MASTER

Material availability planning in a low volume environment

Schouten, T.

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Department of Industrial Engineering & Innovation Sciences
Eindhoven University of Technology

Material availability planning in a low volume environment

a case study at ASML

by Tamara Schouten

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Supervisors TU/e
prof.dr. A.G. (Ton) de Kok
dr. W.L. (Willem) van Jaarsveld

Supervisors ASML
D.M.J. (Dennis) van Boven, PDEng
J.M. (Jack) Stultiens MSc

Eindhoven University of Technology
School of Industrial Engineering
Series master theses Operations Management and Logistics

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Abstract

Supply chain planning requires the use of a planning method to generate supply orders that meet customer demand. Material requirements planning (MRP) is a widely used method in industry. However, MRP does not take material constraints into account, which can lead to an infeasible supply plan. This study proposes the use of the material availability planning method (MAP), a simplified version of the synchronized base stock policies (SBS) method. It is tested in a low volume environment, which is often the situation in high tech industry. The impact of the MAP method is analyzed with use of a case study performed at ASML, a leading manufacturer of chip-making equipment. First, a suitable allocation policy for a low volume environment is defined, which is essential for using the MAP method. The results of the case study reveal the infeasibility of the current MRP plan at ASML. It is shown that the MAP method can determine the impact of shortages on the output of end-items. These insights cannot be obtained with MRP. Usability testing with planners confirmed the added value of the MAP method. An interesting insight is that human planners apply a manual flexible allocation policy. It is concluded that the MAP is applicable in a low-volume environment if the allocation policy is consciously considered. The MAP method generates a better understanding of the supply state, which can lead to better decision-making.

Management summary

This project studies the impact of material availability planning in a low volume environment.

Introduction
ASML is one of the world's leading manufacturers of chip-making equipment. The project is conducted at the supply chain planning department of ASML, which is responsible for constructing a supply plan that is feasible in terms of capacity and material constraints. The objective of the study is to generate insights in the use of a material availability planning method in a low volume environment.

Currently, ASML experiences a considerable number of reschedule messages in their planning system. Reschedule messages are notifications that indicate that the due date of an order is either shifted forwards or backwards in time. At ASML, that due date is equal to the derived demand for items that do not face customer demand. Generally, this is referred to as nervousness, which is a commonly faced problem in companies. Numerous drivers exist that cause changes of the required due date. The focus of this thesis is on the use of material requirements planning (MRP) logic as a facilitator of nervousness. MRP is a planning method that releases a set of external and internal orders. It does not take supply constraints into account, which can result in the generation of an infeasible supply plan. Continuous rescheduling orders to ensure a feasible plan is one of the drivers of nervousness. Consequently, the management problem is defined as follows:

"ASML experiences excessive nervousness in derived demand."

Synchronized base stock policies (SBS) are chosen as a solution direction. It is a planning method that takes material constraints into account and synchronizes the supply chain. A feasible supply plan is the result. However, it has never been analyzed before in a low volume environment. The aim of this research is to understand and test SBS policies at ASML and analyze its usefulness in a low volume environment. This study solely focuses on the material constraint concept of SBS. Hence, a simplified version is considered, named material availability planning (MAP). The main question is defined as follows:

How to design MAP such that it is applicable in a low volume environment?

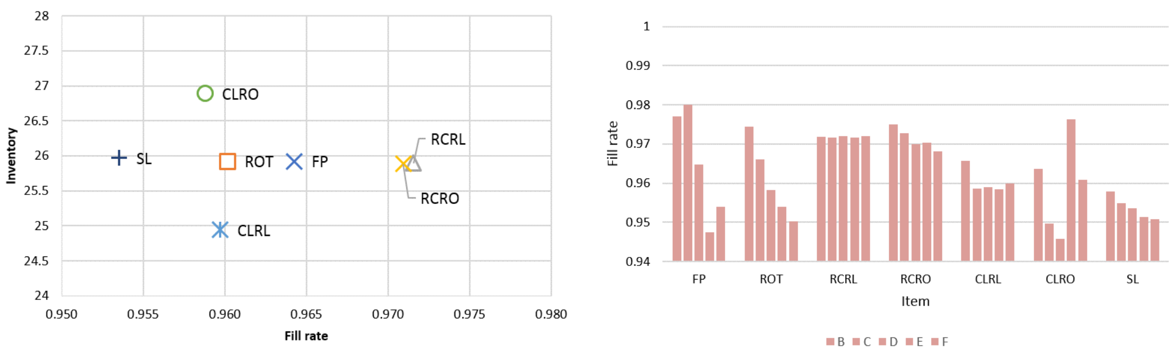
By answering the research question, insights are generated in the difference between an MRP and a MAP generated supply plan. The MAP method takes material constraints into account, on the contrary to the MRP method. Shortages arise if the available supply in the supply chain is not sufficient to meet forecasted demand, thus implying material constraints. In the MAP method, available supply needs to be allocated to items that will and will not receive items to satisfy demand. An allocation policy is therefore essential.

Experimental analysis

Only limited research has been devoted to allocation policies that are applicable in a low volume environment. The combination with a situation where demand is unknown at the moment of allocation has not been researched before. For this reason, seven allocation policies are defined, based on literature and ASML context. These include the fixed priority (FP), run-out time (ROT), rounded consistent appropriate share with random leftovers (RCRL), the rounded CAS with run-out time leftovers (RCRO), critical level with random leftovers (CLRL), critical level with run-out time leftovers (CLRO) and service level policy (SL).

A discrete event simulation is performed to analyze efficient allocation policies. A divergent network is analyzed, including five items that face customer demand. A rolling horizon with periodic review is considered. It is assumed that lead times are deterministic and demand can be backordered. Input parameters include the actual demand, the forecast error, the lead time and the target fill rate. The output parameters of interest are the realized fill rate and the total inventory.

An experimental environment is created to analyze the impact of the input parameters in a controlled setting. Initially, a standard case with homogeneous parameters is defined. Figure 1 (a) shows the aggregated fill rate and total average inventory for each policy. It can be seen that both the RCRL and RCRO perform best in terms of the fill rate. Figure 1 (b) depicts the fill rate per item, indicating the differences per policy. The RCRL rules performs most equal across all items, while the FP and CLRO policy show most variability. In total, 11 different sets of input parameters have been analyzed. Finally the RCRL and RCRO policies are identified as most efficient in terms of the defined output parameters.



(a) Aggregated fill rate and total inventory

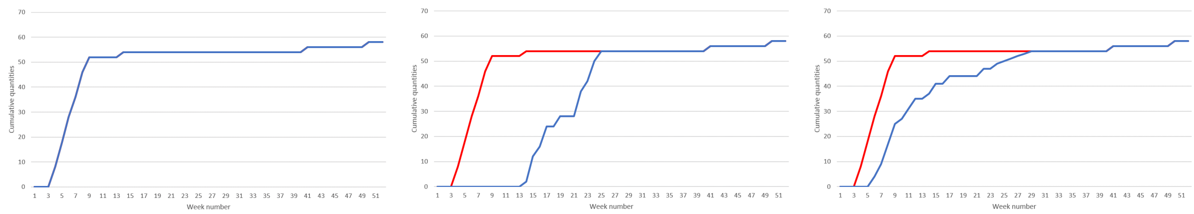
(b) Fill rate per item

Figure 1: Results of the standard case in the experimental analysis

Case study

Although the MAP method is an alternative for the MRP method, this case study is focused on the supply chain planning department of ASML. Critical parts planning is a subgroup which monitor critical parts. These parts have high potential to become a bottleneck and are therefore particularly interesting. Hence, we focus on the applicability of the MAP method specifically for critical parts planning.

Resulting from the experimental analysis, the RCRO policy is chosen to implement in a so-called MAP tool. Additionally, the FP policy is included because it best reflects the allocation procedure of ASML. Two cases are constructed that are based on actual ASML assemblies. The output of the MAP method is compared with the current MRP plan in terms of supply and demand for these cases. Insights as in Figure 2 can be derived for every item in the cases. It shows the calculated supply plan for an end-item according to three methods. Figure 2 (a) shows that in the current MRP plan, supply meets demand during the length of the planning horizon. However, if the MAP method is applied, it is calculated that supply can never meet demand due to shortages at a preceding item. Supply will arrive later than demand, this is shown in Figure 2 (b) and Figure 2 (c). This confirms that the MRP method generates an infeasible plan regarding material availability. The allocation policy determines the distribution of available items. This explains the differences in the quantity and timing of supply between Figure 2 (b) and Figure 2 (c). Hence, it can be concluded that the allocation rule used has considerable impact. The MAP method is applied multiple weeks in a row and compared with the realized supplies. It is shown to perform adequate given the number of assumptions.



(a) MRP plan (b) MAP - FP plan (c) MAP - RCRO plan

Figure 2: Supply plan of an end-item according to three methods (red = demand, blue = supply)

Additional insights are gained regarding the use of the MAP method and the implemented allocation policies, by performing a usability study with potential users of the MAP tool. The computational speed and insights in the consequences of a material constrained supply plan were evaluated as highly valuable. An interesting insight is that ASML prefers a (manual) flexible allocation policy. This differs substantial from the implemented (rational) FP and RCRO allocation policies. Further research regarding the performance of an algorithm compared to human planners is emphasized as interesting. It is suggested to differentiate between short-term and medium-term decision-making regarding allocation. The benefits of the MAP method are considered to be more useful on the medium-term.

Conclusions

This study generates insights in multiple directions. First, an experimental analysis provides understanding in allocation policies in a low volume environment with unknown demand at the moment supply is allocated. Multiple policies are compared in a general setting. Second, a case study shows the differences between the MRP and MAP method quantitatively. Third, allocation in a low volume business environment is considered. It is shown that this is mainly guided by human decision-making, which is different than described in literature.

Finally, it can be concluded that the MAP method generates a better understanding of the supply state, which can lead to better decision-making. The MAP method is applicable in a low volume environment, consciously considering the allocation policy.

Preface

I proudly present my graduation project which is the result of more than seven months of hard work. It does not only mark the end of my time at ASML, but also of my master at TU/e. Moreover, it concludes on more than six years of studying in Eindhoven. Before continuing with the content, I would like to thank a number of people.

First of all, I would like to thank my first TU/e supervisor Ton de Kok. Our biweekly sessions were inspiring and almost never within the time limit. Your knowledge about the topic is limitless and definitively helped to guide the project. I appreciate your positivism and enjoyed our small talks about non-thesis related topics. Thank you for taking the time to travel multiple times to ASML. This helped in constructing a research that is both relevant for literature and business. I would like to thank Willem van Jaarsveld, my second university supervisor. You helped me to approach the case study in a structural manner and thought along with me about issues I encountered along the way.

Without the support of ASML, I would not have been able to complete this research, thanks for giving me the opportunity. I would like to thank Dennis van Boven for his guidance and help during the complete length of the project. You inspired me in telling an understandable and fun story and gave tips and tricks to do this. Jack Stultiens, thank you for your business insights and time. Our meetings always indicated a step forward regarding the direction of this research. Thank you, Fred Janssen, for making time to help me with the tool, and moreover for your inspirational talks. Furthermore, thanks to my colleagues at ASML that made me having an enjoyable time. I felt at ease, had fun and learned a lot about the business. Special thanks to Thijs Vennix, who greatly helped me with gathering the data I needed.

I would like to thank my friends for making the best memories together during the past years. Without the friends I have made during my time in Eindhoven, my study would not have been half as fun. Particularly thanks for helping me through the final phase of this project. Friends from home, thank you for your support and all the memorable moments we have spent together. Our time together is always the best. Final thanks to my fellow students at ASML for the many coffee breaks we have had to discuss our master projects and for listening to my monologues.

Special thanks to my parents, Caroline and Bert Schouten for their unconditional love and motivation. Thank you for supporting me to follow my ambitions, and making me the person I am today. I am grateful for having such a warm family. Finally, I have unlimited appreciation for you, Stefan. For you being you. Thank you for listening, telling me not to worry, and for thinking with me about in-depth topics in the last few months. You made me a better person.

Tamara Schouten

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List of Abbreviations

ATO	Assemble-to-order
BOM	Bill-of-Material
CAS	Consistent Appropriate Share
CLRO	Critical level with run-out time leftovers
CL	Critical Level
DUV	Deep Ultraviolet
ERP	Enterprise Resource Planning
EUV	Extreme Ultraviolet
FP	Fixed Priority
LP	Linear Programming
MAP	Material Availability Planning
MPS	Master Production Schedule
MRP	Material Requirements Planning
OHS	On-hand Stock
POR	Planned Order Releases
RCRL	Critical level with random leftovers
RCRL	Rounded consistent appropriate share with random leftovers
RCRO	Rounded consistent appropriate share with run-out time leftovers
RC	Rounded Consistent Appropriate Share
ROT	Run-out Time
SBS	Synchronized Base Stock
SCM	Supply Chain Management
SCP	Supply Chain Planning
SL	Service Level
SR	Scheduled Receipts
SS	Safety Stock
WIP	Work in Process

1 | Introduction

This report presents the results of a master thesis project conducted by the Eindhoven University of Technology in collaboration with ASML, a leading manufacturer of photolithography systems for the semiconductor industry. The commonly used material requirements planning (MRP) method is likewise applied at ASML. It does not take material availability into account, which can lead to an infeasible supply plan. As opposed to MRP, the material availability planning (MAP) method proposed in this work does take this into account. A case study at ASML shows the infeasibility of an MRP generated plan and the impact of using the MAP method.

This introductory chapter provides the research context of this thesis. First, ASML is briefly introduced, including a small context description. Second, the problem is defined and analyzed. Afterwards, the research design is explained, including the research questions that will be answered in order to solve the problem defined. Next, the methodology used to find these answers is described and the final section outlines the structure of the remainder of this report.

1.1 Company introduction

ASML is one of the world's leading manufacturers of chip-making equipment. It provides its customers with hardware, software and services. The vision of ASML is "a world in which semiconductor technology is everywhere and helps to tackle society's toughest challenges" (ASML, 2018). In 2017, ASML had almost 20 thousand employees within research and development (R&D) and manufacturing locations in the Netherlands, the United States, China, South-Korea, and Taiwan. Furthermore, it has more than 60 offices in 16 countries, with the headquarters located in Veldhoven, the Netherlands. A total net sales of €9.053 million and a net income of €2.225 million was achieved in 2017 (ASML, 2018). The core of their product portfolio is the development and manufacturing of semiconductor lithography systems.

ASML offers three categories of new products: extreme ultraviolet (EUV) lithography, deep ultraviolet (DUV) lithography, and holistic lithography solutions. TWINSCAN DUV systems represent the established business lines, while the TWINSCAN EUV systems include next-generation lithographic systems which are equipped with a new light source technology. The holistic lithography collection includes software and metrology products to complement the products from DUV and EUV. Furthermore, ASML offers refurbished systems called PAS systems. Additionally, the company offers services and applications such as installation services, services for system enhancements, and upgrades and training for customers. Product options and enhancements are designed to increase throughput and accuracy of the products.

Close collaboration with the complete chain is needed, because state-of-the-art knowledge is necessary for the rapid development of new techniques. In 2017, ASML completed the acquisition of 24.9% indirect interest in Carl Zeiss SMT GmbH, a major supplier, and they acquired two suppliers, Cymer and HMI the year before. The customers of ASML include all major memory and logic chip makers such as Intel, Samsung and TSMC.

1.1.1 Supply Chain Management

The supply chain of ASML is a complex, multi-tier chain including numerous suppliers, factories, customers and warehouses for the factories and the customers. Additionally, ASML is confronted with a challenging environment. First, the high-tech character of ASML involves a complex bill-of-material (BOM) which brings additional challenges compared to a simpler assembly process. Furthermore, the output volume is low. On the other hand, the value of components and end-items is rather high and can exceed 100 million euros per delivered system. ASML has a relative high dependency on suppliers. A significant part of the BOM is composed of purchased components. Moreover, a large number of specialized parts are offered by only a limited number of suppliers. Furthermore, the lead times of components can be up to two years, while the customer lead time is only 6 months or shorter. Additionally, both suppliers and ASML factories need to manage capacity restrictions. On the demand site, ASML deals with pressing customers that operate in a fast-paced manufacturing environment that can delay or expedite orders, resulting in demand due date uncertainties. Another characteristic is the unpredictability of service demand that can impact the current supply and demand plan significantly. The complex BOM in combination with demanding customers and high customization options lead to frequent engineering updates, which increases the complexity even more.

The supply chain management (SCM) department is responsible for guiding these complexities. Its mission is to ensure material availability at the right quality and costs. The department manages the flow of goods and services, which includes the movement and storage of raw material, work-in-process (WIP) inventory, and finished goods from the n-tier supply network to the point of consumption. This is coordinated on both short and long term horizons. The organizational chart of this department can be found in Appendix A.

