We want to see the influence of different values of the cost parameters on the capacity decisions and the optimal objective value, i.e., the robustness of the decision. A complete overview of all the results of the sensitivity analysis can be found in appendices E and F.

7.1.1 Holding costs (hf_m)

Holding costs are the cost associated with storing goods. In section 6.1, we defined holding cost as 20% of the product price. Including holding cost in the model ensures that the model will not create excessive stock. We want to see how the change in holding cost effects the optimal objective and the capacity plan. We assume a price range of 500-50.000€. Since the holding cost is 20% of the product price, we let the holding cost change to a maximum of 10.000. We see that for low values for holding cost (between 0 and 80€), the objective value is sensitive to changes. First the holding cost are less important than the back order costs of expensive items, but at some point holding cost becomes more expensive than the back ordering and it becomes linear. After a holding cost of 1000€, we see a linear rise in the objective. We see the same trend in the influence of the capacity plan. Since we used a product price of 5000, we are in the stable region of the model, and a slight difference in the holding cost will not significantly impact the optimal objective or the capacity plan.

7.1.2 Back ordering costs (p_m)

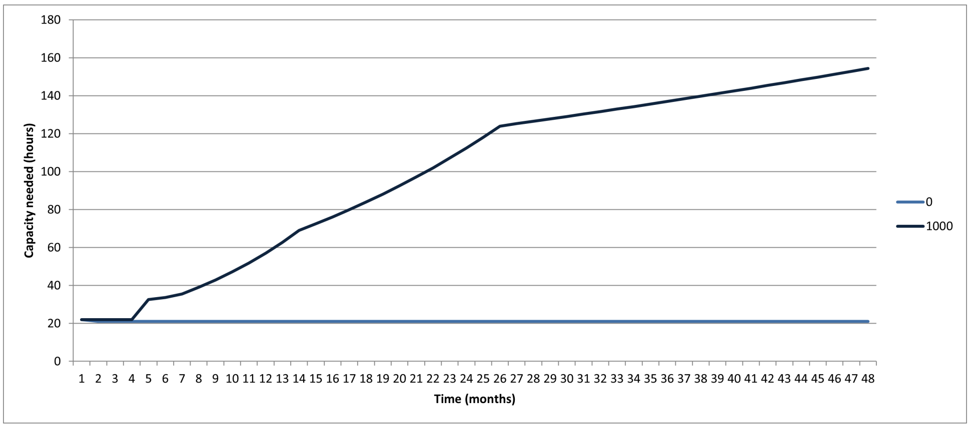


Figure 7.1: Sensitivity analysis on back ordering cost and capacity plan

The back ordering cost is the cost associated with delivering late. In the model, we have put the cost of back ordering to 10.000 since we assume that the cost of back ordering is expensive for ASML. We see that from a penalty cost of around 2000, change in the optimal objective begins to become stable. Thus, the back-ordering cost does not influence the optimal objective. After a penalty cost 2000€, the model will make a trade-off to have a minimum amount of back orders because the cost is too high. In this case, we can set the back ordering costs to 2000€ instead of 10.000€ and still get the same optimal solution. Figure 7.1 shows a capacity plan for back ordering cost for 0 and 1000€. We see that when backorder costs are low, the model will be more eager to have back orders instead of buying capacity to cover the demand.

7.1.3 Cost of obtaining capacity (γ_k)

The cost of obtaining capacity is the cost associated with the cost of buying or hiring a new resource. The cost of obtaining capacity has a broad spectrum as a resource could be a simple tool to a complex machine. We tested the influence of obtaining capacity in a range of 0-10.000. We see a constant linear increment in the cost of obtaining capacity with the optimal objective; this is because we have stated in the model that the capacity needs to be bought to cover the capacity. A change in the cost of obtaining capacity will not influence the optimal solution. The change in the cost of obtaining capacity does not influence the capacity plan.

7.1.4 Cost removing capacity (δ_k)

The cost of removing capacity is included in the model because we want to ensure that a resource is not fired immediately. After all, this can also negatively impact the company. We see that the cost parameter has a linear influence on the optimal objective in regions 0-2000€, but from 2000€, the cost of removing capacity does not influence the optimal objective. In this example, we set the cost of removing capacity to 1000, which means we are in the linear region. This means if the cost of removing capacity changes with one€, the optimal objective will change with 3€, which is the slope of the linear function. This only holds for the region between 537-1250€ of the cost of removing capacity.

7.1.5 Cost idle capacity (ρ_k)

We expect that for low values of the cost of idle capacity, the model will not fire capacity because there is no penalty for underutilized resources. We included the cost of idle capacity because we want to give a supplier insights into the capacity that will be unused and give insights into when a resource could be 'fired.' When we look at small values of the cost of idle capacity, we see exactly that. In figure 7.2, we see that the capacity plan changes for different values of cost of idle capacity. The capacity, at low-cost values for idle capacity, is higher. The demand stays the same, which means that for low values of the cost of idle capacity, the model will create a capacity plan with underutilized machines.

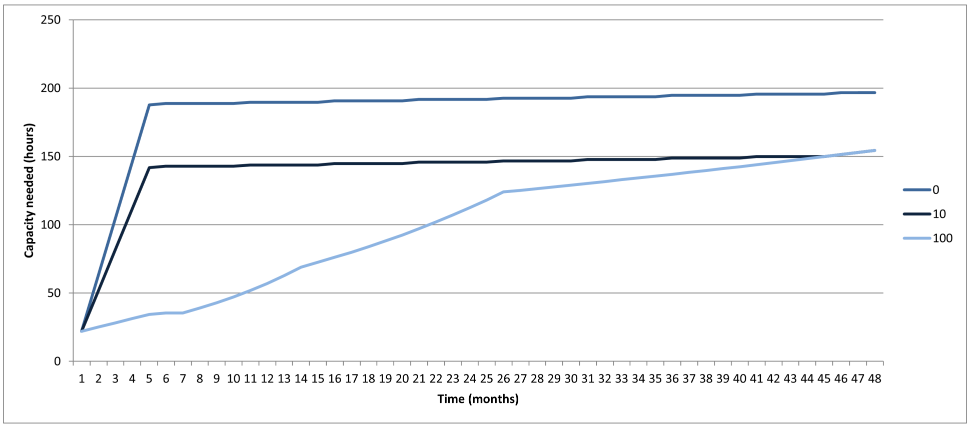


Figure 7.2: Sensitivity analysis on cost idle capacity and capacity plan

Regarding the sensitivity of the solution, we are in the stable region of the optimal solution since we set the cost of idle capacity to 2000€.

7.1.6 Holding cost WIP (hw_i)

We included the holding cost of the WIP to control the work floor's amount of WIP. We want to ensure the model does not release too many orders, as floor stock is expensive. We see a linear trend between the holding cost of WIP and the optimal objective. Since there is no change in the slope of the relation between the cost and the optimal objective, we assume that the optimal solution is not dependent on the holding cost of WIP. We see that with every increment of holding cost, the optimal solution rises to 10700€.

7.1.7 Capacity slack (ψ_k)

We introduce capacity slack in section 5.3. We can put a maximum utilization rate on a resource with capacity slack. We know that the model will hire more capacity when utilization becomes lower, and the cost will be higher due to the capacity needing to buy more. We also see this when we analyze the utilization rate with the optimal objective and the capacity plan, for low values of utilization, the cost is significantly higher than for higher values. The capacity plan for low utilization values needs more capacity, as shown in figure 7.3. Capacity slack is, therefore, a decision that the supplier must determine with the trade-off between cost and slack in capacity.

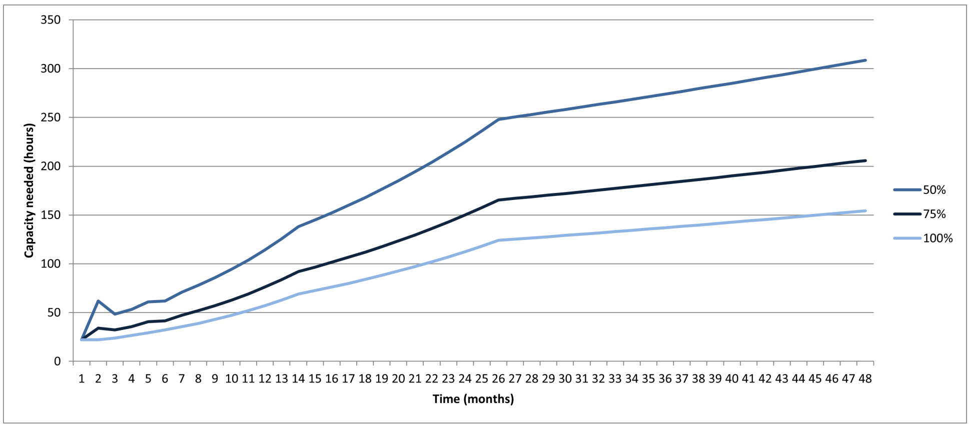


Figure 7.3: Sensitivity analysis on capacity utilization and capacity plan

7.1.8 Safety stock (v_i)

We included safety stocks in the model to hedge for short-term demand uncertainty that could occur in the time horizon of four years. We formulated the safety stock in the model, but we did not have safety stock in the cost objective. We did this because the mathematical programming problem formulation only attempts to model the supply chain operations planning problem under stochastic exogenous demand. In that sense, any such formulation results in a heuristic with respect to the original optimization problem (de Kok and Fransoo, 2003). Therefore we do not see the objective function change if we change the safety stock of an item, the same holds for capacity planning.