1.1.2 Supply Chain Planning

The supply chain planning (SCP) department is responsible to construct a supply plan that is feasible in terms of capacity and material constraints in the supply chain and the factories. This is done by the monthly creation of an 'integral supply plan' that is aligned across the business taking into account risks and opportunities with the use of scenarios. It is aimed to take all (forecasted) demand into account.

1.2 Problem context and definition

A problem experienced by the SCP department of ASML is the significant number of reschedule messages in their planning system (SAP). Reschedule messages are notifications that indicate that the due date of an order is either shifted forwards or backwards in time. An investigation done by ASML showed that on average 70 % of the purchase orders in their planning system have a reschedule message. This implies that of roughly 70% of the purchase orders the due date is shifted, which is substantial. The high number of reschedule messages is referred to as *nervousness*. Mather (1975) define nervousness as "changing the required due date on a related replenishment order for either a purchased or manufactured material". Aside from the messages in SAP, another clear indicator can be found in the so-called CPL (critical parts lines) list, that shows potential shortages on the short to medium planning horizon per part number. A considerable amount can be explained by due dates that have been shifted earlier, but cannot be met and thus result in a shortage in the planning. At ASML, due dates are changed for roughly two causes: 1) due to the monthly updated integral supply plan, and 2) due to execution changes on a daily basis. The former are accepted changes, while the latter are uncontrolled, but inevitable in practice. An analysis done by ASML showed an enormous number of (operational) factors that influence the supply plan nervousness which can be found in Appendix B. An additional cause-and-effect analysis is executed of which the diagram can also be found in Appendix B. It is clear that the combination of a great number of factors result in the nervousness and its consequences at ASML as it is experienced today.

Interesting factors that are of relevance for the research are worth mentioning here. They are extracted from Appendix B and multiple interviews within the SCP department. First, a cultural characteristic of ASML is its flexible state-of-mind. Flexibility is required across all departments and taking "no" for an answer is untypical. Second, ASML is confronted with a high variability of demand which directly impacts the due dates. Third, a number of (operational) factors that influence the amount of nervousness will always be present. Examples are rejects in the factory, unexpected service demand, supplier push-outs and high-priority incidents. Fourth, ASML has a policy to keep an efficient inventory. This is partly due to the high inventory costs and results in relatively low buffers. This leads to a situation where changes in supply or demand have a more direct impact, as less buffers exist to damp the variability of supply and demand. And fifth, the planning system of ASML uses MRP logic as a planning method. When the supply plan is changed, material and capacity constraints are taken into account, but this does not hold for daily changes. MRP does not apply any checks either and in combination with the complex BOM, this easily results in changing due dates and infeasible plans. The latter leads again to rescheduling.

As argued before, a certain degree of nervousness will always be present. This gives a company flexibility to adapt to adjustments in demand and supply. However, a balance between flexibility and robustness is required, otherwise the enormous amount of changes results in unnecessary 'running around'. Taken all of the observations and issues mentioned above into account, the problem statement is formulated as follows:

"ASML experiences excessive nervousness in derived demand."

Excessive nervousness is not unique to ASML, hence the problem statement can be generalized to other high-tech companies. A particularly interesting aspect of high-tech companies is the low volume of their products. It is more common to research a high volume environment, while decision-making in a low volume environment can have a different impact. The problem statement is the starting point of this thesis and will serve as a guideline in developing the research questions mentioned later in this chapter.

1.3 Problem analysis in literature

Nervousness in MRP systems is a widely experienced problem and is extensively discussed in literature. This section discusses how nervousness is defined, what its main drivers are and how it can be reduced.

1.3.1 Nervousness

Besides the term (system) nervousness, authors also have referred to 'schedule instability', 'schedule nervousness' or 'planning instability'. Next to the definition of Mather (1975), Blackburn et al. (1986), define nervousness more general as "instability in planned orders".

Nervousness has numerous (negative) consequences. It results in planning or production problems if production or suppliers need to expedite deliveries, but expedition cannot be met. *Expediting* is shifting a due date earlier, while *deferring* is moving a due date later (Hopp and Spearman, 2011). If deferring is not possible, it results in excessive inventory. Modifying schedules results in reduced productivity, increased costs, reduced inventory availability and confusion on the shop floor (Hayes and Clark, 1985). Furthermore, it can result in an overall loss of confidence in planning (De Kok and Inderfurth, 1997). Moreover, capacity utilization and customer service levels can decrease and throughput times and inventory can increase (Heisig, 2002).

1.3.2 Drivers of nervousness

The causes of nervousness are numerous and cannot be captured by a few specific sources. Very often it is a combination of factors. As the core of nervousness is related to changing schedules, the question arises what leads to frequent rescheduling. Blackburn et al. (1985) stated that schedule instability could be a result of demand and supply uncertainties. More specifically, he mentioned that this is due to errors in the end-item demand forecast. Mather (1975) also mentioned engineering changes as an additional cause, resulting in BOM changes. Changes in MRP parameter values such as safety stock, safety lead time, or planned lead time have a significant influence (Vollmann et al., 1988). Variations in lot-size decisions are even more important (Blackburn et al., 1985) and changing the planning horizon and frozen interval has been found to be of great influence on nervousness as well (Zhao and Lee, 1993). Furthermore, human planners can have an impact, because they can overrule the (system) plan (Moscoso et al., 2010; Fransoo and Wiers, 2008). Lastly, it cannot be excluded that MRP logic in itself triggers nervousness. The BOM explosion of MRP in combination with its inability to include material and capacity constraints, can lead to a cascade effect of reschedule messages in the planning system.

1.3.3 Reduce nervousness

Various strategies to reduce nervousness in MRP systems have been discussed in literature. A distinction can be made between solutions within MRP logic and outside MRP logic. The former keeps the MRP logic intact and looks for a reduction of nervousness in the parameter settings or related factors. These factors include the optimization of lot-sizing rules (e.g. Zhao and Lam, 1997), safety stock and safety lead time (e.g. Sridharan and LaForge, 1989). The influence of dampening procedure (e.g. Ho, 2005) and the impact of freezing the planning horizon is widely discussed (e.g. Xie et al., 2003). Other strategies are related to the reschedule frequency (e.g. Xie et al., 2003), forecasting error (e.g. Ho and Ireland, 1998), influence of planners (Moscoso et al., 2010) and cooperation of buyers and suppliers (e.g. Pujawan and Smart, 2012). Alternatives for MRP logic include inventory control policies (e.g. Jensen, 1993), linear programming (De Kok and Fransoo, 2003) and synchronized base stock policies (De Kok and Fransoo, 2003).

1.4 Research design

This section discusses the steps that need to be taken to come to a solution for the problem statement formulated above. It addresses how the solution direction for this thesis is selected and followed by the definition of research questions and problem scope.

1.4.1 Project selection

Following from the problem statement above, the ultimate goal would be to reduce nervousness. Numerous drivers exist that facilitate the changing of due dates. Appendix B provides an overview of the various solution directions possible within ASML. It is constructed based on information of both ASML and literature. It is decided to focus on an alternative for the MRP logic, namely synchronized base stock (SBS) policies.

As mentioned before, MRP enables nervousness for multiple reasons. It does not take any (material or resource) constraints into account, which stimulates rescheduling due to the generation of an infeasible plan. Moreover, the MRP logic triggers nervousness by applying the MRP BOM explosion and lead time offsetting. In Chapter 2 more information about the MRP logic is provided. Next to SBS policies, linear programming (LP) is another MRP logic alternative that can take material constraints into account. SBS policies are chosen for two reasons. First, it outperforms LP in terms of inventory and customer service (De Kok and Fransoo, 2003). Second, it has a rapid calculation speed (De Kok et al., 2005). Although not mentioned before, ASML needs to deal with shortages in its supply chain, resulting in supply constraints. The combination with the inability of MRP to deal with these supply constraints, triggers nervousness and other problems. The SBS method is able to take material constraints into account, which results in a feasible plan regarding material availability.

Hence, the applicability of SBS policies is analyzed in this thesis. Although SBS policies have been compared to MRP before, it has never been analyzed in the context of a low volume environment. Consequently, it is an interesting direction from the perspective of both business and research. In Chapter 2, SBS policies are explained in detail. It is discussed that SBS policies include two components; allocation and synchronization. Our focus is on the allocation component, hence we consider a simplified version of SBS policies. For this reason, we refer to material availability planning (MAP) rather than SBS from this point on.

1.4.2 Scope

The general application of a planning method such as synchronized base stock policies is extensive and too broad for this study. Consequently, our research is focused on the applicability within the SCP department.

1.4.3 Research questions

Several questions need to be defined in order to guide the project. The main research question of the project is formulated as follows:

How to design MAP such that it is applicable in a low volume environment?

The aim of this research is to understand and test MAP at ASML and validate its usefulness in a low volume environment. The research questions are formulated as follows:

1. *What are the characteristics of the MAP method?*
2. *Which adaptations need to be made to the MAP method?*
3. *How is the current planning process designed at ASML?*
4. *What are the results of using the MAP method if applied to a case study at ASML?*
5. *How can the MAP method be implemented at ASML?*

The capabilities and assumptions of the MAP method will be analyzed in the first question and compared to the MRP method. The MAP method needs to be adapted to be applicable in a low volume environment, of which the how will be answered by the second question. The third question provides more insight in the current situation and processes that relate to planning at ASML. Consequently, the adapted MAP method will be tested in a low volume environment with use of a case study which provides insights in the practical implications. This is captured in the fourth research question. Afterwards, the fifth and final research question discusses how MAP can be used and implemented at ASML.

1.5 Research methodology

According to Van Aken (2004), two approaches for a graduation project can be distinguished, they are based on the explanatory research paradigm or the design science paradigm. This thesis aims at producing a solution to a field problem and can therefore be placed in the design science paradigm. This thesis follows the methodology of Figure 1.1, which is based on the regulative cycle of Van Aken et al. (2012). Research methods include literature study, simulation, data analysis and expert interviews.

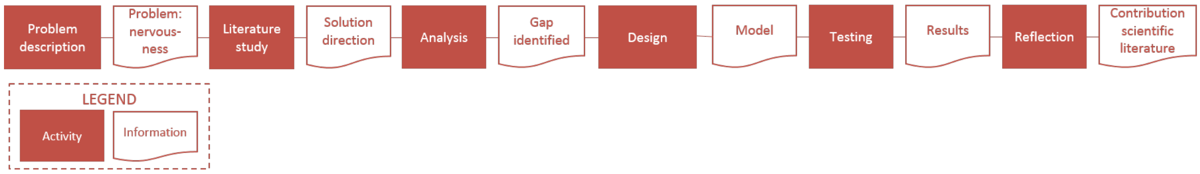


Figure 1.1: Methodology used in this thesis

To start with, the problem is described and defined in the first two steps. Afterwards a literature study is performed, which results in multiple solution directions. Discussions with the company and university supervisors lead to a solution direction that will be analyzed. An analysis of the solution directed results in the identification of a gap. This gap is analyzed and a design is made, resulting in a model. The model is afterwards tested in a case study at ASML. Finally, conclusions are drawn and an academic reflection is performed. This will lead to insights in the contribution to literature.

1.6 Report outline

The remainder of this thesis is structured according to the methodology proposed in the previous section. The problem definition and solution direction have been discussed in Chapter 1. The introduced SBS policies are analyzed and compared with the MRP method in Chapter 2. From then on we refer to material availability planning (MAP) instead of SBS. A gap in literature is identified. In Chapter 3, a design is made regarding the gap: allocation policies for low volume. This is further analyzed with an experimental study in Chapter 4. Chapters 2 to 4 all relate to a theoretic environment and are therefore combined in part one: experimental analysis. The second part focuses on a case study of the MAP method at ASML and embodies the testing phase. Chapter 5 provides more information related to the planning process of ASML. This is useful information later in this study to place the MAP method in context. In Chapter 6, two cases are constructed based on ASML items. The MAP method with two different allocation policies is applied and the output is compared with the MRP plan. Chapter 7 expands on the cases constructed with a qualitative analysis. The final conclusions and recommendations are discussed in Chapter 8. Finally, Chapter 9 deals with a reflection on this thesis, including its academic contribution, limitations and suggestions for further research.

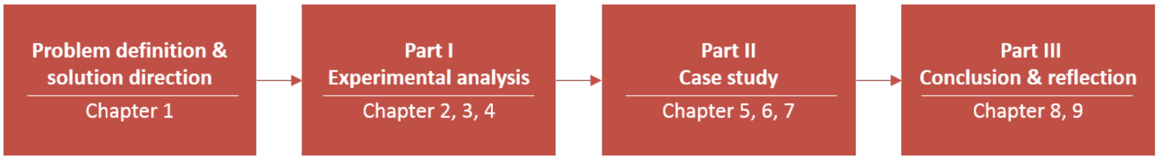


Figure 1.2: Outline of this report combined with research approach

Part I

Experimental analysis

2 | Planning methods: MRP and SBS

This chapter elaborates on material requirements planning (MRP) and synchronized base stock (SBS) policies. It is aimed at answering the first research question: *"What are the characteristics of the MAP method?"*. Both methods are discussed and explained further, after which a comparison is made with a specific example. Finally, a gap in the current applicability of the MAP method in a low volume environment is identified.

2.1 Introduction

This study focuses on the applicability of the MAP method in a low volume environment. The SBS method is explained in more detail, afterwards it is explained why we focus on the MAP method as a simplified version of the SBS method. By comparing the MAP method with the well-known MRP method, more insights are gained. LP is another alternative for the MRP method, but out of scope. The comparison of MAP with MRP is interesting, because MRP is widely used and because it is embedded in the planning system of ASML.

2.2 Material requirements planning (MRP)

Orlicki (1975) first defined and introduced the MRP logic in his book *Material Requirements Planning*. The logic translates demand into material requirements. The aim of MRP logic is to guarantee that demand will be met by releasing a set of external and internal orders for each item of the bill-of-material (BOM). Consequently, it can be used as a planning method. The usefulness of MRP logic is that it takes the actual demand of items during the lead time period and projected future inventory levels into account. The MRP logic assumes a well-known BOM and fixed lead times (Orlicki, 1975). MRP is referred to as a push logic, because it computes schedules what should be started, or pushed, into production based on demand (Hopp and Spearman, 2011). However, MRP logic does not take material and capacity constraints into account, which results in a major drawback of this method: the generation of unfeasible solutions (De Kok and Fransoo, 2003). This was already mentioned by Orlicki (1975); "An MRP system is designed to answer the question of what *needs* to be produced instead of what *can* be produced." An overview of the inputs and outputs of MRP logic can be found in Figure 2.1. The main inputs are the scheduled receipts, inventory data, BOM and master production schedule (MPS). Planned order releases, planned on-hand inventory and change messages are the outputs.

As mentioned before, the *bill-of-material* (BOM) is an overview of which components are needed to produce an item. Additionally, it specifies the usage quantities of each component and related lead time. The *master production schedule* defines the number of end-items that are needed to produce and when they need to be produced (Orlicki, 1975), also called *gross requirements*. It is the overall plan of production. Another input are the *scheduled receipts*: the outstanding orders for both purchase and manufacturing. The MPS can be seen as the scheduled receipts for an end-item within its lead time and as planned order release outside the lead time (De Kok, 2017).

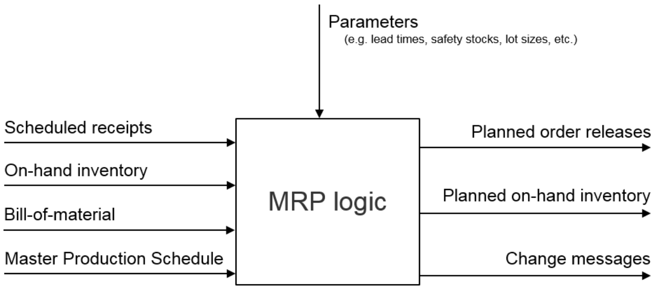


Figure 2.1: Inputs and outputs of MRP logic

The last input is inventory data, which states the current inventory position of each component, also called *on-hand inventory*. Without these inputs, the MRP procedure cannot take place. The following steps are executed in the MRP logic, derived from Hopp and Spearman (2011):

1. *Netting:* Determine net requirements by subtracting on-hand inventory and scheduled receipts from the gross requirements.
2. *Lot sizing:* Divide the netted demand into appropriate lot sizes to form orders.
3. *Time phasing:* Offset due dates of orders with lead times to determine start times.
4. *BOM explosion:* Use start times, BOM and lot sizes the generate gross requirements of components at the next level.
5. *Iterate:* repeat steps for all levels.

Additionally, several planning factors can be necessary for the MRP logic to function. This includes the use of *lot sizes*, *safety stock* and *safety lead time* (Vollmann et al., 1988). Other parameters, such has the planning horizon or freezing period can be used as well.

The main output of an MRP system is a list of orders, also called *planned order releases* (PORs), that can be communicated to the supplier or internally. This POR is created per item and contains the number of required units and the due date. MRP logic also generates the *planned on-hand inventory*. This is a 'forecasted' inventory level, based on orders and gross requirements. Finally, relevant information is sent as feedback to the user of the system in the form of *change messages*. These indicate changes in the PORs, also called reschedule messages. MRP logic is embedded in a rolling horizon planning framework. This implies that every time period the MRP logic is executed, taking into account decisions taken in the previous time period. MRP updates the outputs, as every time period new information (about e.g. demand) is available.

2.3 Synchronized base stock policies (SBS)

The main idea behind the approach of SBS is the natural hierarchy that enables synchronization of order release decisions over time (De Kok and Fransoo, 2003). It is an alternative for MRP logic to translate independent demand into orders. It is a heuristic that generates close-to-optimal policies for general networks, with use of linear holding and penalty costs.

De Kok and Visschers (1999) developed the underlying idea of synchronized base stock policies by defining a decomposition method for general assembly systems that decomposes the network into purely divergent multi-echelon systems. They show that pre-allocation policies perform well compared to common used policies, being a key idea in this method. De Kok and Fransoo (2003) elaborated on the SBS policies for general supply networks and stated that it outperforms other methods, such as MRP. SBS focuses on two concepts: *synchronization* and *allocation*. The former implies that the decision of order releases for items that are assembled into the same sellable items are synchronized, even after changes in supply or demand occur. The latter implies that if a shortage occurs, items are allocated to a parent item according to a defined algorithm. This implies that SBS takes material constraints into account, in contrast with MRP. Capacity constraints are not considered.To exploit the full potential of this heuristic, collaboration with suppliers can optimize performance, because safety stocks can be determined echelon-wide and communication would be more transparent. A benefit of the use of SBS is the reduction of nervousness, among others by consuming safety stocks and safety lead time. Moreover because it generates a feasible supply plan in terms of material availability. It is important to mention that synchronized base stock policies are not cost optimal. This is due to the fact that items can be allocated to cover future demand, earlier than absolutely necessary, pre-allocation. This allocation could have been postponed until the moment items are physically assembled into a (sub) assembly or end-item (De Kok and Fransoo, 2003).

An overview of the inputs and outputs that are used and generated by the SBS logic can be found in Figure 2.2. They are almost similar to the inputs and outputs of MRP, but an important distinction can be made. Where in the MRP logic the MPS is used as an input, this is an output of he SBS logic. In MRP, the MPS is often already smoothened or adjusted compared to the actual demand dates and regularly this is done manually. SBS policies use the actual demand (*sales plan*) as an input and generate a material feasible MPS as an output.

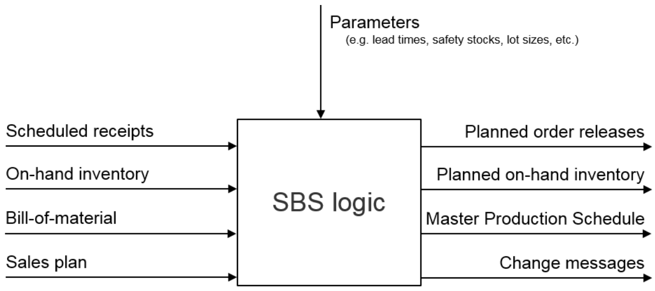


Figure 2.2: Input and output of SBS logic

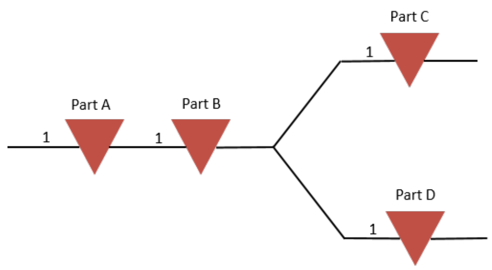
SBS policies have been implemented at Philips Electronics without the synchronization of order releases for the same component (De Kok et al., 2005). This is because synchronization for general networks on a large scale is difficult to implement and was not a focus points in this project. However, the allocation component, implying material constraint planning, was included. This implementation resulted in a reduction of inventory, nervousness and the bullwhip effect.

2.4 Material availability planning (MAP)

It is decided to use the algorithm proposed by De Kok et al. (2005) as the applied and tested logic in this research. This algorithm does not include the synchronization component. ASML has shown its curiosity in results of the allocation component, hence material availability planning, compared to the current used MRP logic. Less interest exists for the impact of synchronization due uncertainty in the ASML supply chain. In addition, actually implementing synchronization in a general and complex network is very complicated. Furthermore, the tool developed for the implementation at Philips (De Kok et al., 2005) is available for application in this project. The tool has proven its usefulness as it was used for more than seven years. The tool is used for testing and validation of the method in the final chapters of this research with use of a case study. A detailed description of the algorithm embedded in the tool can be found in Appendix E. The tool that is available for research is focused on the material availability functionality of SBS. Hence, we consider the term *material availability planning* (MAP) rather that synchronized base stock policies in the remainder of this study. The inputs and outputs are similar as in Figure 2.2.

2.5 MRP vs MAP

As mentioned before, the biggest difference between MRP and MAP is related to the MPS. MAP has the MPS as an output. MAP takes material constraints into account, while MRP has the MPS as an input, not considering material constraints. It is shown how material availability influences the output with use of an example. Figure 2.3 (a) shows the network of case X and Figure 2.3 (b) shows the current state of the network, including on-hand stock (OHS), scheduled receipts (SR) and the forecasted demand (demand) at the end of $t = 0$. At this moment, scheduled receipts have arrived, demand has been satisfied and orders have been placed. The next order can be placed at time $t = 1$. It is assumed that the sales plan input for MAP is equal to the MPS input for MRP, hence equals demand. No safety stock or safety time is considered.



(a) Network including lead times

	OHS	SR	Demand				
Time	0	1	1	2	3	4	5
item A	0	1	-	-	-	-	-
item B	0	1	-	-	-	-	-
item C	0	1	2	1	1	1	2
item D	0	1	2	1	1	1	2

(b) Current state and input parameters

Figure 2.3: Network and supply state of case X

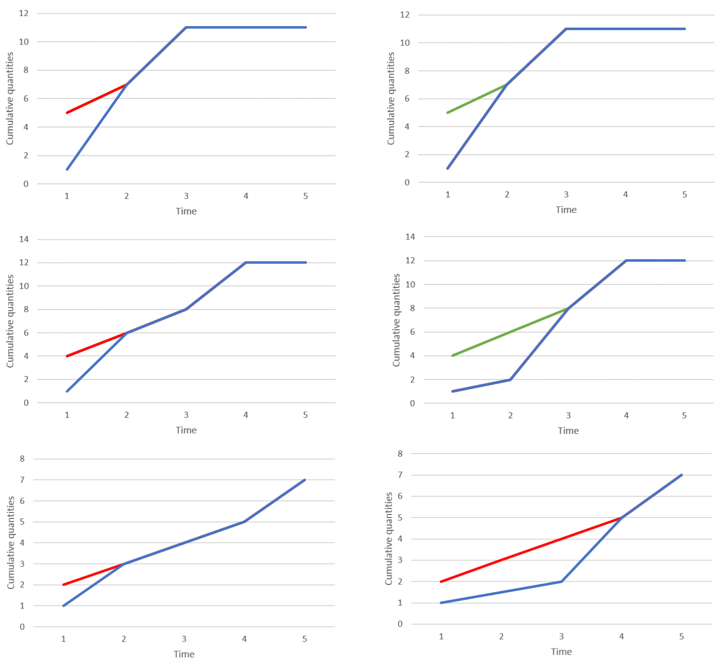
Figure 2.4 shows the supply and demand plan for both the MRP and MAP method, given the supply state mentioned in Figure 2.3 (b). The "MRP" column displays the plan as it would be in an MRP generated planning. The "MAP" column shows the plan calculated with the algorithm described in Appendix E. The "Output MAP" column shows the numerical output of the MAP method. item C and item D have an equal output, and are therefore shown in the same row. Let us first introduce three important terms. *Cumulative supply* includes the scheduled and planned receipts. *Cumulative demand* are the gross requirements of an item, derived from the number of items required by the succeeding item(s). *Cumulative unconstrained demand* is the translated end-item demand, taking into account lead times, SRs and OHS.

In the MRP column, it is shown that item A faces shortages till $t = 2$. Demand exceeds supply during this period. The unconstrained demand is equal to the demand. Item A is a buy item with lead $t = 1$, and therefore supply 'catches up' with demand after one period. Item B shows also shortages during the first period. However, according to MRP, sufficient supply (from item A) to cover demand is delivered at $t = 2$. Item C and D also show a shortage, and again, sufficient supply (from item B) is delivered at $t = 2$.

If the MAP method is applied on the same input parameters, a different plan arises. Regarding item A, the cumulative demand equals the cumulative supply. Thus, the derived demand from item B for item A is equal to the supply capacity of item A. However, the cumulative unconstrained demand shows what should have been supplied in an ideal situation to avoid shortages. The lead time of item A is equal to 1, and therefore cumulative supply catches up with the cumulative unconstrained demand after one period. A similar figure is shown for item B. The cumulative demand is equal to the cumulative supply. Hence, the derived demand from item C and D to B are equal to what actually can be supplied by item B. The cumulative supply catches up with the cumulative unconstrained demand after two periods, as the total lead time of item B is equal to 2 (item A plus item B). For items C and D, the cumulative supply shows what will be supplied from item B. As they are both end-items, the cumulative demand is equal to the cumulative unconstrained demand. It can be seen that cumulative supply catches up with cumulative demand after three periods, which is equal to the total lead time of item C, respectively D. The impact of the current supply chain state on the actual end-item demand can be seen, because with the MAP method, shortages are shown at the end-item level. The end-item figure indicates that demand must be backordered for three periods.

It can be concluded that the MRP plan is not feasible in terms of material availability. Although the MRP figure shows sufficient supplies at time 2 for item C and D, this catch-up of supply with demand cannot be realized due to current shortages at item A and item B. Another interesting observation is done. As can be seen clearly in the "Output MAP" column, the supply (SR) of item C and D can be a non-integer. As we focus on a low volume environment, an integer is essential because 0.5 systems cannot be supplied. To supply either 0 or 1 item is a substantial difference. Hence, the current used allocation policy in case of shortages is not feasible. This is an important observation in this research, and elaborated upon in the next section.

Item | **MRP** | **MAP** | **Output MAP**



item A

Time	1	2	3	4	5
SR	1	6	4	0	0
OHS	0	0	0	0	0

item B

Time	1	2	3	4	5
SR	1	1	6	4	0
OHS	0	0	0	0	0

item C & D

Time	1	2	3	4	5
SR	1	0.5	0.5	3	2
OHS	-1	-1.5	-2	0	0

Figure 2.4: Supply and demand plan of the MRP and the MAP method

2.6 Allocation for low volume

As mentioned before, this study will evaluate the performance of the MAP method in a low volume environment. As explained above, using the MAP method implies that allocation policies must be used. However, the allocation policy implemented in the provided tool, is not feasible for integers. As we focus on a low volume environment, this is essential. The following chapter, Chapter 3, defines a number of allocation policies suitable for integers. In Chapter 4, these will be analyzed in a numerical experiment. Finally, two policies will be implemented in the provided MAP tool and the MAP method will be tested in a case study.

3 | Allocation for low volume

This chapter focuses on identifying effective allocation policies that are feasible in a low volume environment. The second research question is discussed here: "*Which adaptations need to be made to the MAP method?*". The next chapter is also related to this question. To start with, relevant literature related to stock allocation is reviewed and discussed. Both the literature and ASML business process lead to a number of allocation policies that will be analyzed further. These are described and explained in the second part of this chapter.

3.1 Position in literature

Literature is often focused on the optimization of safety stock and order-up-to levels (see e.g. Axsäter, 2003; Axsäter and Marklund, 2008), while the influence of optimal allocation policies is not researched extensively. However, this is an interesting topic, because frequently the occurrence of shortages cannot be avoided. This section aims to provide a short overview of current literature about this topic. Our focus is on a low volume environment with a periodic review.

The consistent appropriate share (CAS) policy is currently used in the MAP tool discussed before. It is derived from Van der Heijden et al. (1997), where stock allocation policies in general N-echelon distribution systems are analyzed. Next to this policy, the authors discuss the balanced stock rationing (BS) policy, which is a generalization of the CAS policy. The authors conclude that the BS policy outperforms the CAS policy. However, if the imbalance is reasonable, the CAS policy performs similar to the BS policy. These policies are not suitable for integers and they have not been analyzed in a low volume environment.

De Kok and Visschers (1999) introduced a decomposition method for general assembly systems. The authors use different allocation policies in their analysis. These include the series systems allocation, fixed order allocation, random order allocation, series system allocation in combination with random order allocation, and runout time order allocation. The authors analyzed assembly systems that decompose into series inventory system and concluded that the runout time policy performs best. However, the series system policy, which is a pre-allocation policy, performs rather well. Again, these policies are not designed to handle integer values. On the other hand, they are able to deal with low volume scenarios.

Véricourt et al. (2001) discus a first-come first-serve (FCFS) policy, the strict priority (SP) policy and the multi-level (ML) rationing policy in a make-to-stock environment. An overview of other research related to inventory rationing can be found in the work of Alfieri et al. (2017). We restrict ourselves to Véricourt et al. (2001) due to the focus on a periodic review and low volume environment. The SP policy indicates that stock is allocated to the class with the highest backorder costs. The ML policy implies that stock can be rationed for reservation for future demand arrivals. Optimal parameters of ML policies for a fill rate constraint formulation and of FCFS and SP policies for both fill rate and backorder cost are obtained. The ML policy outperforms the others, and both the SP, FCFS, and ML policy can be applied to integers. However, the performance has not been evaluated for low volume.

Atan et al. (2017) reviewed assemble-to-order (ATO) systems, including papers that analyze periodic-review, multi-period systems. It is concluded that the optimal rule is case dependent, but that the FCFS rule is never optimal. Mohebbi and Choobineh (2005) apply a policy where backorders are satisfied after the current period orders are met. Additionally, a rationing rule is used that gives priority to product requirements of smaller quantity. However, this rule does not generate solutions feasible for integers. An interesting paper is the work of Huang and de Kok (2015), because it takes discrete demand into account. Three simple policies are analyzed against an optimal lineair programming (LP) policy. The simple policies include the product-based-priority (Zhang, 1997), the fair-share (Agrawal and Cohen, 2001) and the order-based-component-allocation (Akçay and Xu, 2004) with an integer formulation. It is shown that the LP formulated policy outperforms the other policies. An important remark is that in ATO systems demand is known at the moment a component is allocated. This is not the case in the situation considered in this thesis. Although a demand forecast is known, it is still uncertain and demand might change in the next period. This situation is of greater difficulty than the more simplistic ATO systems and impacts the decision-making process.

It can be concluded that only limited research has been devoted to allocation policies that are applicable in a low volume environment. Furthermore, we consider a situation where demand is unknown at the moment of allocation. This combination has not been researched so far and therefore draws attention. Hence, we will analyze a number of allocation policies that are suitable for integers in a situation that demand is unknown at the moment of allocation. This research extends the current base of literature, because this has not been analyzed so far. In the remainder of this chapter, a number of suitable allocation policies are defined.

3.2 Allocation policies

Based on the literature review and context of ASML, a number of interesting allocation policies are formulated. An explanation of these policies can be found in this section. In this study, a two-echelon divergent network is considered (see Chapter 4). All policies have a changing priority every period, except for the fixed priority policy. This policy has an equal a fixed priority every period. For ease of presentation, it is assumed that $a_{ij} \in \{0, 1\}$. The allocation policies consider the situation in which a shortage occurs; i.e. when the sum of unconstrained orders is smaller than the available stock. A definition of the variables can be found in Appendix D.

3.2.1 Fixed priority policy

The idea of this policy is that stock is allocated based on a fixed order: *priority*. This can be found in the work of Véricourt et al. (2001) and De Kok and Visschers (1999). Zhang (1997) introduced this policy as the product-type-based priority rule. This is useful when end-items (or customers) have different priorities. Even if backorders arise at a lower priority item, preference is given to higher priority items. Unconstrained orders q_j, see Appendix E for the definition, are assigned a priority derived from the item-type. Consequently, the order is fulfilled completely (if possible) in decreasing order of priority. This results in the constraint orders Q_j. Algorithm 1 provides a step-wise overview. A drawback of this policy is the creation of an imbalance in terms of service (De Kok and Visschers, 1999). This holds if the target service level is equal for all items. The fixed priority policy is referred to as FP in the remainder of this study.