7.2 Operational validation

Operation validation generates information that assists decision-makers in accepting or rejecting the solutions and recommendations of the formal models to be adopted. It also reveals whether the model can justify the investment of time, effort, and money (see section 5.10). Interviews with suppliers were conducted after the model was created to obtain operational validation. In the interviews, the supplier was asked if they find the output helpful and if they would use this method. In total, three suppliers were interviewed. The outcomes of these interviews are referred to as face validation and are quantitative. We split the face validation into two main questions: 'What are the additional benefits to the current process?' and 'What are improvements on the method?'.

What are additional benefits compared to the current process?

The model that was developed has three main advantages compared to the current method that each supplier uses. The first is that the method is standardized which gives the suppliers a frame of reference for what ASML wants to see in their analysis. The suppliers are now relatively free to explore their own methods for determining their capacity plan on men and machine which sometimes leads to a mismatch compared to ASML's expectations. Standardizing the method also leads to the second benefit which is that the step to supply chain capacity planning is relatively easy to implement. In section 5.5 we propose an extension to the model which leads to supply chain capacity planning, which will create meaningful insights for ASML. This does not only benefits ASML but especially suppliers which are nested in the supply chain. Multi-tier suppliers have difficulties with getting information on the forecasted demand from ASML and when they need to ramp up their production. The third main advantage is that the static data of the model only has to be filled in once because it will not change over time. In section 5.8 we discussed the difference between dynamic and static input parameters. In this way, the supplier only has to update their capacity per period on each resource and the demand that they expect for each item. This, in the end, will save the supplier time.

What are improvements on the method?

Several improvements to the model have been proposed by the suppliers. One extension that would make the model easier to use is that it would be linked with their ERP system. Some suppliers have more than 100 items that they need to deliver to ASML and even more items that are produced on one resource. The dynamic data (capacity per month and demand per month) for example could be retrieved from a supplier's ERP system. However, this requires the model to be customized for each supplier, assuming that they all have different ERP systems. Another improvement to the method would be to eliminate the step to open Python and run the model. Unfortunately, the IT structure of ASML currently does not allow for this to happen. Another improvement that a supplier suggested was to expand the number of resources that can be needed for producing one item, as now in the input only one machine and one man can be selected. Other directions for future research are given in section 9.3.

7.3 Conclusion

This section concludes with the applicability of the capacity planning model and method. We looked at the sensitivity of the model to the objective function and the capacity plan. With this section, we aimed to answer the following research question:

3.2 What are the results of implementing a standardized rough-cut capacity plan at a supplier?

From the second round of supplier interviews, it can be concluded that the model adds value. The model provides the supplier and ASML with transparency and visibility in terms of where the capacity plan is based upon, due to the standardization. Next to that, the method is standardized which gives the suppliers a frame of reference for what ASML wants to see in their analysis. It also gives ASML the information if a supplier is able to comply with their forecasted demand. The model takes into account lead time offsetting of items, making it easy to implement into a supply chain. Suppliers that are nested in the supply chain could benefit from this as they have difficulties as multi-tier suppliers to get information about the forecasted demand from ASML. Improvements to ASML's and the supplier's IT infrastructure are required to make the model more user-friendly and ready for implementation.

8 Conclusion & Recommendations

This section discusses the conclusion of this research and practical recommendations for ASML.

8.1 Conclusion

In this research, a model for determining capacity at a supplier and in a supply chain was made. This section concludes the research by providing answers to the defined research questions. Based on the problem statement, the following main research question was formulated: *How to design a standardized method for suppliers to perform their Rough-Cut Capacity Planning of their Men and Machines?* The sub-research question are answered one by one.

1.1: How do suppliers of ASML currently determine their capacity on men and machines?

The 4M-analysis is presented in a PowerPoint format, where the results are shown graphically. Two suppliers performed their calculations in Excel and one in PowerBi. Suppliers indicated that there was no single way of working and that the results they needed to show were also dependent on the LSMer who was working with them on the analysis.

We got an understanding of who performed the analysis and what the processes are that the supplier uses to get their information. We observed that every supplier had their own way of working on the 4M-analysis. We found some insights for ASML around the 4M-analysis, like the Where-Used and enriched demand is often missing or incomplete. The in- and outputs the suppliers use for the capacity analysis on the men and machines are also known. The in- and outputs will later be used as a guide to make a model to determine the capabilities of the men and machines.

1.2 What methods exist in the literature for assessing suppliers' capacity and their network?

We have identified the following levels of capacity planning: strategic, tactical, and operational. We found that the 4M method is used on a tactical level. With that, mathematical programming, specifically linear programming, appears as a typical solution for aggregation planning type problems. Its benefits include solving the problem time-efficient, especially when what-if analysis is required. We discussed models in Multi-item Multi-level Capacitated Lot Sizing Problems. We saw that current research focuses on tractable uncapacitated stochastic models with low structural complexity for convergent and divergent structures and a mathematical programming technique for solving deterministic cases. Lastly, we discussed the role of uncertainty in capacity planning and how to cope with the uncertainty in modeling.

2.1 How can a framework be made where suppliers can be standardized on their rough-cut capacity plan?

We developed a model for aggregate capacity planning in the context of S&OP. We used linear programming because it is a time-efficient way of obtaining results. The model includes item lead times, hiring and firing capacity, safety stock, and workload control. We had capacity slack in the model to cope with uncertainty, and we developed a method to include norm capacity, something that to the best of our knowledge we currently do not see in the literature. The first goal is to check whether the supplier has enough capacity to produce the items from the given forecast. The second goal is to give suppliers insight into their capacity planning.

2.2 How is a standardized framework, where suppliers' rough-cut capacity plan can be checked, structured?

The interface of the model is a spreadsheet, as it is the industry standard and most known. The model's input will be split into three categories: input men, input machines, and input items. The inputs will then be loaded into a Python-based model, and the output will be again shown in a another spreadsheet. The in- and output files will be separate files because the input file contains sensitive information about the supplier that they might not want to share with ASML. The output of the model will show the capacity plan per resource. This capacity plan will provide transparency and visibility in terms of available options to increase/decrease capacity and trigger the discussions and scenarios to be evaluated in every quarter.

2.3 How can a rough-cut capacity plan be made for a supply chain?

We use the model to calculate suppliers' internal capacity plan and extend the resources. Supply chain planning is the same as production planning, but with more resources. We propose two extensions to the model for first-tier and N-tier capacity planning. The difference between first-tier capacity planing and N-tier capacity planning is the linkage between the suppliers. First-tier supply chain planning will provide ASML with an overview to which suppliers propose a risk to their forecasted demand. Whereas N-tier capacity planning provides suppliers with insight into where demand is coming from and the capabilities of other suppliers.

3.1 What are the results of using a rough-cut capacity model on synthetic data?

The proposed model is used to analyze different supply (chain) structures. We made simplified cases where we looked at lead time offsetting, material flow and demand flow. We have seen that the model can incorporate capacity and demand lead time offsetting. The model can cope with demand variation and capacity variation and will hire and fire capacity according to the forecasted demand. We have seen that the model can make capacity planning for different supply chain structures.

3.2 What are the results of implementing a standardized rough-cut capacity plan at a supplier?

From the second round of supplier interviews, it can be concluded that the model adds value. The model provides the supplier and ASML with transparency and visibility in terms of where the capacity plan is based upon, due to the standardization. Next to that, the method is standardized which gives the suppliers a frame of reference for what ASML wants to see in their analysis. It also gives ASML the information whether a supplier is able to comply with their forecasted demand. The model takes into account lead time offsetting of items, making it easy to implement into a supply chain. Suppliers that are nested in the supply chain could benefit from this as they have difficulties as multi-tier suppliers to get information about the forecasted demand from ASML. Improvements to ASML's and the supplier's IT infrastructure are required to make the model more user-friendly and ready for implementation.

How to design a standardized method for suppliers to perform their Rough-Cut Capacity Planning of their Men and Machines?

This research takes a step-wise approach in designing a method for suppliers to perform their rough-cut capacity planning of their men and machines. From information from supplier interviews to a conceptual model, to a mathematical model. Finally, the scenarios that are generated from the synthetic data prove that the model works and can be applied to various situations, like supplier capacity planning but also supply chain capacity planning.

8.2 Recommendations

Several recommendations for ASML and their suppliers are formulated related to applying and improving the model developed in this thesis.

First of all, it is highly recommended to implement this model at suppliers. Even if the method might not be fully developed, it would still give insights into the validation of the model. We tested the model in this thesis on synthetic data, but confirming that the model reflects the real processes at a supplier would be advised.

It is also recommended to explore the possibility of using the ERP system of suppliers to update the dynamic demand, such as capacity planning per month and demand per month. It will enhance the user-friendliness of the model since it will become easier to use each quarter.

Furthermore, it is recommended that ASML improve its process to deliver the information needed to perform the 4M-analysis; Where-Used list and their enriched demand. The Where-Used list is often missing or incomplete. Suppliers need that list to transform the Red Table containing the demand for the coming four years into forecasted demand per item. If this list is incomplete or contains the wrong information, the supplier cannot perform a complete analysis. The same holds for the enriched demand; this is the service demand that suppliers need to deliver on top of the Red Table demand. If the enriched demand is incomplete or missing, the supplier cannot make a complete analysis and thus will make wrong capacity decisions.