Algorithm 1 Fixed order policy

```
Set leftover inventory equal to inventory of item i: LO_i = I_i
for all items j ∈ C_i in decreasing priority do
    if q_j ≤ LO_i then
        Q_j = q_j
        LO_i = LO_i − q_i
    else if q_j > LO_i then
        Q_j = LO_i
        LO_i = 0
    end if
end for
```

3.2.2 Run-out time policy

In this policy, stock is allocated based on the run-out time order allocation rule of De Kok and Visschers (1999), though slightly differently formulated. Run-out time is defined as the time period a parent item can satisfy forecasted demand without using its safety stock. Items with a short run-out time require an allocation more desperately than a longer run-out time. Hence, items are allocated in non-decreasing order of run-out time. If the run-out time of certain items is equal, a fixed order is applied. This policy is a special case of the fixed-priority policy, with a priority that can change every period, based on the run-out time. In the remainder of this study, we refer to the run-out time policy as ROT.

Algorithm 2 Run-out time policy

```
for all items j ∈ C_i do
    Determine run-out time rt_j: I_i − SS_j ≤ Σ_{s=1}^{rt_j} D_j(s)
end for
for all items m ∈ C_i in non-decreasing run-out time do
    if q_j ≤ LO_i then
        Q_j = q_j
        LO_i = LO_i − q_i
    else if q_j > LO_i then
        Q_j = LO_i
        LO_i = 0
    end if
end for
```

3.2.3 Rounded CAS policy

This policy is aimed at staying as close as possible to the original CAS policy implemented by De Kok et al. (2005), by rounding the non-integer solution. The CAS policy intends to allocate the shortage according to the cumulative safety stocks in the network, see Appendix E for the algorithm. The cumulative safety stocks are based on the (forecasted) demand during the lead time plus additional safety time. Consider again the example shown in Figure 2.4. Only 0.5 item was received by item C en D at time 2. This implies that the released order at time 1 for item C and D is equal to $Q_C = Q_D = 0.5$. This is a non-integer and therefore infeasible. Hence, we need to round the released order. However, we need to round *down* both, otherwise the possibility exists that the sum of released orders (of item C plus item D) will exceed the available net stock of item B. Yet, as we round down both, the released order equals $Q_C = Q_D = 0$. Hence, we have a 'leftover' stock of 1 item. Appendix F shows a more elaborated calculation of the released orders with an example that includes safety time. Consequently, the potential stock that is 'leftover' after applying rounding, needs to be allocated according to an additional rule. We apply a random allocation rule and a run-out time allocation rule. The description of the latter rule can be found in the previous section. See Algorithm 3 for a description of the rounded CAS policy. In the remainder of this thesis, RCRL stands for the rounded CAS policy with random leftovers, and RCRO stands for the rounded CAS policy with run-out time leftovers.

Algorithm 3 Rounded CAS policy

Determine $EIP_j^+ = S_j - \frac{CSS_j}{\sum_{m \in C_i} CSS_m} \left(\sum_{m \in C_i} q_m - I_i \right)$
$Q_j = \left\lfloor \frac{(EIP_j^+ - EIP_j)^+}{\sum_{m \in C_i} (EIP_m^+ - EIP_m)^+} I_i \right\rfloor$
$LO_i = I_i - \sum_{j \in C_i} Q_j$
Option 1 Allocate LO_i randomly to parents with unsatisfied orders
Option 2 Allocate LO_i according to the run-out rule to parents with unsatisfied orders

3.2.4 Critical level policy

The ML policy of Véricourt et al. (2001) and the series system allocation of De Kok and Visschers (1999) form the basis of our so-called critical level policy, though adapted to fit a periodic review. This implies that stock can be rationed to satisfy future demand, which can be beneficial if customers have different priorities or service levels. A number of stock levels (or inventory layers) is defined based on the number of customer classes of an item. Consequently, each class has its own stock level, which implies pre-allocation of inventory to a certain class. In our case, only two different classes are distinguished. One inventory layer for one item, class 1, and one inventory layer for the other items, class 2. Inventory level z_0 and inventory level z_1 need to be determined. If the net stock of item i is below z_o, no orders can be satisfied. If the net stock is between level z_o and z_1, only demand of class 1 will be satisfied. Even if no demand of class 1 occurs, while class 2 has adequate amounts, class 2 will stay empty-handed. If the net stock is above inventory level z_1, z_1 inventory can be allocated to class 1 and $I_i - z_1$ can be allocated to class 1 and 2 according to two different options. The first considered rule is the random allocation policy and the second rule is the run-out time allocation policy. For this reason, the critical level policy can be seen as a special case of the fixed priority allocation policy, where the priorities vary over time, but class 1 continuous to be of extra importance. See Figure 3.1 for a visual overview of the inventory layers and Algorithm 4 for the procedure. The critical level policy with random leftovers is further referred to as CLRL policy and the critical level policy with run-out time leftover is named CLRO.

Algorithm 4 Critical level policy

Set $z_0 = 0$ and $z_1 = \lambda_1$
if $I_i \leq z_0$ **then**
  $Q_j^1 = Q_j^2 = 0$
else if $z_0 < I_i \leq z_1$ **then**
  $Q_j^1 = [q_j(t), z_1]^-$
  $Q_j^2 = 0$
else if $I_i > z_1$ **then**
  Set $LO_i = I_i - z_1$
  Option 1 Allocate LO_i randomly
  Option 2 Allocate LO_i according to the run-out policy
end if

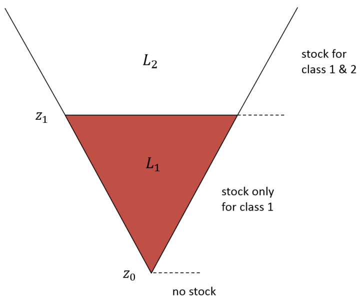


Figure 3.1: Critical level policy with two demand classes

3.2.5 Service level policy

This policy is aimed at allocating stock based on the realized service level so-far. It seems reasonable to reflect on the realized service level when allocating stock. However, stochastic demand is not taken into account in this situation. Each item is assigned a target fill rate, which is compared to the realized fill rate (Table 4.1). The realized fill rate is defined as the actual demand D_i minus stock-outs SO_i divided by the actual demand, summed for all end-items. Stock-outs are the number of items of demand that cannot be fulfilled from stock. The relative gap G_i between the target and realized fill rate is then calculated and the complete unconstrained orders of items are satisfied (as far possible) in a non-decreasing order of this gap. Again, this is a special case of the fix priority rule, with changing priorities over time based on the performance so far. See Algorithm 5 for the step-by-step description. This policy can be related to the customer-focused view of ASML has on allocation decisions. In this policy, a higher priority is given to the lowest relative service level. In case the fill rate gap of certain items is equal, a fixed order is applied. In the remainder of this study we refer to the service level policy as SL.

Algorithm 5 Service level policy

```
for all items j ∈ C_i do
    Set leftover inventory equal to inventory of item i: LO_i = I_i
    Determine fill rate β_i(t) = Σ_{s=1}^t (D_i(s) − SO_i(s)) / Σ_{s=1}^t D_i(s)
    Determine relative gap G_i(t) = (β_j(t) − β_j^(t)) / β_j^(t)
end for
for all items m ∈ C_i in decreasing gap G_i do
    if q_j ≤ LO_i then
        Q_j = q_j
        LO_i = LO_i − q_i
    else if q_j > LO_i then
        Q_j = LO_i
        LO_i = 0
    end if
end for
```

3.3 Conclusion

In this chapter, five allocation rules have been discussed. This results in the definition of seven different allocation policies that will further analyzed. These include the FP, ROT, RCRL, RCRO, CLRL, CLRO and SL policy. In the next chapter, a discrete-event simulation is performed in an experimental environment. The goal is to determine the most efficient allocation policy, which will be implemented in the MAP method that is suitable for a low environment.

4 | Numerical analysis

This chapter focuses on an experimental analysis of the allocation policies discussed in Chapter 3. Together with Chapter 3, it is related to the second research question: *"Which adaptations need to be made to the MAP method?"*. A discrete-event simulation is executed in a numerical experiment setting which results in performance insights of each policy.

4.1 Model description

The algorithm proposed by De Kok et al. (2005) is the guideline of this study. Several characteristics and assumptions are accompanying this algorithm. It concerns a rolling horizon, thus multi-period system, with periodic review. Figure 4.1 gives an overview of the order of events in this rolling horizon simulation. Two events are of importance, the period and the planning epoch. Every period orders are generated for every planning epoch until the maximum (planning) horizon. Demand is stochastic, so every period a demand forecast is made. Consequently, a planning is made (and orders are generated) for the length of the planning horizon, based on the forecasted demand. Actual demand arrives and orders are satisfied to the extend possible. The next period, demand forecasts are updated and the process repeats. It is assumed that demand that is not satisfied is backordered. Furthermore, it is assumed that scheduled and planned receipts arrive according to their planned lead times (deterministic). This complete process is repeated n times to reduce the influence of randomness factors. Increasing n increases the confidence of the estimated output parameters.

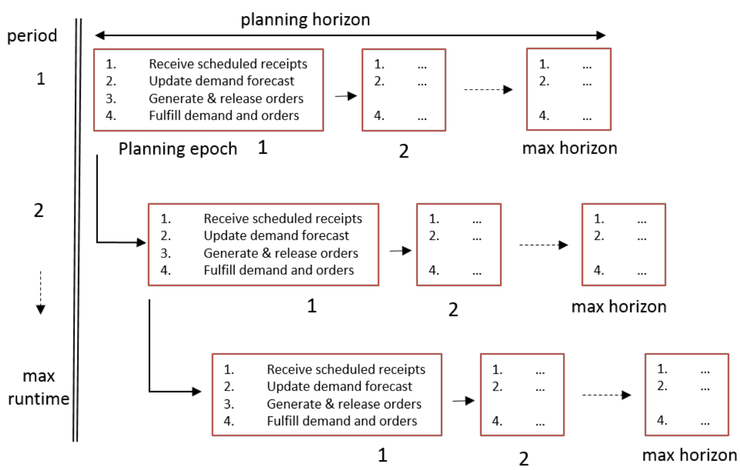


Figure 4.1: Rolling horizon simulation

The review period and considered lot sizes are both equal to 1. A 2-echelon network with six items is used for simulation and analysis. As allocation is only necessary when a child has multiple parents, we restrict ourselves to a strict divergent network. We assume that the multiplicities, the BOM quantities, are equal to 1. The network in Figure 4.2 is constructed, which is based on the structure of a particular item of ASML. The simulation is performed in MathWorks Matlab R2017a.

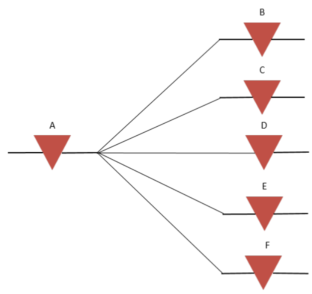


Figure 4.2: Divergent 2-echelon network with six items

4.2 Input parameters

This section describes how the parameters used for analysis are determined. They can be divided into fixed parameters, variables and dependent parameters.

4.2.1 Fixed parameters

These parameters will not be changed during the analysis and are thus fixed.

On-hand inventory The on-hand stock of each item at the start of the first period needs to be determined. This is set equal to 0.

Scheduled receipts The scheduled receipts of each item at the start of the first period need to be determined. This is set equal to the arrival rate (λ) of each item.

Planning horizon and maximum runtime The planning horizon at ASML is 1.5 years, but as we only review a small part of the network, this is relatively long. Therefore, we consider a horizon of half a year (26 weeks). The runtime, i.e. the periods that are considered, is equal to two year (104 weeks).

4.2.2 Variables

Variables are parameters that can be changed during the simulation to determine their effect on the output parameters. These include the actual demand, the demand forecast and the lead times of items.

Actual demand To simulate demand, we need to determine both the actual demand and the forecast error. As mentioned before, we consider discrete demand due to the low volume environment. First, demand data of the specific ASML parts is analyzed to gain some information about its characteristics. Following the approach of Adan et al. (1995), the mixed binomial distribution is applicable to the analyzed demand data. However, the mixed binomial distribution is not a common used distribution in an experimental setting. Fitting the Poisson distribution on the available data with use of Matlab, Pearson's Chi squared tests cannot exclude Poisson. We will use the Poisson distribution to generate the actual demand, as this distribution is very common for arrival processes and suitable in our experimental environment. As can be seen in an example of one of the analyzed parts in Figure 4.3, a Poisson distribution seems reasonable. It is assumed that the analyzed parts are representative for other parts. The arrival intensity is also derived from this historical data, indicating that on average 1 to 2 arrivals a week is common.

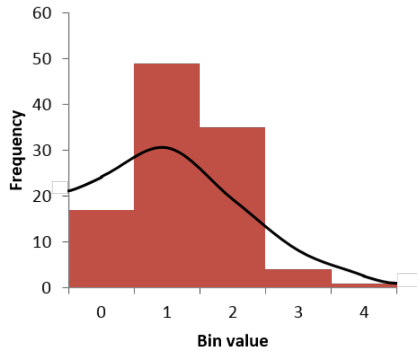


Figure 4.3: Histogram of the analyzed data of a part

Demand forecast At the start of the simulation, the actual demand of each end-item will be determined for the complete length of the maximum runtime plus planning horizon. This is done by generating Poisson random numbers, based on a arrival rate per item. However, at the start of each period, the actual demand for the length of the planning horizon is not known in advance. Therefore, a demand forecast must be made. This forecast is updated every period. A forecast is defined that is dependent on the actual demand during the planning horizon and a forecast error (De Kok, 2015). The actual demand is multiplied with a relative forecast error to calculate the demand forecast. Equation 4.1 shows how the forecast is calculated. The relative error, $RE_{t,t+\tau}$, is normally distributed, $N(0, c_\tau^2)$, with the variance as a measure of the accuracy of the forecast. This allows for increasing the forecast error over time (increasing as τ increases), because uncertainty increases. Hence, the forecast will be increasingly less accurate as the planning epochs increase. To suffice the integer requirement, the forecast is rounded after multiplying with the relative error. In case the actual demand is equal to zero, the forecast is equal to the (rounded) relative error, otherwise it can never exceed zero. Obviously, the forecast should be non-negative at all times.

$$F_{t,t+\tau} = \begin{cases} (1 + RE_{t,t+\tau}) * D_{t+\tau}, & t \geq 1 \quad \tau > 0, \quad D_{t+\tau} > 0 \\ RE_{t,t+\tau}, & t \geq 1 \quad \tau > 0, \quad D_{t+\tau} = 0 \end{cases} \tag{4.1}$$

It it assumed that the relative forecast errors for different items are independent and that relative forecast errors for the same item in different periods made at the start of the same or different periods are independent. The variance $\sigma_{t,t+1}^2$ is is the forecast inaccuracy at the start of the first following epoch. $\Delta\sigma_\tau^2$ is defined as the increase in forecast inaccuracy (compared to the first epoch) for the length of the planning horizon.

Lead times The lead time of each item of Figure 4.2 is specified. Only whole weeks are taken into account. After an analysis of the production process of ASML, assembly times of multiple weeks are common and therefore guiding in determining the analyzed lead times.

Target service level Several service measures, see Table 4.1, can be identified. We are interested in the fill rate, which is defined as the percentage of demand that is met from stock. This is interesting, because it reflects the customer service levels. Common applied fill rates include 0.90, 0.95 and 0.99.

Table 4.1: Service level definitions of Silver et al. (1998)

P_i	**Service level**	**Definition**
P_1	Cycle service level	Fraction of replenishment cycles in which the on-hand stock does not drop to zero
P_2	Fill rate	Fraction of customer demand that is met from stock
P_3	Ready rate	Fraction of time during which the net stock is positive

4.2.3 Dependent parameters

The following input parameters are dependent on the set of variables used.

Safety stock The algorithm of De Kok et al. (2005) calculates the target base stock levels S_i based on demand during lead time and safety time. We adapt the algorithm slightly and determine a fixed safety stock per item, SS_i, instead of a dynamic target base stock level. In our simulation, the cumulative safety stock CSS_i is determined using Equation 4.2, which results in Equation 4.3 as a calculation of the target base stock level. The safety stock per item is calculated by using the safety stock adjustment procedure (SSAP) of Kohler-Gudum and De Kok (2002). This technique determines the safety stocks such that target service levels are ensured, which makes it particular suitable for simulation studies. We are interested in the target fill rate, see Table 4.1. By determining the discrete probability density function of the net stock, the amount of average backorders that satisfies the target fill rate can be determined. This results in an adjustment quantity of the safety stock. A detailed explanation can be found in Appendix G. This technique is suitable for the safety stock levels of the end-items and must be executed for each set of parameters to calculate the safety stock level for that set of parameters. However, target service levels are not guaranteed, because we deal with discrete demand. Rounding can influence the determination. The safety stock level of item A is always set equal to 0, implying that all stock of item A must be allocated. This is comparable to the model of Eppen and Schrage (1981). This situation is interesting, and therefore chosen, because the focus of this study is on allocation policies.

$$CSS_i = SS_i + \sum_{j \in C_i} SS_j, \qquad i \in \mathcal{M} \tag{4.2}$$

$$S_i = CSS_i - \sum_{k \in F_i} \left\{ \sum_{s=1}^{L^*_{i,k}+1} D_k(s) \right\}, \quad i \in \mathcal{M} \tag{4.3}$$

Inventory layers For the stock rationing policy, the inventory levels of item A need to determined. As mentioned in the Chapter 3, z_o is always set equal to 0 and we set z_1 equal to λ_B. These parameters can be optimized, but this is outside the scope of this thesis.

4.3 Output parameters

Realized service levels The realized service level is the main output parameter and we focus on the aggregate fill rate. The aggregate fill rate is defined by multiplying the item fill rate with the demand weight of that item. The weights are determined as defined by Van Houtum and Zijm (2000); $w_i = \frac{\lambda_i}{\sum_{j=1}^{6} \lambda_j}$, with λ_i equal to the arrival rate of demand for item i. Backorder cost are associated with the ready rate via the Newsvendor equation (De Kok, 2017), and thus impact the service levels.

Inventory levels Besides the customer service levels, the inventory levels are interesting. Both are necessary to evaluate a policy and decide on the trade-off. Inventory levels can be related to the holding costs of items. The average on-hand stock at the start of a period is taken as measurement.

Confidence intervals To determine the confidence of our output parameters, we calculate the confidence intervals of the fill rate and the inventory levels. Law et al. (1991) developed a confidence interval expression suitable for simulation studies with $\overline{X}(n)$, indicating the sample mean and $S^2(n)$ the sample variance. It is shown that for large n the sample mean is approximately distributed as a normal random variable with mean μ and variance σ^2/n. Based on this information, the exact confidence interval of μ can be formulated, as found in Equation 4.4. Our objective is to construct a 95 percent confidence interval for μ with $n = 2000$, which results in $t_{\infty,0.975} = 1.960$.

$$\overline{X}(n) \pm t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}} \tag{4.4}$$

4.4 Results

This section outlines the results of the numerical experiment as described in the previous section. The standard case with standard parameters is discussed first. Subsequently, the variables are adjusted to identify the impact on the output parameters. Finally, a specific case based on ASML parameters is considered.

4.4.1 Standard case

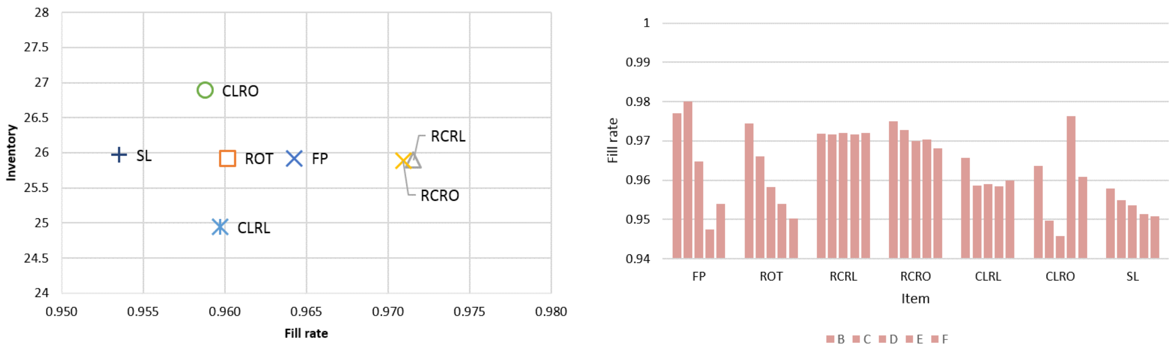
The parameter settings of this standard case can be found in Table 4.2. The safety stocks shown are the result of the safety stock procedure described earlier in this chapter and are dependent of the combination of parameters used in the simulation. This is a homogeneous case, implying that all parent items have the same values.

Table 4.2: The standard parameters including corresponding safety stocks

item	$\boldsymbol{\lambda}$	**lead time**	**target** $\boldsymbol{\beta}$	**forecast**	**safety stocks**						
					FP	ROT	RCRL	RCRO	CLRL	CLRO	SL
A	-	3	-		0	0	0	0	0	0	0
B	1	3	0.95		2	3	3	3	2	2	3
C	1	3	0.95	$\sigma^2_{t,t+1} = 0.5$	3	3	3	3	3	3	3
D	1	3	0.95	$\Delta\sigma^2_\tau = 0.05$	3	3	3	3	3	3	3
E	1	3	0.95		3	3	3	3	3	4	3
F	1	3	0.95		5	3	3	3	3	4	3

Figure 4.4 shows the aggregated fill rate en total inventory of all items, including inventory of item A. In addition, the fill rate per item per policy is shown. It can be seen that in general, item B performs better than item C, and so on. This is due to the fact that when a certain parameter is equal, a fixed order (from B to F) is applied. This happens for example if the run-out time of certain items is equal in the RCRO policy. If this is not the case, it is because the subsequent item has a higher safety stock level, increasing its service level. Both the RCRL and RCRO perform best in terms of service level. The CLRL policy has a lower total inventory, because the sum of the safety stocks is lower. If a closer look is taken at the individual fill rates, the RCRL policy performs most stable across all items. The SL and CLRO policy are both

outperformed by the others. The confidence interval for the aggregated fill rate is smaller than 0.001 for each policy. Regarding the total inventory, the confidence interval is smaller than 0.02 for all policies. This implies that the performance does not vary much.



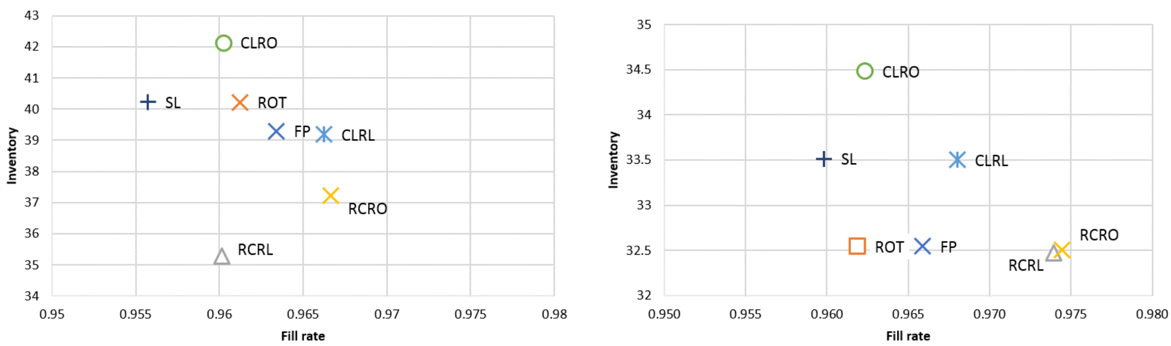
(a) Aggregated fill rate and total inventory

(b) Fill rate per item

Figure 4.4: Results standard case defined in Table 4.2

4.4.2 Arrival rate

In these cases, the arrival rates of the end-items is changed, but the other parameters are identical to Table 4.2. In the first case the arrival rate is increased to $\lambda = 2$ for all end-items. In the second case the arrival rates differ per item and are as follows: $\{\lambda_B, \lambda_C, \lambda_D, \lambda_E, \lambda_F\} = \{2, 1.5, 1.5, 1, 1\}$. Both results can be found in Figure 4.5. It can clearly be seen that increasing the arrival rates causes an increase of the required safety stock. In the left case, the RCRO and CLRL policy perform best in terms of service level, while the RCRO policy performs best in terms of total inventory. The latter can be explained by a smaller cumulative safety stock level. The right case shows superiority of the RCRL and RCRO policy, performing best on both service levels and total inventory. Again, both the SL and CLRO perform poor. The confidence intervals of the aggregated fill rate are smaller than 0.001 and for the total inventory level smaller than 0.02.



(a) Arrival rates for all items equal to $\lambda = 2$

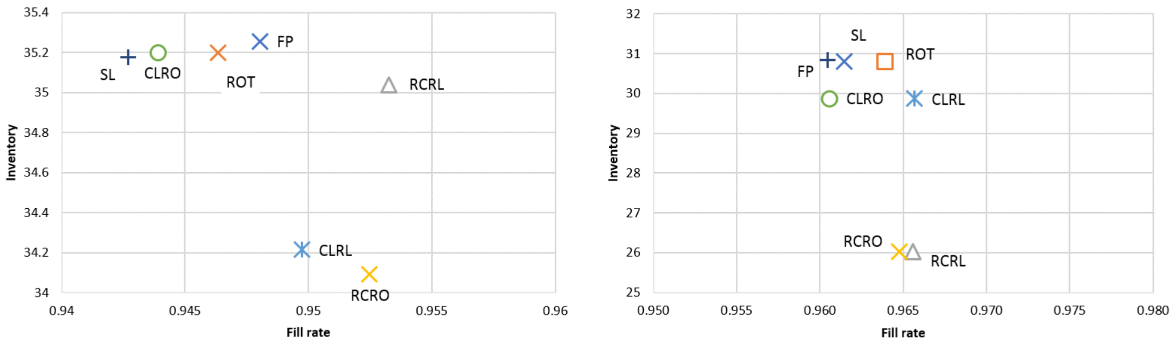
(b) Mixed arrival rates

Figure 4.5: Results for modified arrival rates

4.4.3 Lead times

Figure 4.6 shows the results for adjusting the lead time. Figure 4.6 (a) shows the result of increasing the lead time to 6 weeks for all items (including item A) and Figure 4.6 (b) shows the output for mixed lead times. The lead times are as follows in the latter case:

$\{LT_A, LT_B, LT_C, LT_D, LT_E,\ LT_F\} = \{3, 6, 5, 4, 3, 2\}$. The figures shows that lengthening the lead times leads to an increase of the required safety stock, which is intuitive. Figure 4.6 (a) shows that the RCRO and RCRL policy outperform the others in terms of the fill rate. The aggregate fill rate confidence interval is smaller than 0.002, which is significant. However, the CLRL and RCRO policies outperform the others regarding inventory. The confidence interval of the total inventory is smaller than 0.02, implying that the differences in total inventory are considerable. In Figure 4.6 (b), the RCRL and RCRO policy perform significantly better in terms of inventory.

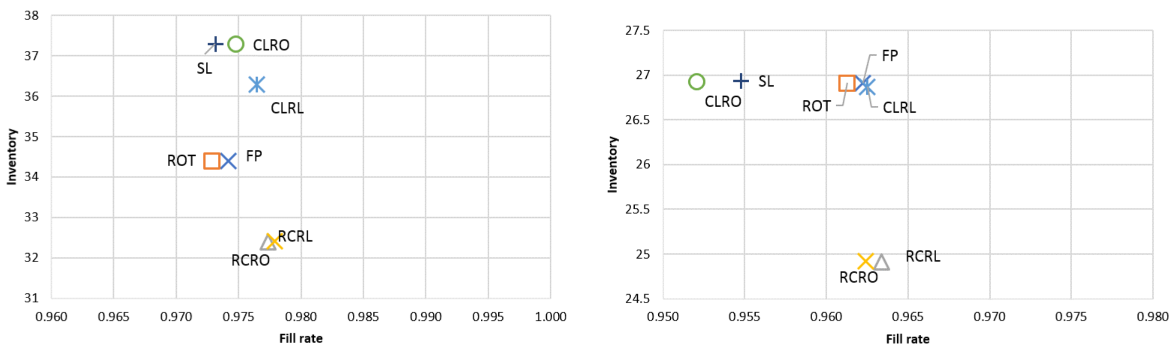


(a) All lead times increased to 6 (b) Mixed lead times

Figure 4.6: Results for modified lead times

4.4.4 Service levels

In this setting, the target fill rate is adjusted. In the first case, the target fill rate is increased to 0.99 for all items, while in the second case the target levels are equal to the following: $\{\beta_B, \beta_C, \beta_D, \beta_E, \beta_F\} = \{0.99, 0.95, 0.95, 0.90, 0.90\}$. The results of both cases can be seen in Figure 4.7. Although the second case has different target fill rates per item, the aggregated fill rate is depicted. It does not show any information about the individual fill rate performance, but it does tell something about the overall performance. In both cases the RCRL and RCRO perform best in terms of total inventory. In the second case RCRL and RCRO also perform best regarding the fill rate. The SL and CLRO policy have in both cases the worst performance. The confidence interval is smaller than 0.001 and 0.02 for the fill rates, respectively total inventories. An additional observation is that the fill rates of the first case does not touch the 99%. This could be due to the rounding of safety stocks.



(a) All target fill rates increase to $\beta = 0.99$ (b) Mixed target fill rate

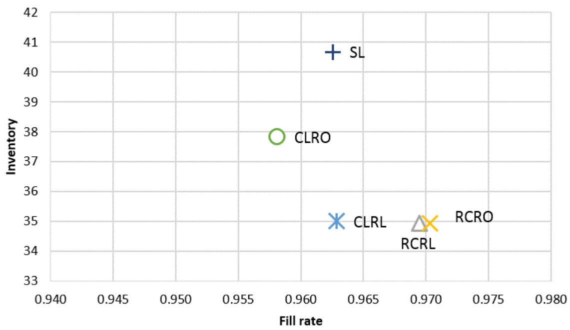
Figure 4.7: Results for modified target service levels

4.4.5 Mixed

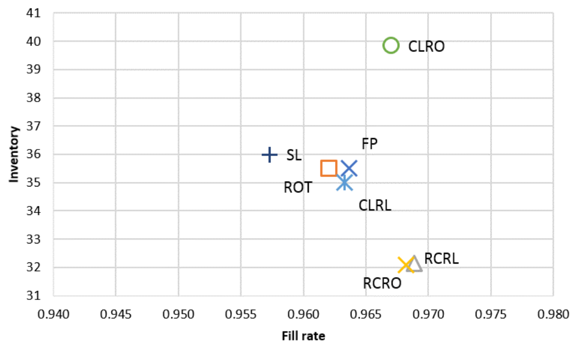
This section discusses two cases that have multiple adjusted parameters. Table 4.3 shows the adjusted parameters for the case A and case B. The forecast accuracy remains unchanged. The performance can be found in Figure 4.8. For both cases holds that the confidence interval is smaller than 0.002 for the aggregated fill rate and smaller than 0.02 for the total inventory. Again, RCRL and RCRO perform best, while SL and CLRO perform worst. The RCRL and RCRO do not differ significantly.

Table 4.3: The parameters for the case A and case B

item	**Case a**			**Case B**		
	λ	**lead time**	**target** β	λ	**lead time**	**target** β
A	-	3	-	-	3	-
B	2.0	6	0.99	1.0	6	0.95
C	1.5	5	0.95	1.0	5	0.95
D	1.5	4	0.95	1.5	4	0.95
E	1.0	3	0.90	1.5	3	0.95
F	1.0	2	0.90	2.0	2	0.95



(a) Results 'left case'

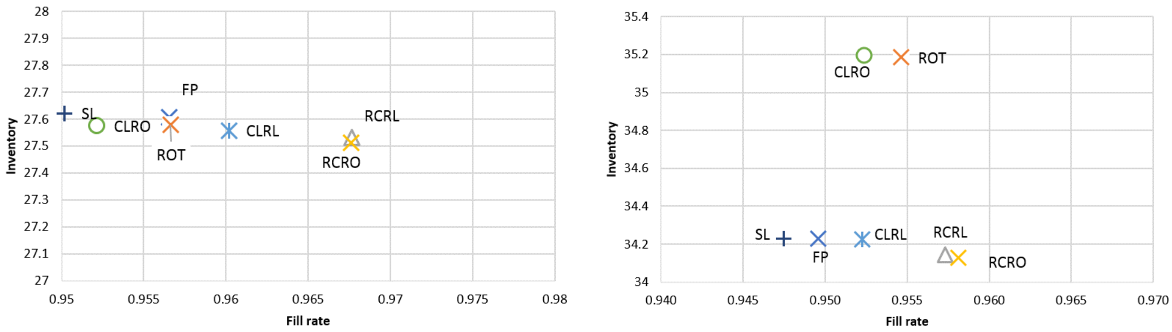


(b) Results 'right case'

Figure 4.8: Results for modified arrival rates, lead times and target fill rates

4.4.6 Forecast accuracy

Two cases have been analyzed, with the parameters equal to the standard case, except the forecast accuracy. In the first case, the 'starting' variance is equal to $\sigma^2_{t,t+1} = 1.0$ with the increase equal to $\Delta\sigma^2_\tau = 0.10$. The second case has an equal forecast for the complete length of the planning horizon, identical to the arrival rate of the corresponding item. The results can be found in Figure 4.9. It can be seen that both perform worse (both inventory and fill rate) than the standard case, which is explicable. RCRL and RCRO perform best. The CLRO performs in both cases less in terms of inventory and the SL policy in terms of the fill rate. The confidence intervals are similar to the standard case.