Lastly, in section 2.3 we identified two main problem causes of the unreliable RCCP. One of the main causes was that the strategic demand is the maximum capacity ASML wants to reserve to their suppliers. Suppliers therefore know it to be lower than the actual demand. This means that the forecasted demand from ASML already introduces slack in the form of over forecasting. Therefore we advice the supplier to try different scenarios on the slack parameters that we introduced to find the optimal fit.

9 Reflection

This section reflects on the performed research. The first section discusses how the research contributed to academics. The section discusses the research's limitations, and the final section makes recommendations for future research.

9.1 Academic implications

The main contribution to the current literature is proposing a model for strategic capacity planning that can be used in a practical setting. Decision-makers can use the model to generate tactical decisions on capacity. We found a method that allows variation in capacity due to holidays, maintenance, etc., to be used as input in the model. Including the norm capacity is something we currently do not see in the literature.

9.2 Limitations

The current research is subject to several limitations. In the modeling phase, we simplified some assumptions that might influence its reflection on reality. The main limitations imposed by the design of this study are presented, with their impact:

- **Constant lead times** - In the model, we assume constant lead times; this holds for the lead time of items and the lead time of obtaining capacity. These lead times shift due to uncertainty in process times and the supply chain. Therefore the lead time needs to be checked every quarter to see if they are still in line with the lead times given in the previous period. Underestimating lead times can significantly impact delivery performance and capacity planning.
- **Deterministic parameters** - In the model, we assume deterministic parameters; in reality, these parameters are stochastic. In the model, we apply exogenous input variables such as planned lead times and safety stocks. However, the stochastic nature of parameters could still greatly impact the results.
- **Numerical verification** - The outcomes discussed in section 6 are not numerically verified. We based the model on synthetic data, but preferably the model is validated by historical data or a pilot.
- **Bias due to interviews** - In this thesis, a total of six different companies have been interviewed, which is a limited number considering all suppliers of ASML. We made decisions on modeling based on the supplier interviews, therefore the model could include bias, thus, cannot be used for every supplier.

9.3 Future research

Several directions for future research follow this study.

The first possibility for future research is improving the IT infrastructure of ASML and the suppliers in a way that automatic conversion from the Red Table to actual demand for the supplier is possible. Furthermore, as proposed earlier, it would be a beneficial addition to the model as data on capacity planning and information on items can be extracted via the ERP system of the supplier.

Secondly, implementing the model at a supplier by performing a pilot would also be a direction for future research. In this thesis, we only applied the model on a synthetic data set, but it would be valuable to perform a pilot so it could be verified that the model reflects reality. The same holds for applying the model to a supply chain.

Next to that, it would be useful to include new product development in the capacity analysis as this could significantly impact the capacity in the future. Currently, only the forecasted demand is given for products in series production. By also accounting for possible demand from new products (that will be produced for ASML) as companies could already prepare for that capacity need.

Several extensions could be added to the model, depending on the supplier's needs. One possibility for extending the model would be the possibility for outsourcing, as we now assume that every operation is done at the supplier. Another extension to the model would be to include the learning effect and scale-up effect in the model. This could be done by having a time-dependent lead time or process time. In the model, we include WIP to have workload control. A constraint on the amount of WIP is currently not included in the model. This constraint can be necessary for specific manufacturing applications, such as a clean room. In appendix G, we propose two possible extensions to the model where a WIP constraint is included.

Lastly, in this thesis, we only developed a model for two of the 4M's from the 4M-analysis. For consistency, it might be valuable to have all analyses in one document, so a direction for future research could be to develop a method for materials and methods.

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A Definitions for supply chain readiness

		Capability requirement (6 to 36 months)	Operational execution (0 to 12 months)
Red	Factory or field impact	▪ No agreed plan to timely install requested capability on 1 or more aspect of 4M elements	▪ CSC (parts) currently in L2/L3 escalation
Yellow	Readiness not secured	▪ Supplier late in agreed plan but requested capability will still be installed on time or ▪ Only high level plan shared but actions to install capability on time are not due yet	▪ SAP demand structural same as or exceeding max MR or ▪ Peak loading above max MR and no/limited ability to mitigate
Light Green	Readiness on track	▪ Plan in place and agreed to timely install capability and all actions within plan on track. DGM approval not yet due or approved	▪ Peak load in month(s) exceeding maximum MR and plan in place to mitigate peak loads
Green	Ready today	▪ Capability already in place today to meet future Move Rate requirement, no gaps identified in 4M analysis	▪ SAP demand below maximum MR or ▪ Peak load with sufficient time to recover within normal operations

Figure A.1: Definitions for supply chain readiness

B Proposal dashboard man & machines capacity analysis

Supply chain readiness

Not ready

Suppliers	Capacity year 1	Capacity year 2	Capacity year 3	Capacity year 4	Conclusion
Supplier 1	At risk	Not ready	Not ready	Not ready	Not ready
Supplier 2	Ready	Ready	Ready	At risk	At risk
Supplier 3	Ready	Ready	Ready	Ready	Ready
Supplier 4	Ready	Ready	Ready	Ready	Ready
Supplier 5	At risk	Not ready	Not ready	Not ready	Not ready
Conclusion	At risk	Not ready	Not ready	Not ready	Not ready

Figure B.1: Proposal dashboard man & machines capacity analysis supply chain level

Supplier 1

Not ready

Resources	Capacity year 1	Capacity year 2	Capacity year 3	Capacity year 4	Conclusion
Resource 1	90%	110%	120%	150%	Not ready
Resource 2	70%	75%	80%	83%	At risk
Resource 3	75%	70%	75%	77%	Ready
Resource 4	75%	76%	78%	80%	Ready
Resource 5	95%	105%	110%	120%	Not ready
Conclusion	At risk	Not ready	Not ready	Not ready	Not ready

Figure B.2: Proposal dashboard man & machines capacity analysis supplier level

Resource 1

Not ready

Month	Capacity needed (hours)	Model capacity (hours)	Current capacity (hours)	Order capacity	Utilization current situation
1					
2					
3					
4					
5					
6					

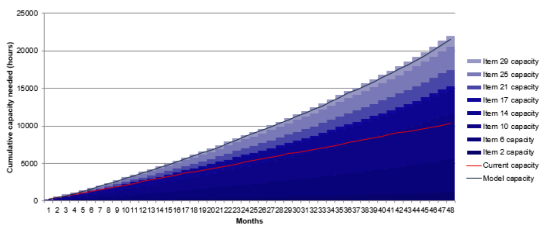

Figure B.3: Proposal dashboard man & machines capacity analysis resource level

C Results on computing time

The programming of the model is done in Spyder (Python) and the optimization programming (MIP) and solved with CBC MILP Solver. All the experiments have run on a PC having an 11th Gen Intel(R) Core(TM) i5-1145G7 @ 2.60GHz 2.61 GHz, and 16.0 GB RAM. The computing times of different sizes of data sets are shown in table C.1.

Table C.1: Computing time on different data set sizes

Number of items	Number of resources	Number of constraints	Computing time
30	7	61470	$\approx$ 1.5 s
120	28	855720	$\approx$ 25 s
360	28	2553720	$\approx$ 60 s

As expected the number of constraints grows exponentially with the increase of the size of the data set. The computing time however still stays within acceptable computing time, especially since this model only has to be evaluated every quarter.

D An example of a prescribed N-tier supply chain

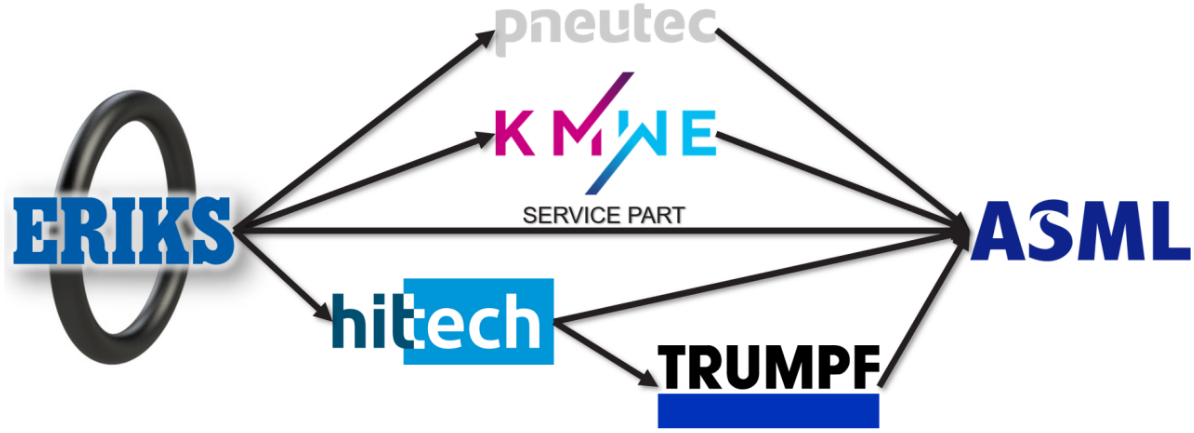

Figure D.1: An example of a prescribed N-tier component and its material flow towards ASML (Beeks et al., 2023)