(a) Forecast accuracy: $\sigma^2_{t,t+1} = 1.0$ and $\Delta\sigma^2_\tau = 0.10$

(b) Forecast for item i equal to λ_i

Figure 4.9: Results for a modified forecast accuracy

4.5 Verification

It is important to verify the correctness of the model and the simulation. Therefore, we apply two different verification methods. First, the output, including safety time instead of safety stock, is compared to the output provided by the tool. The tool is assumed to be correct, as it has been developed and implemented during a period covering over seven years. Secondly, a 'single-echelon check' is executed. This implies a situation with infinite supply at the child part, item A, resulting in the situation that constrained orders equal constrained orders. When the lead time increases this results in a negative impact on the fill rate. This is reasonable, because the uncertainty increases.

4.6 Conclusion

In this chapter a numerical experiment has been performed with 11 different sets of input parameters. The performance of seven different allocation policies is analyzed. This analysis differs from the reviewed literature because it analyzes allocation policies in a (integer formulated) low volume environment with unknown demand at the moment of allocation. This chapter compares a large number of allocation polities, which has never been investigated in literature before. This is even the case for high volume situations. Furthermore, the RCRL policy is introduced as a new rule, and performs very well.

It is concluded that the RCRL and RCRO policy outperform the other policies in all experiments regarding the fill rate and average inventory level. Hence, it can be concluded that these polities deal best with a stochastic low volume demand. In general, the SL and CLRO policy perform considerably worse. The SL policy only considers past data: the achieved service level so far. It seems convenient to do this. However, it does not anticipate on stochastic (forecasted) demand, which can explain its poor behavior. The CLRL and CLRO can not directly be compared to the other allocation rules in cases where the fill rate of item B is not higher than the other policies. This is due to the 'preference treatment' of this item in CL policies. This partly explains the lower performance of this policy compared to the RC policies. Nonetheless, even in the experiments that discuss a higher target fill rate of item A, all other policies outperform the CL policies. Interesting is that the CLRO policy performs worse than the CLRL policy, implying random leftovers are preferred over run-out time leftovers. Although the ROT policy does anticipate on forecasted demand, it performs less than the RCRO and RCRL policies. This can also be explained by the stochastic behavior of demand. It is interesting that the RCRL and RCRO policy differ minimally in performance, while the CLRL and CLRO differ significantly.

This can be explained by the order of allocation within the rule. For CLRL and CLRO, only a small portion is reserved for item B, whilst the other leftovers are allocated randomly or according to the ROT rule. For the RCRL and RCRO policy the majority is allocated with the rounded CAS and only a small portion is allocated randomly or according to the ROT rule.

Balancing between fill rate performance and inventory levels is always key. Which performance indicator is considered most important depends on the situation or company. An additional analysis can be performed to get insights in the effect of the penalty cost ratio between the fill rate and inventory costs. As expected, increasing the lead time, target fill rate or arrival rate, results in a need for a higher safety stock level. Furthermore, the safety stocks considerable affect the performance. Last, the fill rate has a positive relation with the total inventory per policy.

Several directions for further research can be determined. It is interesting to extent the research to a multi-echelon network and analyze the performance. Additional allocation policies can be considered, such as the linear allocation rule of Diks and De Kok (1998). Other input parameters could extent the analysis, such as demand distribution, longer lead times or safety stock settings. The impact of other performance indicators can be analyzed as well.

This chapter concluded on an analysis of allocation policies in a low volume environment. The RC policies have been identified as most efficient. The next part of this research is focused on testing the impact of the MAP method in a low volume environment by means of a case study at ASML. Hence, an integer feasible allocation policy must be implemented in the MAP tool. The RCRO policy will be used. It is preferred over the RCRL policy to limit the impact of randomness on a short horizon.

Part II

Case study

5 | Planning at SCP

This chapter provides information about the planning process at ASML, focusing on the SCP department. It provides an answer to the third research question: *"How is the current planning process designed at ASML?"*. Furthermore, it partly answers the fifth research question: *"How can MAP be implemented at ASML?"*. Relevant planning processes are discussed step-by-step. Finally, a specific environment for testing the MAP method is defined.

5.1 Demand

Information about the types of demand at ASML is essential to understand the planning processes. A distinction needs to be made between independent and derived demand. Independent demand originates from the outside, while derived demand is demand for components that make up independent demand products (Hopp and Spearman, 2011). An overview of the types of independent demand can be found in Figure 5.1. New system demand takes the biggest portion of independent demand. Other demand is generated from, for example, defects in the factory or spare-part services.

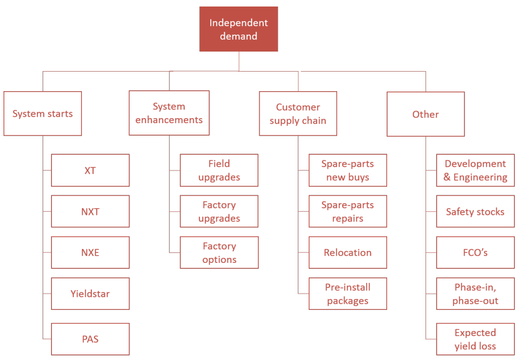


Figure 5.1: Overview of independent demand at ASML

5.2 MRP at ASML

An important resource for planning at ASML is the currently used planning system, referred to as an enterprise resource planning (ERP) system. At ASML, the ERP system makes use of MRP logic to translate independent demand into derived demand for all items of the BOM. The MRP method is explained in detail in Chapter 2. Next to MRP related information, ERP systems offer additional features, for example project management and finance. However, if we mention *ERP* in this study, we refer to the demand and supply related information. The independent demand, as depicted in Figure 5.1, is carefully planned by ASML, mainly focusing on systems and service enhancements. This is equivalent to the MPS of Figure 2.1 in Chapter 2. The derived demand for all other items of the BOM is calculated weekly with MRP logic. A small portion of items are planned using 'simple' inventory control policies, such as replenishment policies However, the majority of the parts is planned following MRP logic.

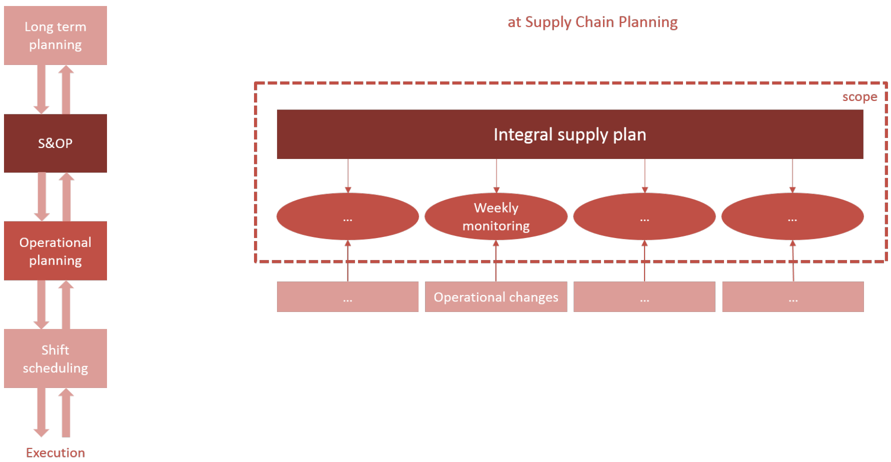
As mentioned in Chapter 2, the MAP method is an alternative for the MRP method. Since it is too broad to test MAP as an actual planning method of the ERP system at ASML, this is considered out of scope. To test the applicability of MAP in a low volume environment, a smaller environment needs to be defined. This is the starting point for further analysis. Therefore, this study scopes on the applicability of MAP within the SCP department. The next section elaborates on planning processes that lead to the identification of a specific test environment.

5.3 Planning

In a company where throughput times exceed customer lead times, planning is a key element and needs to be aligned with all company stakeholders. Consequently, the planning process is extensive and complex. We focus on the contribution of the SCP departments. This section explains the role of this department and concludes on an interesting direction for this study.

5.3.1 Planning levels

In general, there are three levels of planning processes that can be differentiated: strategic, tactical, and operational. ASML considers an additional layer, namely execution. Figure 5.2 (a) shows an overview of the planning layers at ASML. At ASML, the strategic planning is related to the long term planning - more than 1.5 years ahead - and is discussed quarterly. The tactical planning is related to the sales and operational planning (S&OP). This layer is focused on the medium term - a few weeks to 1.5 years ahead - and is discussed monthly. The operational planning is short term - 0 to 4 weeks ahead - and changes weekly or even daily. This depends on the focus of the relevant department. Execution focuses on the immediate events and is continuously monitored on a daily basis. While multiple departments have a share in these planning layers, we focus explicitly on the role of the SCP department. SCP contributes to the S&OP, referred to as tactical, and the operational layer. This is shown in Figure 5.2 (b).



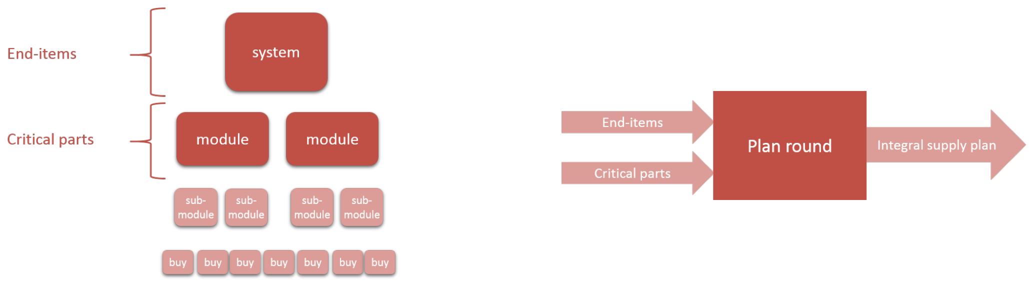
(a) Planning layers (b) The S&OP and operational layers

Figure 5.2: The planning layers at ASML related to the focus of the SCP department

5.3.2 Tactical & operational planning at SCP

Monthly, an *integral supply plan* is created in collaboration with all relevant stakeholders. Stakeholders are for example the sales department and the factories. The SCP department is responsible for constructing this supply plan. The construction of the integral supply plan takes place in the so-called *plan round*, the tactical responsibility of SCP. Additionally, the SCP department is responsible for overseeing the execution of this plan. This is done by monitoring the operational changes in the supply chain and managing them within the boundaries of the integral supply plan. This is the operational responsibility and is performed on a weekly basis, see Figure 5.2 (b).

The SCP department is responsible for constructing a feasible supply plan that meets customer demand. This is done by determining and securing the output dates of *end-items*. End-items are parts that face independent demand, see Figure 5.1. The majority of end-items that are taken into account when making the integral supply plan are new systems, system enhancements and relocations. These items form the biggest demand volume. As said before, the internal and external orders of other parts of the BOM are generated with MRP logic by the ERP system. Hence, MRP translates the tactical plan into an operational plan. Next to information of the end-items, additional information about the *critical parts* is important. These are (sub-)assemblies that need special attention because they lie on the *critical path*. The critical path includes all items that determine the longest path of completion of the final product (Nahmias and Cheng, 2009). Hence, critical parts impact the possible output date of end-items. Because of their importance, critical parts are monitored separately next to the end-items. Information of both end-items and critical parts is input for the plan round. The input of the plan round can be divided in both end-items and critical parts, see Figure 5.3. The weekly monitoring as depicted in Figure 5.2 (b) can also be divided in the two groups of end-items and critical parts.



(a) Simplified model of a BOM

(b) Input & output of the plan round at SCP

Figure 5.3: Relation between end-items,critical parts and the plan round at SCP

5.3.3 Plan round

During the monthly plan round, the SCP department plans the outputs of end-items in weekly time buckets. It is aimed to take all (forecasted) independent demand into account, although in reality it is difficult to include all demand completely. A simplified overview of this process can be found in Figure 5.4. Although SCP is responsible for the creation of the supply plan, steps are executed by all stakeholders. An elaborate overview of the plan round process, including all related parties, can be found in Appendix C. The first step includes commercial demand consolidation. Additionally, information is collected, mainly including information about capacity of the factories and the suppliers. The majority of all independent demand is included, but it cannot be guaranteed that all is taken into account. Next, all data is combined with SAP data. At this moment, a *plan approach* is created, which implies a rough check of both infeasibilities and possibilities at the factory and relevant suppliers. Subsequently, scenarios are analyzed and discussed. Amongst others, this can include the moving of supply, demand, or changing a certain system type to another. An agreed scenario is consequently analyzed in detail, by all the involved stakeholders. This detailed sector analysis should identify possible bottlenecks, risks and solutions and takes material and resource constraints into account. All this information is combined and used to take a final demand and supply decision. The final output is an aligned integral supply plan with consciously made decisions and defined actions. This is finally implemented in SAP. It can happen that an infeasible supply plan is implemented, which is done intentional. Material and resource constraints are often flexible and can improve.

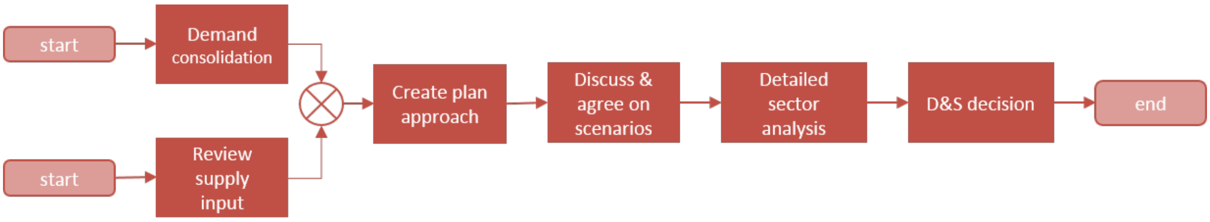


Figure 5.4: Simplified process description of the plan round

5.3.4 Critical parts planning

As mentioned before, critical parts are (sub-)assemblies that are on the critical path. Therefore, demand and supply need be monitored closely, as changes can have direct impact on the end-item output. These items are particularly interesting regarding material availability, as they *are* the material constraints in most cases. These items have a high potential shortage risk. Hence, the focus lies on the applicability of MAP specifically for CPP. A detailed description of the critical part plannings process can be found in Chapter 7.

5.3.5 Allocation

If a shortage actually occurs, available items need to be allocated. We have seen this in Chapter 2. At ASML, potential shortages are managed on different levels and obviously are tried to prevent. However, it can happen that shortages cannot be solved regularly. In that case, the so-called *escalation process* is in place. The focus is on a four weeks horizon. Three escalation levels exist, increasing in urgency. In a case where a shortage cannot be solved at the first level, it is taken to the second, and otherwise to the third. Each level has its own processes and decision-meetings, it depends on the escalation level which departments join. If a shortage cannot be avoided and actually occurs, a part needs to be allocated to a certain demand. Allocation rules are in place to guide these decisions, based on both customer satisfaction and potential revenue impact. However, these are guidelines and no strict rules. It is difficult to capture the impact of a shortage in costs. Despite these guidelines, priorities can change from week to week. ASML applies a manual allocation policy that can best be described as a flexible priority policy.

5.4 Conclusion

This chapter provided information about the planning process at the SCP department. The plan round is the main driver of tactical planning. It is concluded that critical parts are specifically interesting, as these parts cause material constraints in the majority of the cases. A case study is performed in Chapter 6, focusing on critical parts. It is the first step to compare the MAP method with the MRP method in a low volume environment.

6 | Case study

This chapter discusses a case study based on ASML data. The fourth research question is elaborated upon in this chapter: *"What are the results of using the MAP method if applied to a case study at ASML?"*. The case selection is discussed, including the considered constraints and assumptions. Afterwards, the impact of the MAP method is analyzed for the discussed cases. Finally, the applicability of the MAP method at ASML is determined and discussed.

6.1 Implementation of allocation policies into a planning tool

As shown in Chapter 2, an allocation policy is necessary for using the MAP method. In addition, it was shown that the current implemented policy (the CAS rule) is not feasible for integers. To execute a case study with the MAP tool, the allocation policy has to be adjusted. Hence, we integrate allocation policies for low volume into a planning tool for multi-item multi-echelon inventory systems under low-volume demand.

Two allocation policies are implemented in the provided MAP tool. First, a slightly adapted rounded CAS with run-out leftovers (RCRO) policy is chosen. This policy performed best in the numerical analysis as concluded in Chapter 4, and is therefore implemented. Second, a policy reflecting the procedure of ASML is selected. As mentioned before, the policy of ASML is rather complicated and can best be described as a 'flexible priority' policy. These priorities depend on numerous factors and are determined manually. The fixed priority (FP) policy is the best approximation of the ASML approach. ASML focuses on the prioritizing of end-items, which is also the case in the FP policy. For this reason, this policy is implemented as well. A brief descriptive explanation of the integrated policies can be found in Appendix H. In order to be able to use the tool, other changes have been made. These include adjusting the length of the planning horizon, the inclusion of priorities in the item-overview, and other small adjustments.

6.2 Case construction

The complete network of ASML is too extensive to research in this study, therefore two representative cases have been constructed. These are used for analysis in this chapter and for a pilot study in Chapter 7. Two cases have been constructed based on critical parts. Data is extracted from the ERP system of ASML and transformed into the required format by the tool. To enable the case construction, several assumptions and decisions are taken into consideration.

6.2.1 Case selection

Several interviews have been conducted to construct cases that represent the network structure of ASML. This led to the following formulation of requirements:

1. The network must be comprehensible
2. The network includes service parts
3. The network includes parts that are (or have been) critical

4. The network includes both assembly and buy parts

Two networks have been constructed with use of knowledge experts; case Y and case Z. These cases have different characteristics, but face one common problem; they include critical components. Critical implies that it is likely that shortages will occur. An overview of the networks can be found in Appendix I.

Case Y This case relates to a part that is assembled in one of the abroad factories. Afterwards, the part is transported to Veldhoven for further assembly. It is an interesting case because the part is used in almost all types of end-item demand, e.g. XT systems, NXT systems, upgrades and replenishments. The network created is a simplified version of the actual part, only including the core item as a child-item, which results in a strictly divergent network. Other child-items are left out of scope. The end-items are divided into service and non-service demand. Demand and supply data is not exactly equal to the data from the ERP system, but based upon. The part has a long lead time and finite capacity. The latter is represented by a constant *move-rate*, the throughput per week. This implies that the scheduled receipts are smoothened over time.

Case Z This case is an actual, complex case of a part that is assembled in Veldhoven. From all parts that are included in the network, the end-items are traced and added. After checking, a few exceptions are left out of scope, e.g. stock at the supplier. The end-items include system starts, system enhancements, spare parts, safety stocks, supply chain buffers and 'other'. The selection of parts for this network is done with help from a knowledge expert from Veldhoven and is based on possible criticality. This results in a general network, including both a convergent and a divergent structure.

6.2.2 Data transformation

As the tool solely works with on-hand stock, WIP and end-item demand (see Figure 2.2), the data from the ERP system needs to be converted to the right format. As the ERP systems holds a wide range of additional information, this implies 'squeezing' the data into the right format. First, data is extracted from the ERP system and downloaded to spreadsheets. Afterwards, data is converted to the correct format and saved to a file that can be loaded into the tool. Difficulties and exceptions have been discussed with ASML employees to take valid decisions. Figure 6.1 shows the process of translating the data. Once constraints and assumptions are determined, this process can be automated using rules. However, the design of such a general automation tool is out-of-scope in this study.

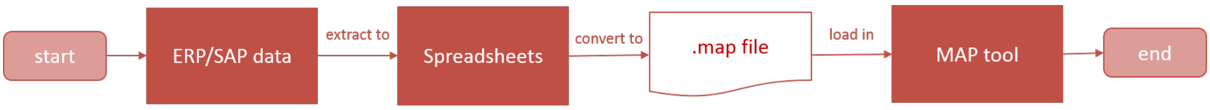


Figure 6.1: Process of translating ERP data to data required by the MAP tool

6.2.3 Constraints, assumptions and decisions

Several choices and assumptions have been made to be able to transform the elaborate amount of data extracted from the ERP system of ASML to the format required by the tool.

Lead times The tool considers whole weeks in its calculations. As ASML works with days, these are rounded up or down. The exact influence is unclear and not analyzed further. Furthermore, the tool cannot deal with lead times equal to zero, therefore a lead time equal to one is chosen for parts that have zero lead time. The lead times are derived from the planned lead times in the current plan and include safety times.

Safety times It is typical in real-life systems that lead times are split into many sub-stages to keep track of status of orders. Each sub-stage lead time is accompanied by a safety time in the ASML process. In addition, other time frames are used, such as goods receipts time (time to receive, unpack, pack and distribute parts). As this gets very complex, it is chosen to omit additional time frames and include all in the lead time.

Data in the past Supply and demand quantities in the past are added to the current week.

Safety stock Next to safety times, ASML works with safety stocks. However, the MAP tool is not able to deal with this. Therefore, safety stock is modelled as a separate end-item that faces a demand equal to the safety stock quantity. The advantage of this modelling choice is that the safety stock can be assigned a low priority. The disadvantage is that once a the demand for safety stock is satisfied, it cannot be consumed any more.

Double parts Discontinuities are parts that are followed-up by an upgraded part with a different part number. This happens at a certain point in time (e.g. when the stock is finished). The data of these discontinuities are merged as if it would be one part.

Incomplete WIP The MAP tool assumes that all scheduled receipts (within lead time) are WIP and that all necessary child items have arrived. In real life, this can be different. It can happen that a certain child item is used in assembly at a later stage than planned. Hence, it can happen that an item that is marked as a scheduled receipt, still requires certain child items. Consequently, every week it needs to be checked which scheduled receipts are (in)complete. It is decided to postpone orders just outside lead time if any child item is missing. Although this implies that a scheduled receipts arrives later than might be the case in reality. Mostly, it are the critical parts that are assembled at a later stage, and it is better to delay a scheduled receipt than counting a critical item that is not actually WIP. A negative consequence is that the child items that *do* have arrived, are not taken into account as WIP.

Dynamic BOM Asides from discontinuities, modules can have a dynamic BOM structure. In our case, a fixed BOM is assumed. If an end-item requests child A *or* child B, the end-item is modeled twice. Both the demand, scheduled receipts and on-hand inventory are divided.

Capacity constraints In real life, ASML faces capacity constraints in their supply chain. An example is when a limited number of work-centers ('rooms') is available to assemble an item. The MAP tool considers unlimited capacity.

Out of scope The ERP system of ASML includes so-called non-MRP items. These are not planned with the MRP BOM explosion, but planned otherwise (e.g. re-orderpoint policies). These are left out of scope, because they mostly imply bulk items that are not relevant for criticality. Repair flows, including inventory that is on stock at the supplier, is also left out of scope.

SPOT is a supporting tool used in the plan round, and specifically takes capacity constraints of the factory into account. MRP does not take any capacity or material constraints into account. Discontinuities are difficult in both SPOT and MRP. This also holds for a flexible BOM in MRP, while SPOT does take this into account. In both SPOT and MRP, safety stock and safety time cannot be 'consumed' in case this is desired. SPOT can deal with a large number of assumptions discussed above, but has a considerable calculation time. Overall, the MAP tool has more assumptions than MRP and SPOT, but this results in a remarkable fast calculation.

6.3 A one week analysis

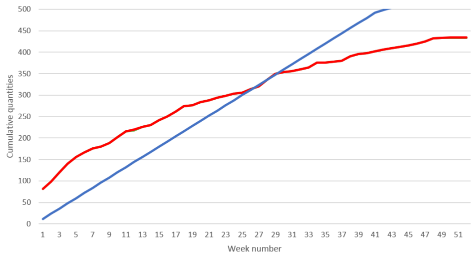
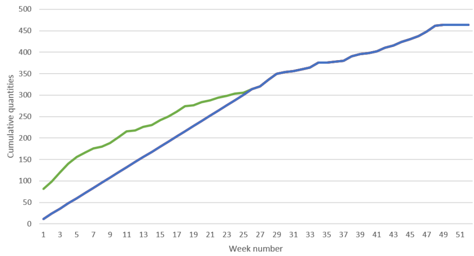
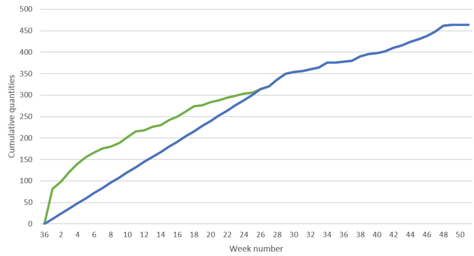
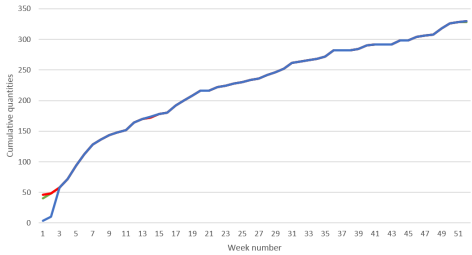
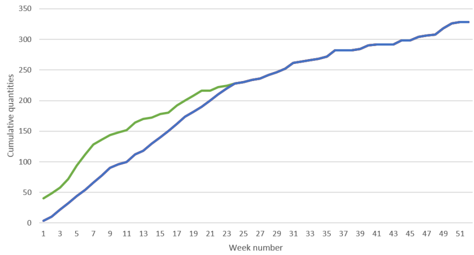
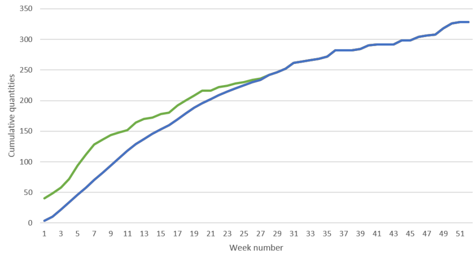
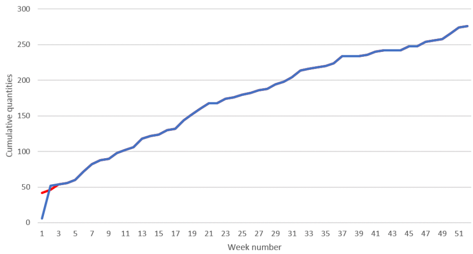
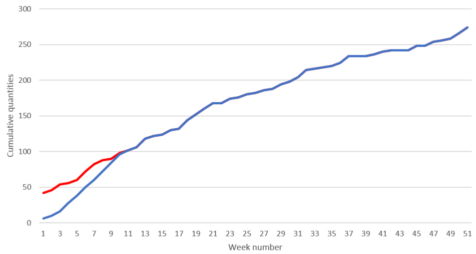
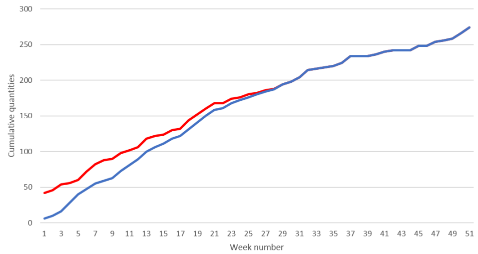
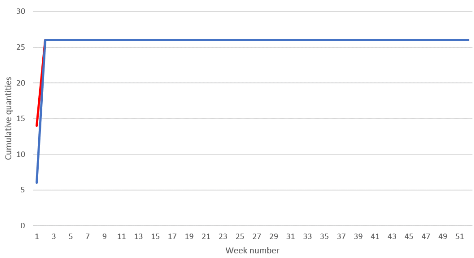
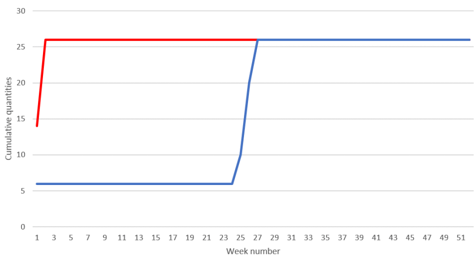
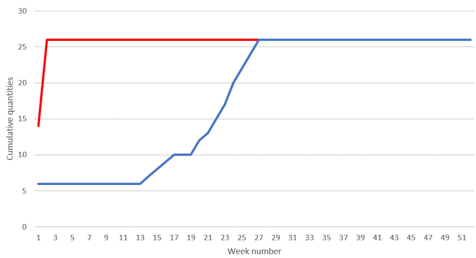
This section discusses the results of applying the MAP method to the two cases discussed above: case Y and case Z. The MAP method is applied with two different allocation policies. As mentioned before, these are the fixed priority (FP) policy and the rounded CAS with ROT leftovers (RCRO) policy. The quantities and week numbers have been adjusted for confidentiality reasons. For an elaborate explanation of the terms *cumulative unconstrained demand*, *cumulative demand*, and *cumulative supply*, we refer to Section 2.5.

6.3.1 Case Y - one week

Referring back to Figure 2.2, it is stated that the actual sales plan is the input for the MAP method. Case Y is only a minor part of the BOM of an actual output item. Therefore, it is assumed that the derived demand on the end-items of case Y is equal to the actual sales plan of that end-item. Figure 6.2 shows the results of case Y for four parts of the network. It observes the supply chain data of one certain week. The planning horizon is one year, expressed in week numbers. Part Y is the 'root-item' of the divergent network and hence the bottleneck item. Part Assy B is an assembly, and parts Non-service B and Service Y are end-items.

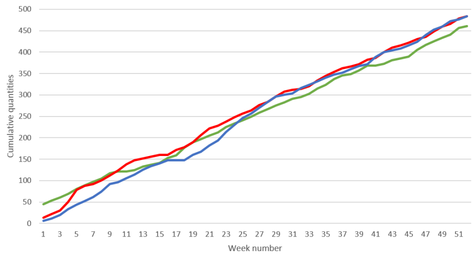
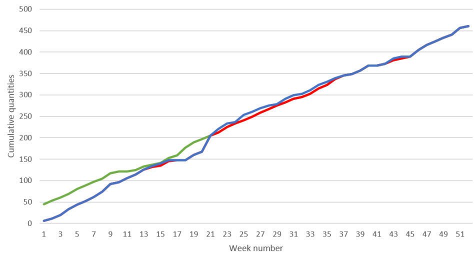
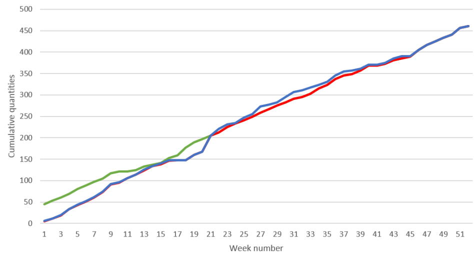
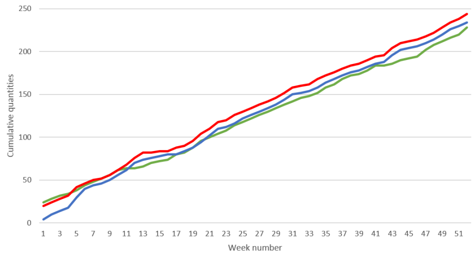
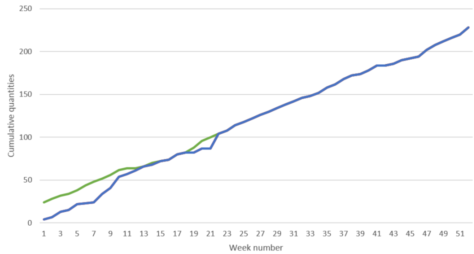
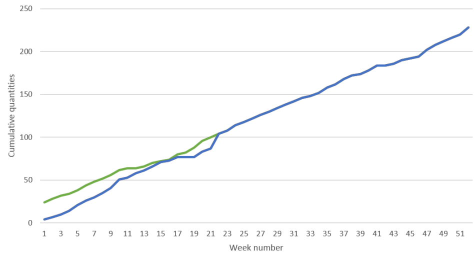
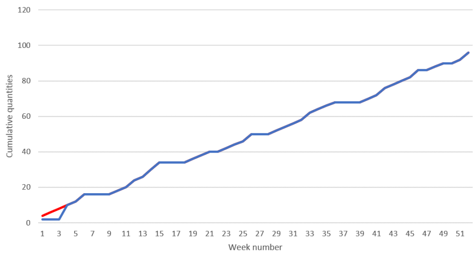
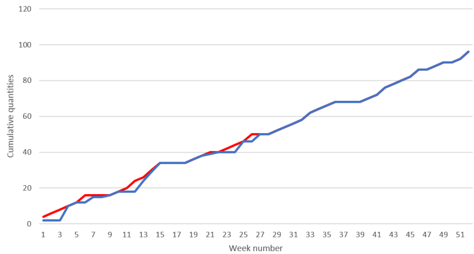
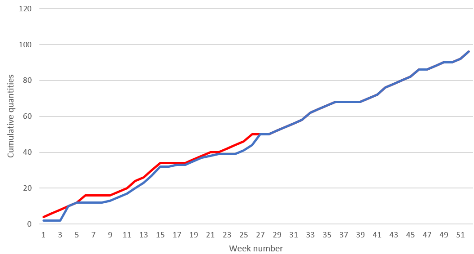
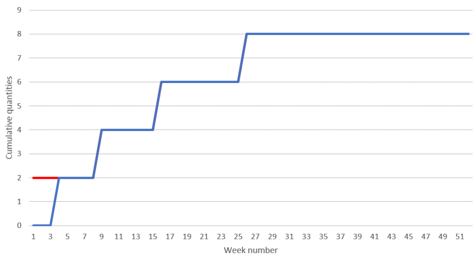
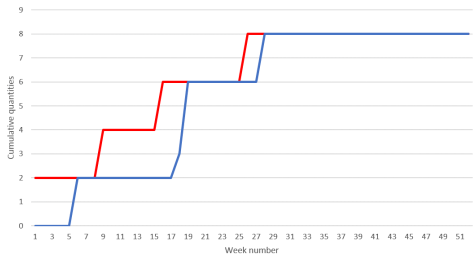
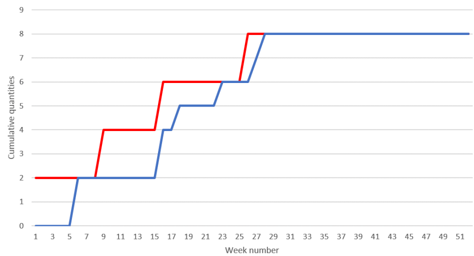
The MRP column shows the current supply plan derived from the ERP system. For Part Y it can be seen that demand exceeds supply, resulting in shortages for the next 27 weeks. This period is referred to as *recovery time*: the time needed to let supply 'catch up' with demand. The other parts show a minor shortage during the first week, but supply is equal to (unconstrained) demand during the rest of the planning horizon. This implies that if only the end-items are observed in the MRP plan, no problems are foreseen. However, we know that Part Y encounters considerable shortages during the planning horizon. This must have an impact on the rest of the network. If the MAP method is applied to generate a supply plan, the middle and right column emerge.