E Sensitivity analysis - optimal objective

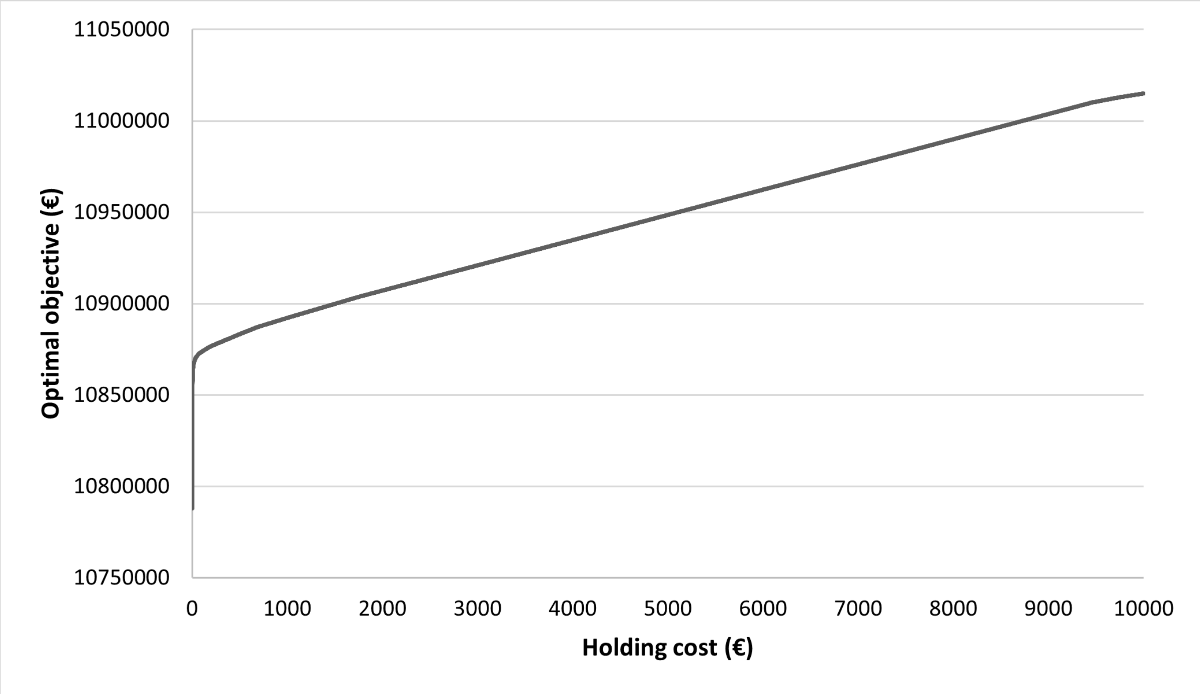

Figure E.1: Sensitivity analysis on holding cost and optimal objective

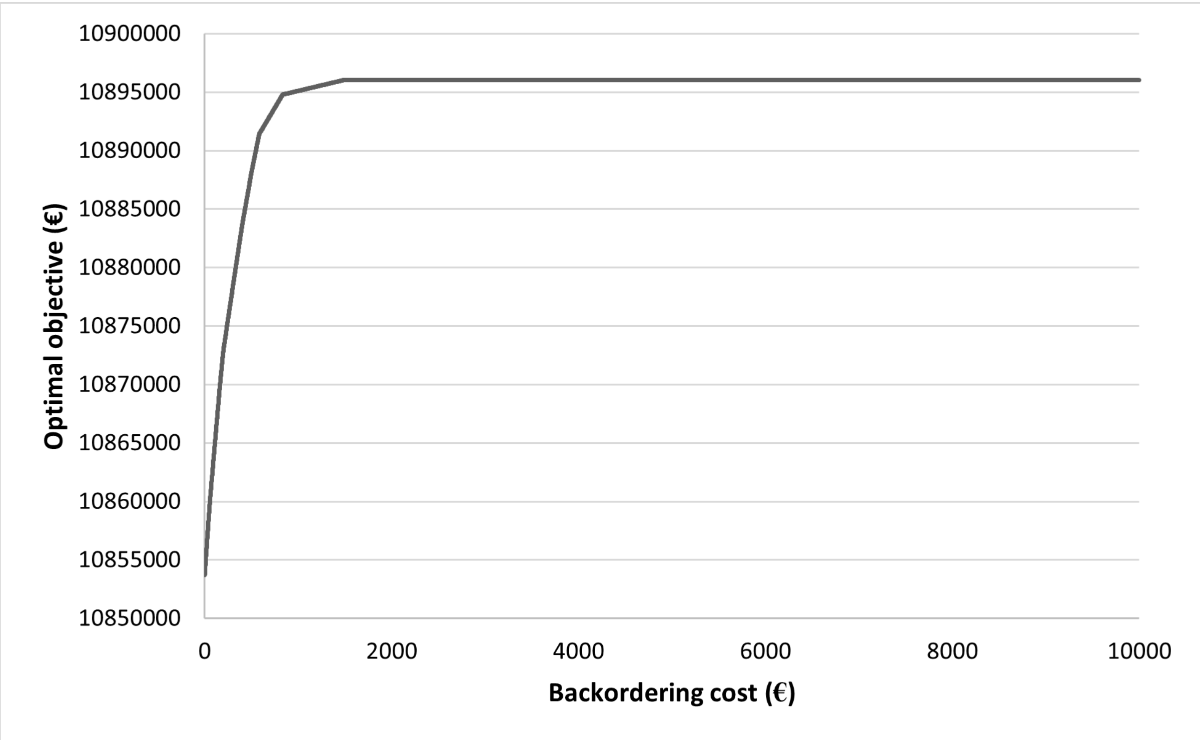

Figure E.2: Sensitivity analysis on back ordering costs and optimal objective

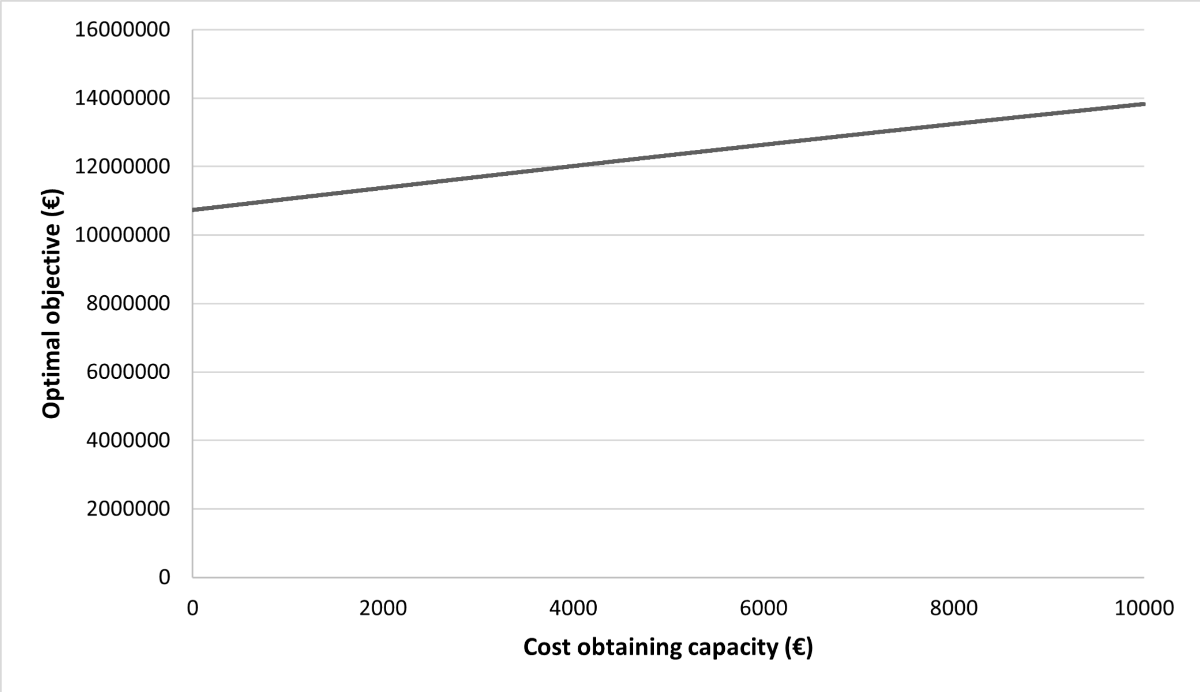

Figure E.3: Sensitivity analysis on cost obtaining capacity and optimal objective

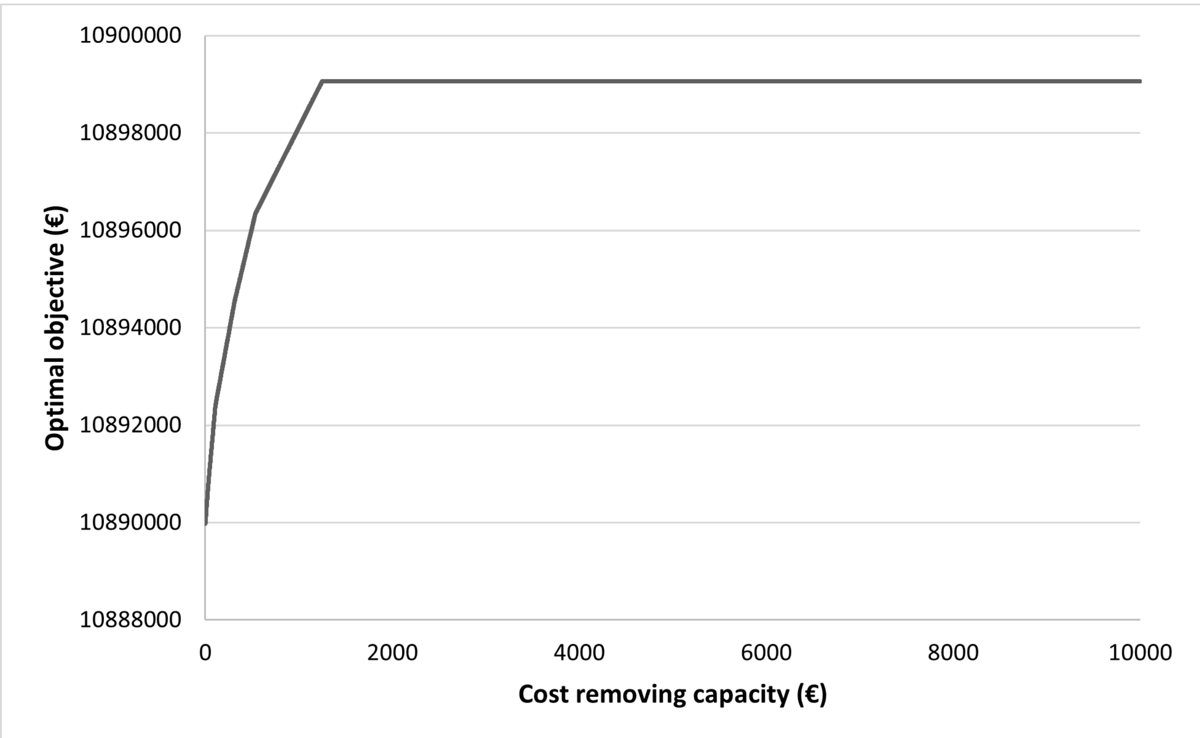

Figure E.4: Sensitivity analysis on cost removing capacity and optimal objective

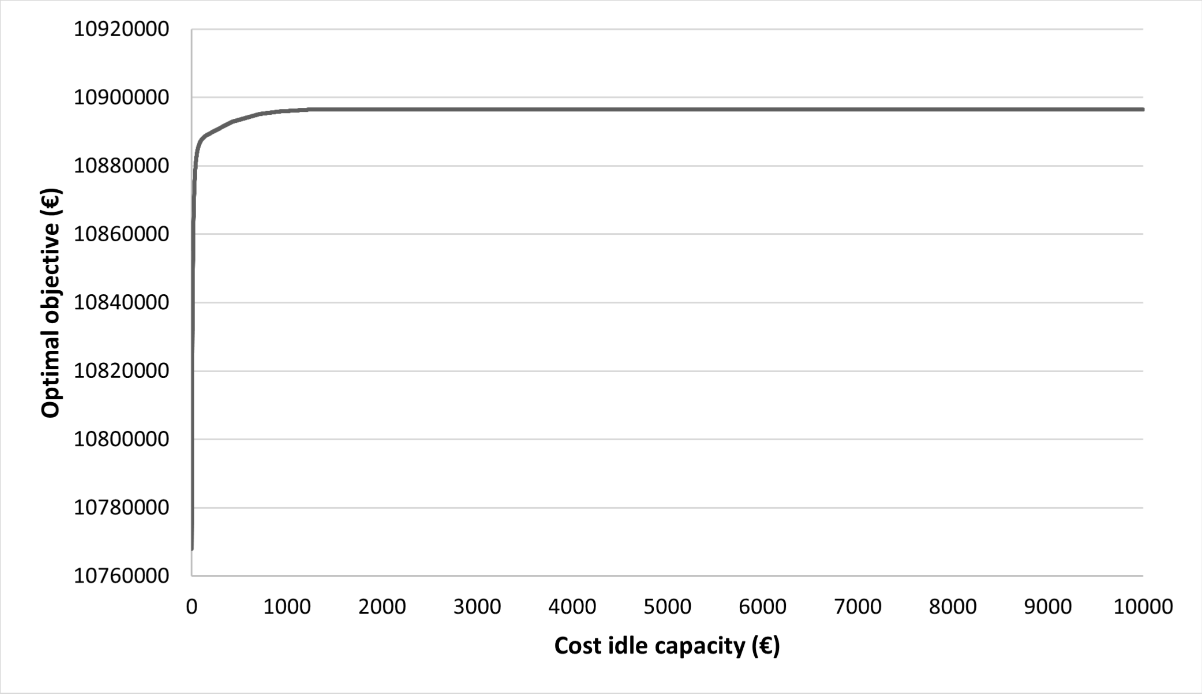

Figure E.5: Sensitivity analysis on cost idle capacity and optimal objective

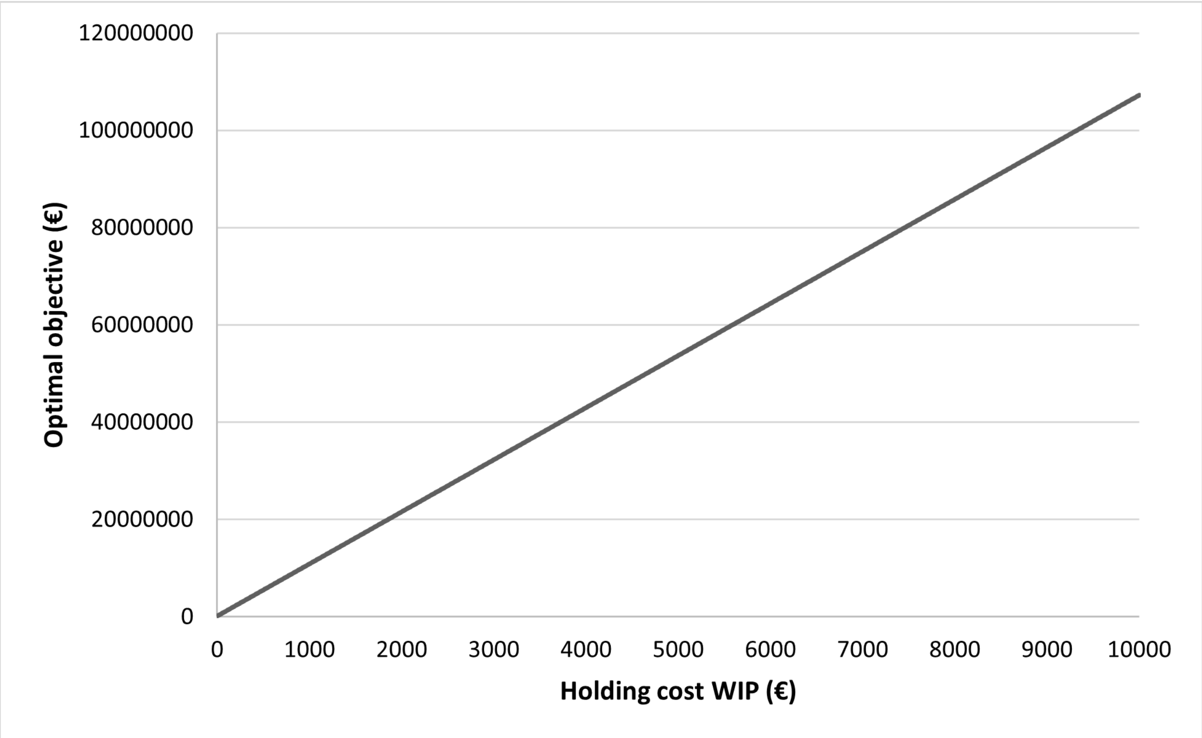

Figure E.6: Sensitivity analysis on holding cost WIP and optimal objective

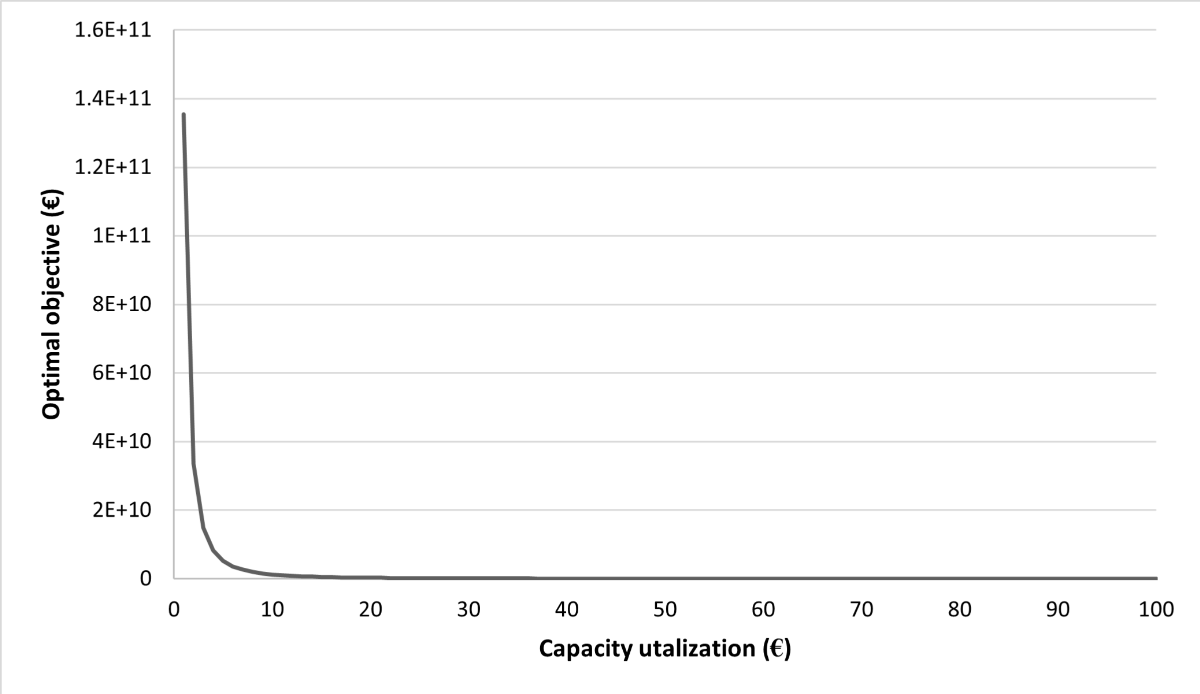

Figure E.7: Sensitivity analysis on capacity utilization and optimal objective

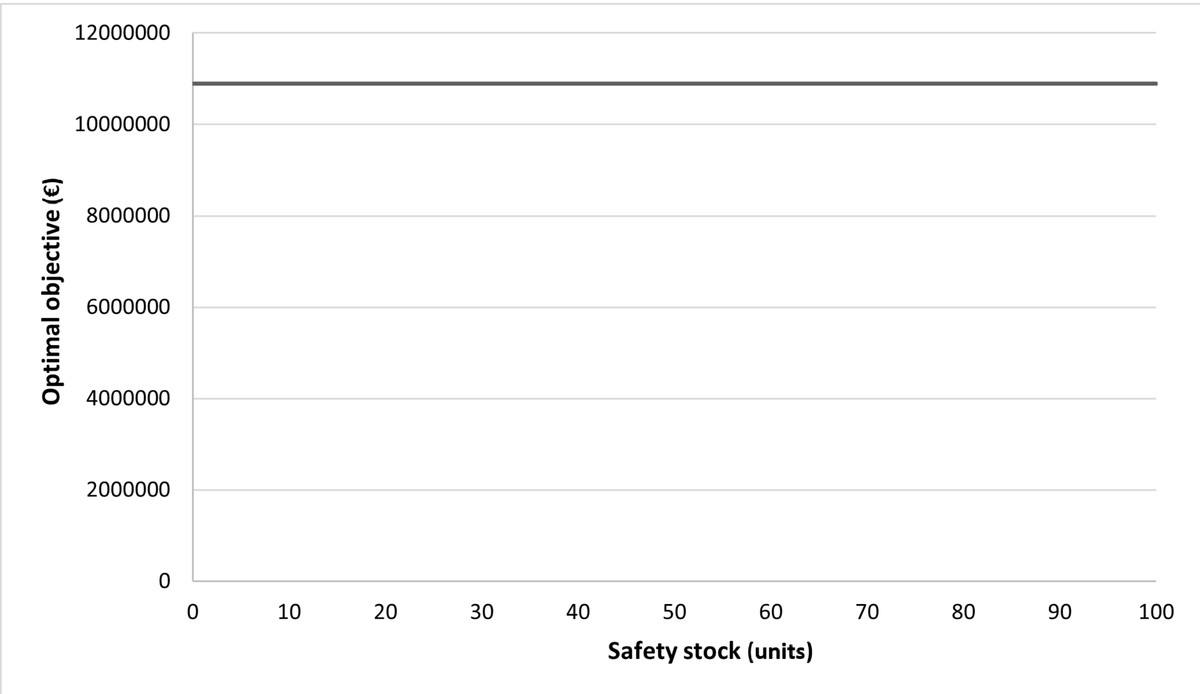

Figure E.8: Sensitivity analysis on safety stock and optimal objective

F Sensitivity analysis - capacity plan

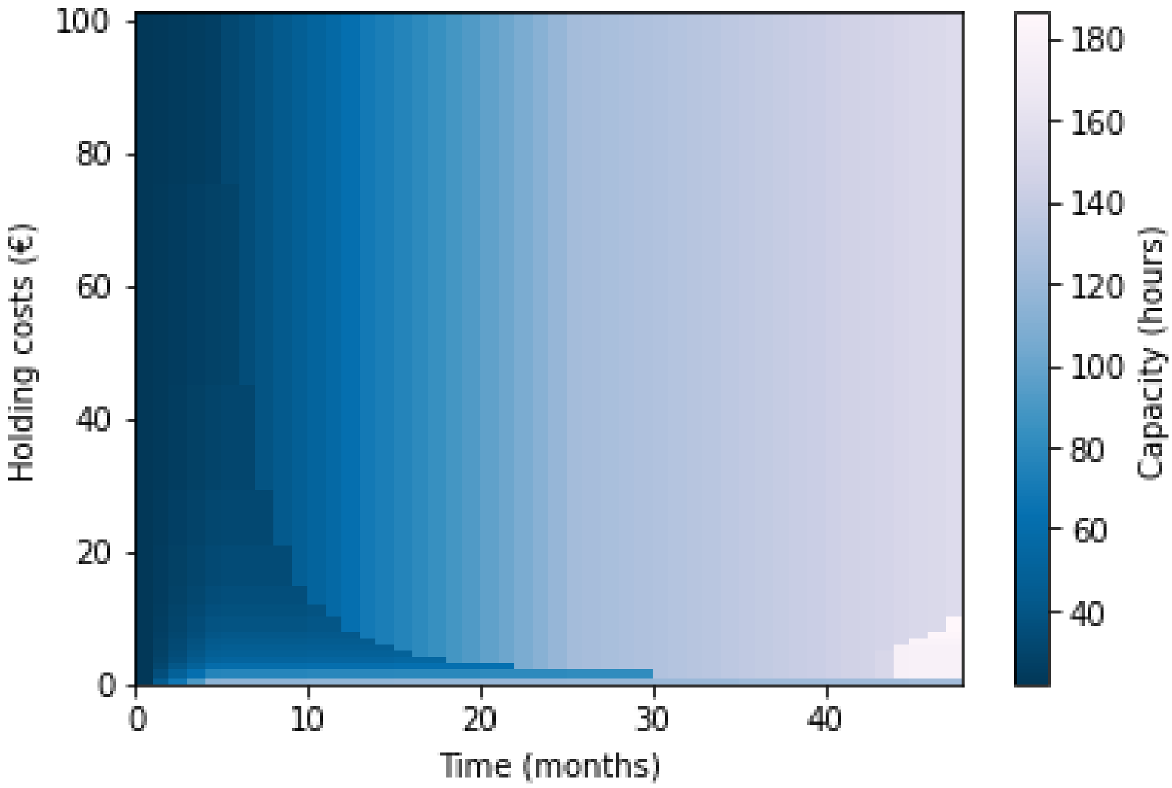

Figure F.1: Sensitivity analysis on holding cost and capacity plan

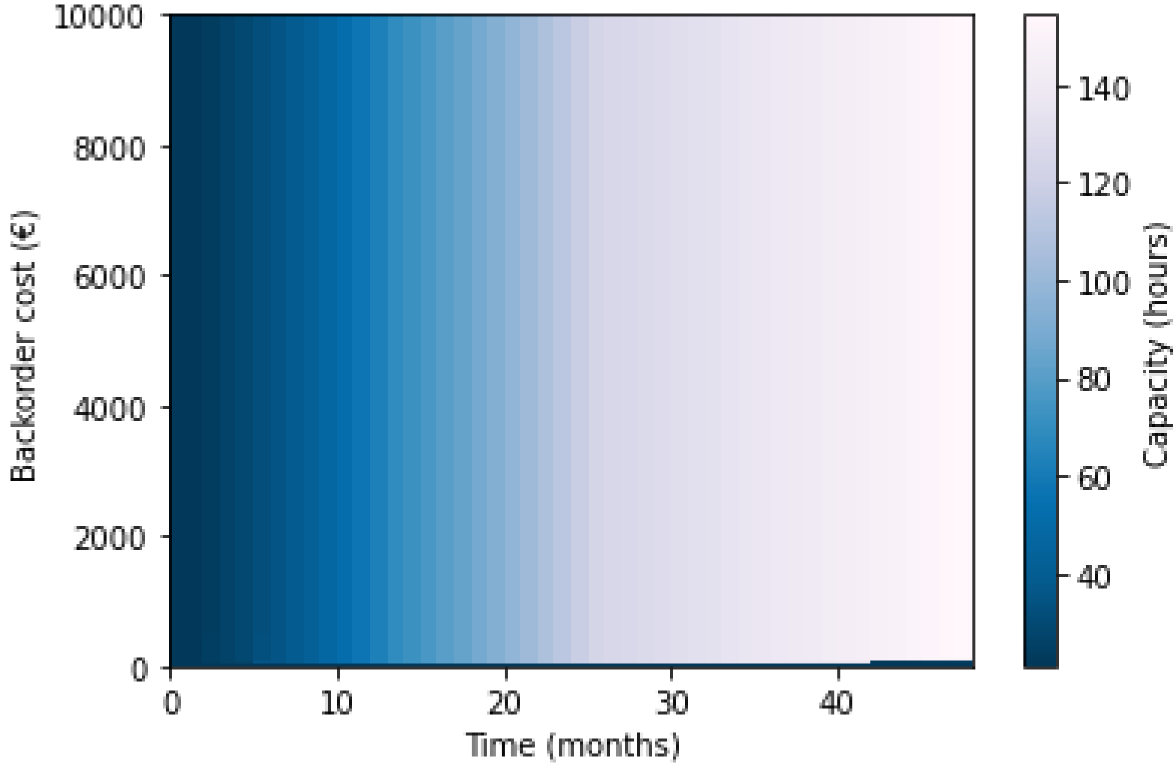

Figure F.2: Sensitivity analysis on back ordering cost and capacity plan

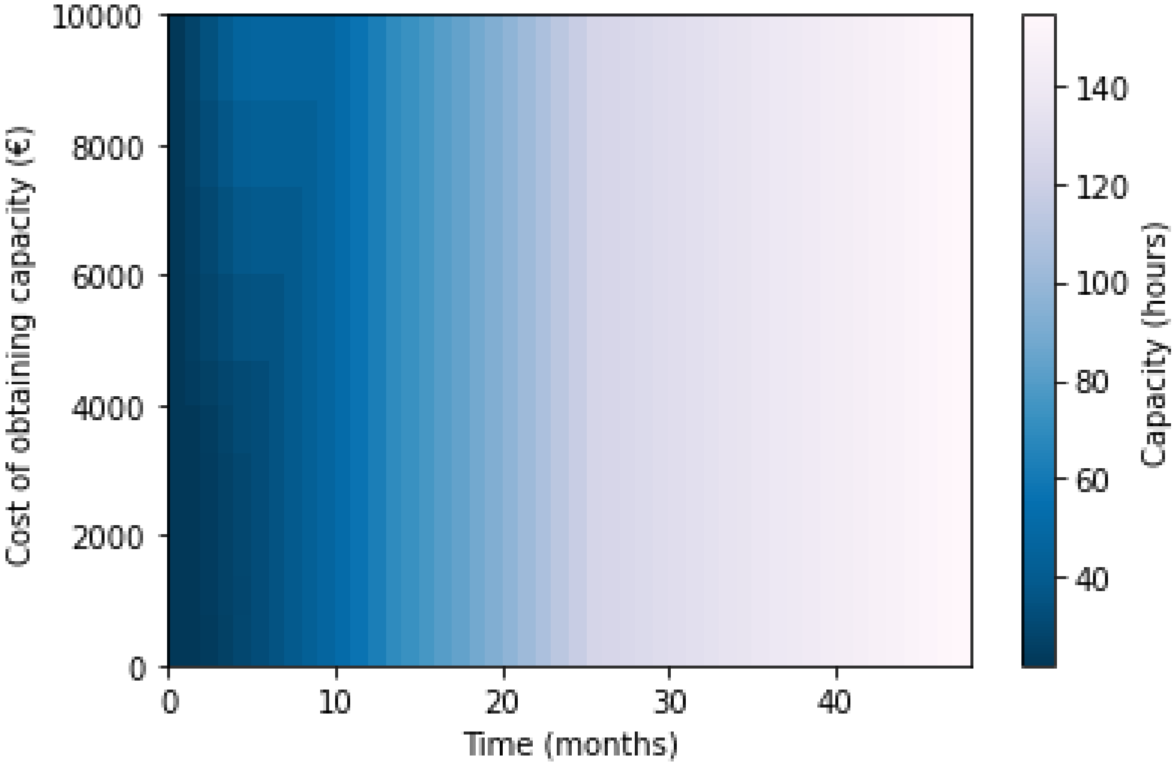

Figure F.3: Sensitivity analysis on cost obtaining capacity and capacity plan

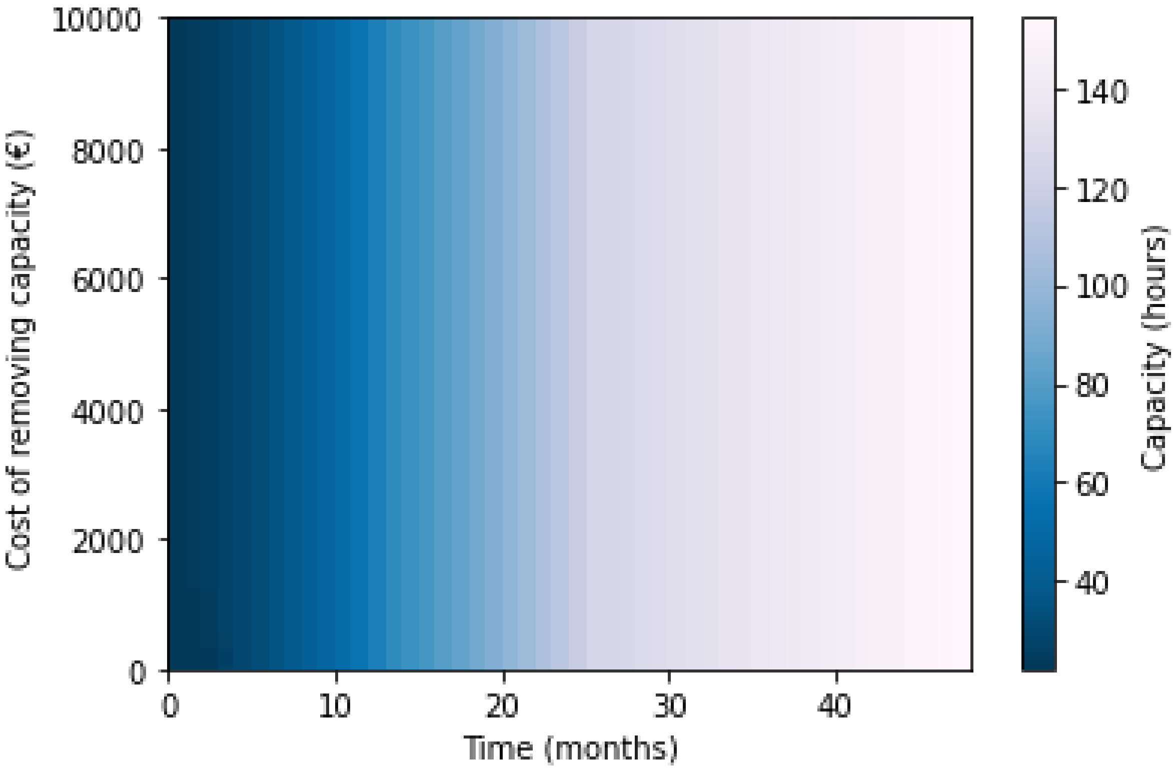

Figure F.4: Sensitivity analysis on cost removing capacity and capacity plan

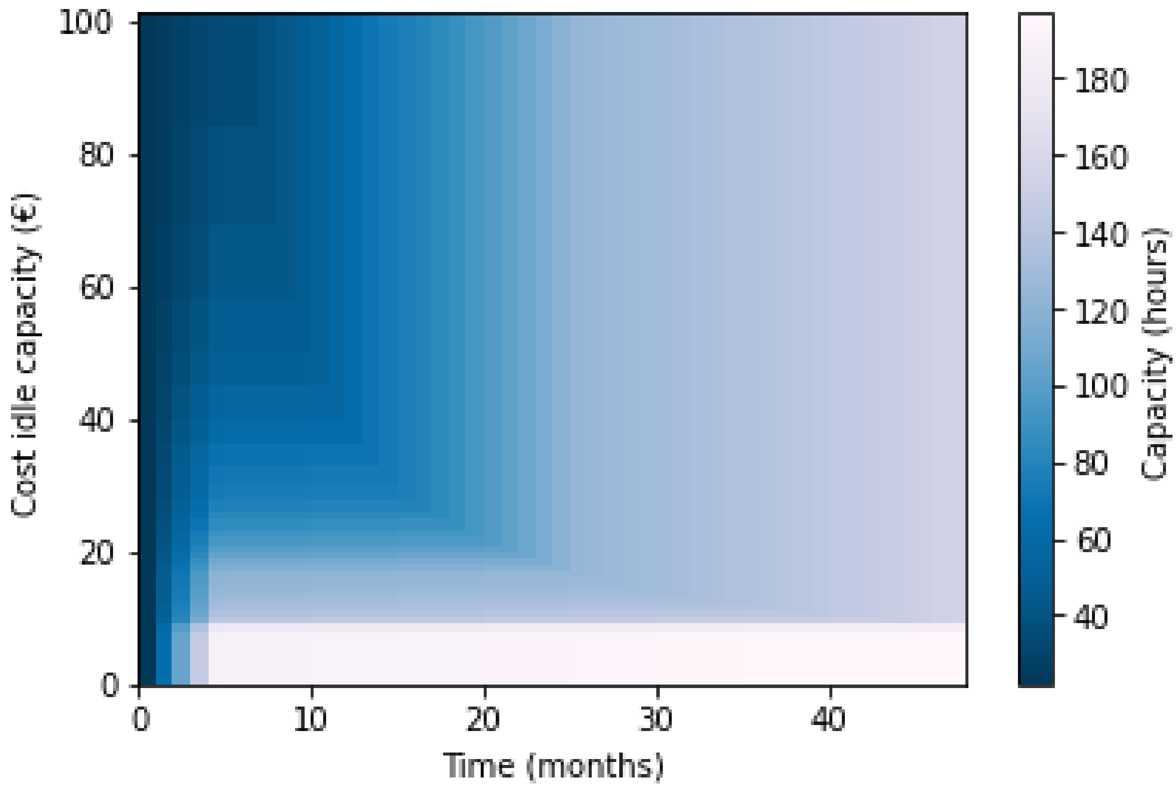

Figure F.5: Sensitivity analysis on cost idle capacity and capacity plan

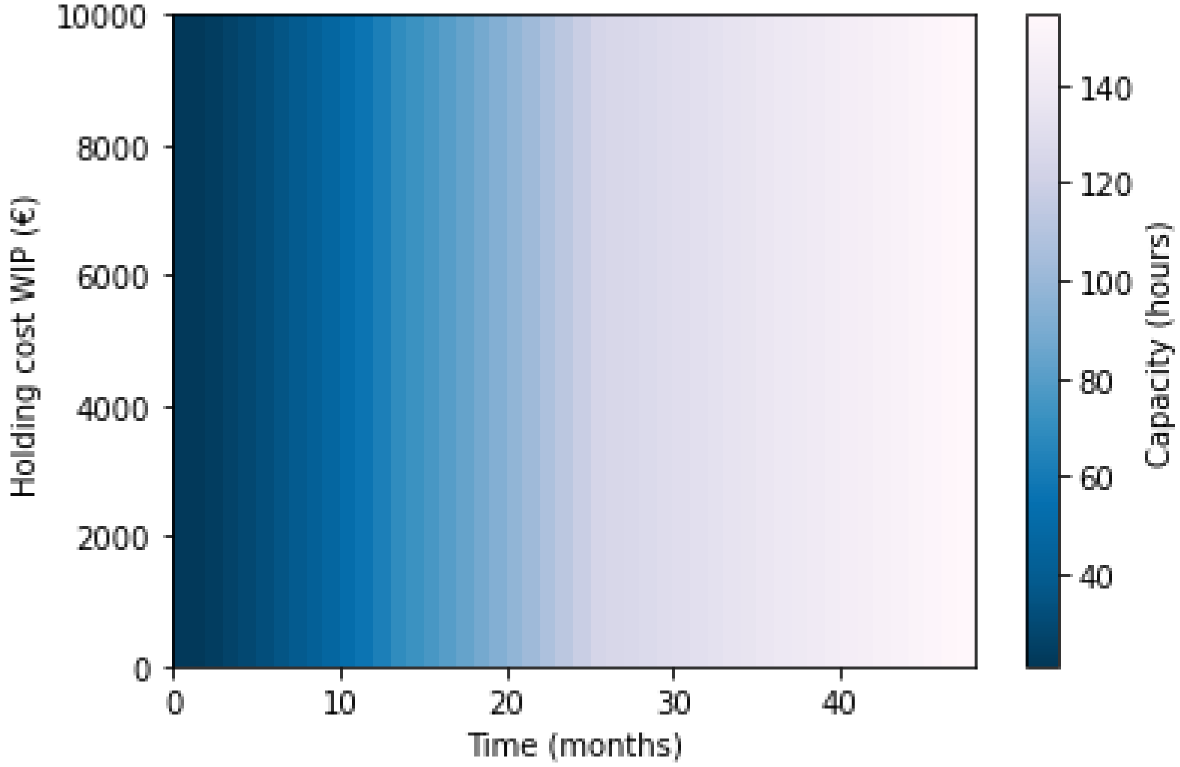

Figure F.6: Sensitivity analysis on holding cost WIP and capacity plan

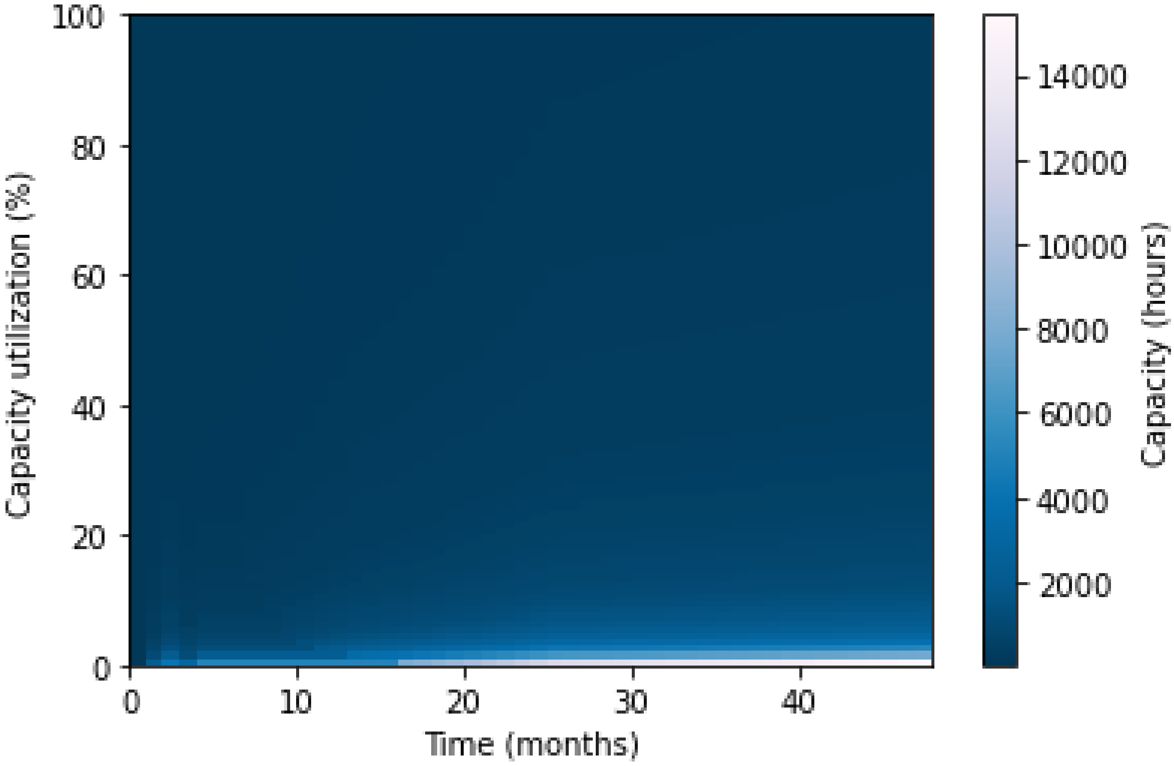

Figure F.7: Sensitivity analysis on capacity utilization and capacity plan

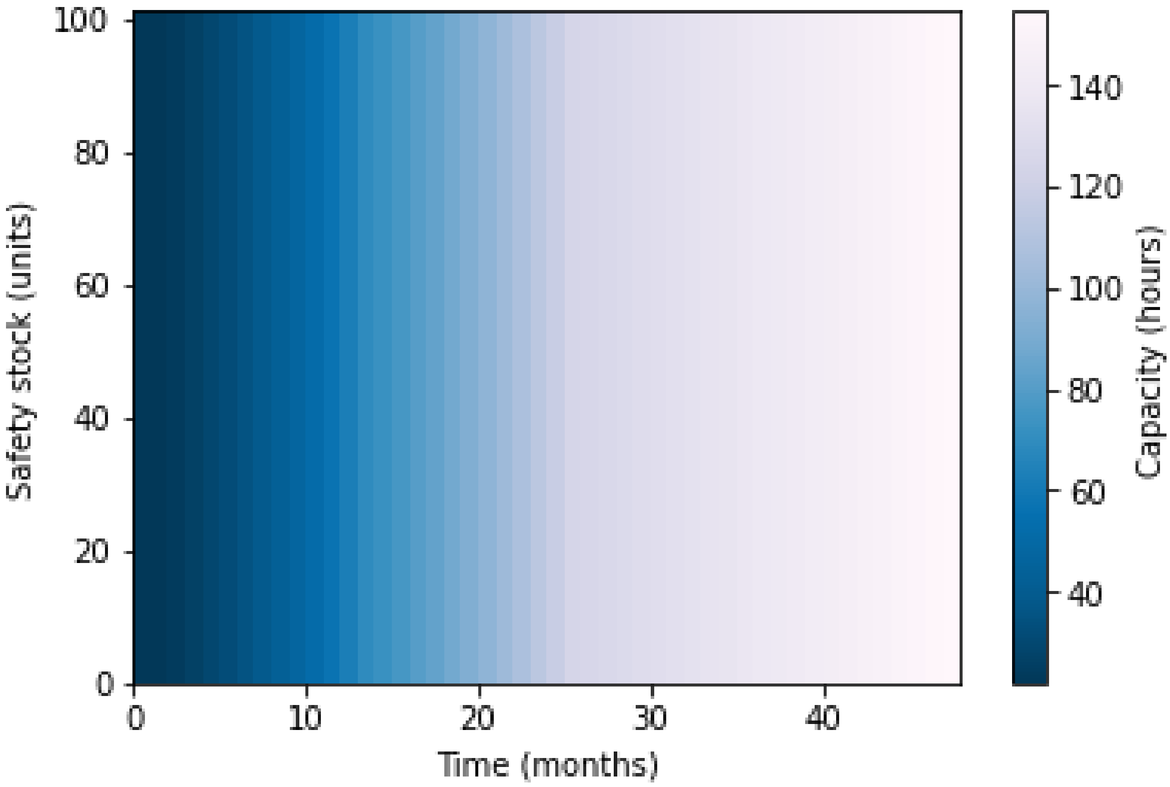

Figure F.8: Sensitivity analysis on safetystock and capacity plan

G WIP constraint

In the model, we include WIP to have workload control. A constraint on the amount of WIP is currently not included in the model. This constraint can be necessary for specific manufacturing applications, such as a clean room. We define two different extensions to incorporate a constraint on the amount of WIP in the production environment. We define Υ as the maximum WIP.

The first possible extension on a constraint is having a WIP constraint on resource level. This could be applied in, for example, CONWIP systems where the amount of WIP is defined as the maximum items allowed on a resource.

$$\sum_{i=1}^{N} \hat{W}_{ik} \leq \Upsilon_k \tag{G.1}$$

The second extension of a constraint on WIP is to have the constraint on item level. This could be applied in, for example, a clean room where only one item can be processed per time unit.

$$\hat{W}_i \leq \Upsilon_i \tag{G.2}$$