Let us first focus on the MAP method with the FP allocation policy. For Part Y, this results in a supply equal to the derived demand. This implies that the parent items of Part Y only request the number of parts that can actually be supplied by Part Y. The unconstrained demand shows the demand that should have been supplied to avoid shortages, implying the ideal situation. For Assy B, a bigger difference can be identified between MRP and MAP. While in the MRP plan almost no shortages can be seen, the MAP FP method does indicate shortages. The unconstrained demand exceeds the supply and demand for the upcoming 23 weeks. This also holds for the end-items, showing that demand (equal to unconstrained demand for end-items), exceeds the supply. The recovery time between both end-items differs, however, indicating different priorities. It can be seen that Service Y, with priority 6 out of 6, receives supply only in week 8, while Non-service B already receives supply in week 1. The right column shows the output using the RCRO allocation policy. The figures look similar to MAP method with FP policy in terms of shortages. However, the difference in allocation can properly be seen on an end-item level. Stock is divided more equally in the RCRO policy than in the FP policy, resulting in smaller differences in the recovery time of end-items. A complete overview of all items in the network of case Y can be found in Appendix J.

Item	Priority	MRP	MAP - FP	MAP - RCRO
Part Y	-			
Assy B	-			
Non-service B	2			
Service Y	6			

Cumulative unconstrained demand — Cumulative demand — Cumulative supply

Figure 6.2: MRP and MAP supply plan for four items of case Y

Item	Priority	MRP	MAP - FP	MAP - RCRO
Part α	-			
Assy β	-			
Item γ	2			
Item δ	20			

Cumulative unconstrained demand — Cumulative demand — Cumulative supply

Figure 6.3: MRP and MAP supply plan for four items of case Z

6.3.2 Case Z - one week

It is known that the derived demand for the end-items of case Z is the MPS, and is therefore already smoothened. Nonetheless, it is assumed that the derived demand is equal to the sales plan. The planning horizon for case Z is one year. The total network of case Z consists of 56 items, including 7 buy-items, 19 assemblies and 30 end-items. The end-item priorities have been defined together with a knowledge expert of case Z. Figure 6.3 shows the results for four parts of the network. The supply chain state is observed during one certain week. Part α is the main bottleneck item, Assy β is an assembly, item γ and item δ are end-items.

Case Z shows similar results as case Y, although less extreme. Part α is traced as the bottleneck item, having a recovery time in the MRP plan of 27 weeks. Assy β also shows shortages that are not (yet) covered in the MRP plan: demand exceeds supply for the whole horizon. Part α and β shows something interesting. The derived demand in the MRP plan is higher than the actual unconstrained demand. This suggests that WIP and OHS are not subtracted in the MRP BOM explosion, although this should be the case. End-items γ and δ only show shortages in the first two weeks, afterwards supply and demand are equal. When the MAP method is applied, the impact of the shortages of part α can be seen. End-items γ and δ show a considerable recovery time. Assy β also has an adjusted plan, showing shortages during 22 weeks.

The difference in impact of the allocation policies is also evident. Item γ has priority 2 in the FP policy, showing little shortages in the MAP FP plan. The RCRO allocation rule results in a longer recovery time of item γ compared to the FP plan. The opposite holds for item δ. The FP policy, with priority 20, results in less supply than the RCRO policy. Similar results are obtained for the other parts of the network.

Taking the results of the two cases into account, it can be stated that MRP generates an infeasible supply plan. In an MRP plan, shortages can be seen at the bottleneck item, but the actual impact on end-items cannot be retrieved. The MAP method shows the impact on the end-items, given the current supply chain state and an allocation rule.

6.4 A rolling horizon analysis

Section 6.3 analyzed the supply chain situation of one certain week, this section analyzes data over multiple weeks. First, it is shown that orders are shifted, which indicates nervousness. Second, the effect of the MAP method applied over multiple weeks is briefly considered, taking 8 items into account.

6.4.1 Case Z - nervousness

The MRP data of case Z, shown in Section 6.3, is available for 10 consecutive weeks. If this is further analyzed, it is found that orders are shifted on a regular basis. As explained in chapter 1, this is called *nervousness*. Although it is known at ASML that this occurs frequently, our data supports this phenomenon. Figure 6.4 visualizes a data sample of item γ. Three specific orders are tracked for 7 weeks. The figure shows the supply plan, hence the planned and scheduled receipts, for those 7 weeks. Week 1 shows the supply plan for week 1 through 7, week 2 for week 2 through 7, and so forth. The asterisk indicates the week that the order is actually finished. It can be seen that orders are shifted frequently. Orders 1 and 2 are interesting. In week 1, order 1 was planned for week 1, while it was realized in week 6. A similar observation is done for order 2. In week 1, order 2 was planned for week 4. Eventually it was realized in week 7. It suggests that items are deferred, which might happen because the plan is not feasible.

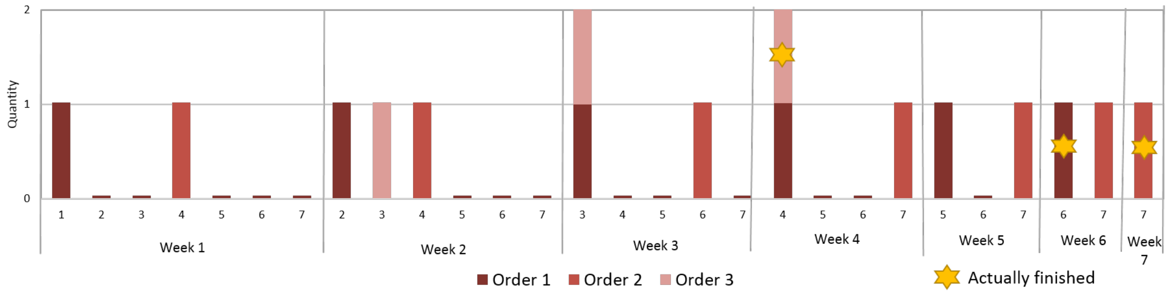
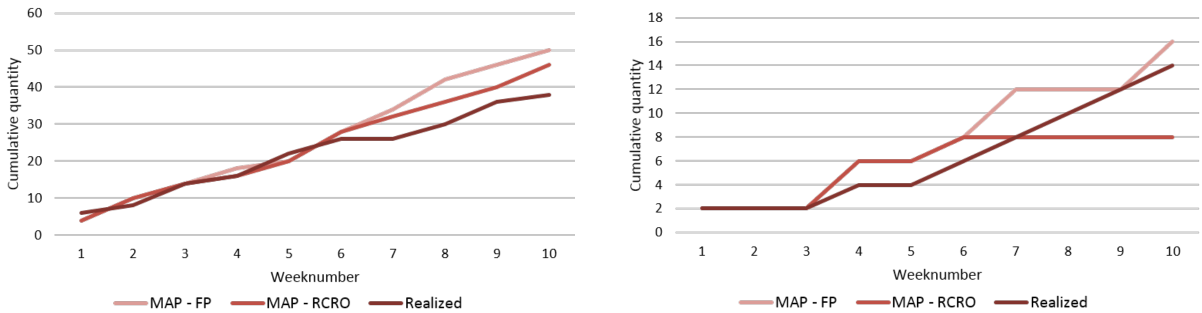


Figure 6.4: Supply plan of three orders of item γ during 7 weeks

6.4.2 Case Z - rolling horizon

From the previous analyses, it can be concluded that the current supply plan generated by MRP is not feasible. This section takes an extra step regarding the effect of the MAP method if it would be used during multiple weeks. This is done by using the MAP method for 10 consecutive weeks and compare the results with the realized output. The MAP method, with both allocation policies, is applied to data of week 1. The generated and constrained output, including WIP and planned OHS, is taken as the supply plan for week 2. The demand data is updated with the actual information of week 2. This implies that WIP and OHS will be allocated according to the MAP allocation rule, and later allocation decisions take this into account. This process is continued 10 times, thus for 10 weeks. It is assumed that scheduled receipts do not change, e.g. yield is not taken into account. Now, the output of the MAP method can be compared with the actual realized output. Figure 6.5 shows the results of the finished orders for the 10 weeks for two items. It is shown that the output of the MAP-FP method, MAP-RCRO method differ. This was expected, as different allocation policies were used. Regarding assy β, the output of the MAP method is higher than eventually realized, especially in week 6. This is assumably due to changes in the scheduled receipts. Regarding item γ, it can be seen that the output of MAP-FP exceeds MAP-RCRO. This can be explained by the fact that item γ has a high priority and MAP-RCRO allocates a predecessor to another end-item. Figures of six additional items can be found in Appendix J. Although several assumptions are considered, the MAP method shows that without re-planning the majority of the output is equal to the realizations. Furthermore, only a short horizon, 10 weeks, is considered. Differences with the actual realized output can partially be explained by changes in the environment, such as postponed demand and shifted scheduled receipts. This implies that the results of the MAP method can only increase if assumptions are better analyzed and taken into account. This supports that the MAP method generates useful insights. Nonetheless, an analysis over a considerable longer horizon would be interesting and is recommended.



(a) Assy β (b) Item γ

Figure 6.5: Cumulative finished orders generated by MAP-FP, MAP-RCRO and realized

6.5 Limitations

Several limitations are part of this case study and may influence the insights obtained. First, safety time is included in the lead time, which implies that it cannot be consumed if necessary. This influences the order generation of the MAP method. Second, the decision to delay WIP if child items are incomplete, impacts the timing and therefore performance of the scheduled receipts. In real-life, they might not be deferred. Third, yield is not taken into account. This influences the comparison with the realized orders in the rolling horizon analysis. In practice, (internal) orders can be deferred or canceled. Fourth, it cannot be guaranteed that the critical item in Case Z was actually the bottleneck item in all 10 weeks analyzed. Other parts that were not included could have impacted the realized output dates.

6.6 Conclusion

In this chapter, the MAP method is tested in a low volume environment, including two different allocation policies. The differences between an MRP plan and a MAP plan are shown with use of two cases. These cases are based on actual assemblies of ASML. MRP shows shortages at the bottleneck item, but for all other parts the deficits cannot be determined. Consequently, it is unclear what the actual impact of shortages would be on the supply dates of output items. The MAP method is able to calculate this impact. The used allocation policy determines which items *do* receive a bottleneck item, hence determine the quantitative impact of shortages per end-item. Given the cases discussed above, it can be confirmed that the supply plan shown in MRP is infeasible in terms of material availability. Although it is known that MRP logic is not able to deal with a constraint supply, this case clearly shows the implications in practice. This information can be useful, because the long-term impact of shortages can be determined. It is expected that implementing a material constrained plan would decrease nervousness in the system. This is because only material feasible derived demand is generated.

The cases also show a distinction between the FP and RCRO policy. The difference in impact on the service level of the end-items can be seen clearly. It is company-dependent which allocation policy is preferred and the guidelines of ASML are more comparable with the FP policy than the RCRO policy. However, every company deals with uncertainty and the results of Chapter 4 show the efficiency of the RCRO policy. Furthermore, the rolling horizon analysis shows that the output of the MAP method is relatively reliable, despite the assumptions and limited horizon.

Hence, these cases proof that the MAP method is applicable in a low volume environment. The allocation policy used has a substantial effect on the end-item impact resulting from shortages, hence should be considered carefully. It is shown that the MAP method generates a better understanding of the supply state, which can lead to better decision-making. This eventually leads to less nervousness in the chain. Table 6.1 shows a brief overview of the differences considered. It is concluded that the MAP method generates useful insights that cannot be obtained with MRP. Hence, MAP can be beneficial for decision-making in critical parts planning. To test this qualitatively, the tool, method and allocation rules are evaluated together with critical part planners in Chapter 7.

Table 6.1: The main differences between MAP and MRP resulting from the case study

MRP	**MAP**
Shows shortages mainly at bottle-neck item(s)	Shows shortages at end-items
Infeasible plan regarding material availability	Feasible plan regarding material availability
No shortages - no allocation policy	Allocation policy required
Flexible derived demand - nervousness	Less flexible derived demand - less nervousness

7 | Usability study

The quantitative analysis discussed in Chapter 6 identified the differences between the MRP and the MAP method tested on an ASML specific case. This chapter focuses on the qualitative insights. The MAP method is evaluated in collaboration with critical part planners of the SCP department of ASML. The results are gathered using a structured approach. This chapter concludes on the fifth research question: *"How can the MAP method be implemented at ASML?"*.

7.1 Task analysis

A task analysis is constructed in order to gain insights regarding the processes and tasks that are executed by an ASML critical part planner. This provides an improved understanding of the potential benefits of the tool. A task analysis is described as "any process that identifies and examines the tasks that must be performed by users when they interact with systems" (Kirwan and Ainsworth, 1992). The flow found in Figure 7.1 indicates the current process that is executed on a weekly basis and spans multiple days. It elaborates on the weekly monitoring activity for critical parts planning mentioned chapter 5. It is constructed during multiple interviews together with multiple planners.

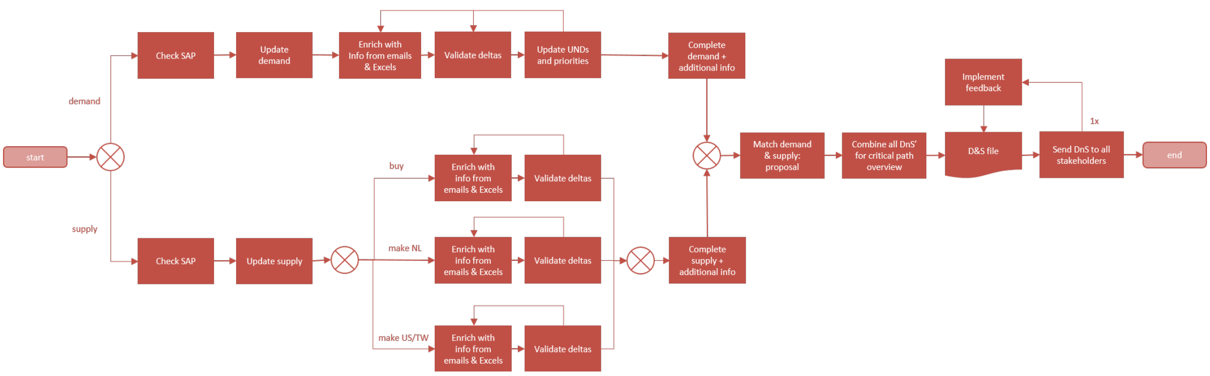


Figure 7.1: Weekly process flow of a critical part planner

The process aims to create a complete overview of all supply and demand for a specific critical module. Solely the supply and demand quantities from SAP are not sufficient to cover the complexity. Therefore additional (expert knowledge) information needs to be gathered. All this information is scattered.

Both demand and supply information is collected simultaneously, afterwards the *DnS* ('demand and supply') file is created. This DnS file includes information that is necessary for decision-making; e.g. expected arrival date of supply, the *ultimate need date* (UND), and end-item type. The UND is the absolute last date on which an item is required to not impact a delivery to the customer. This excludes all safety buffers. For both the demand and supply collection holds that SAP data is enriched with information acquired from emails and spreadsheets. *Deltas* are the quantitative differences compared to the DnS of last week. Hence, they indicate the quantitative supply or demand change. On the demand gathering side, the data enrichment, delta validation, and UND updates are an iterative process and can take up to a few days. A distinction is made between supply items that are a buy-item, an assembly in Veldhoven, or an assembly in one of the foreign factories (US or Taiwan) in the supply gathering. Although the steps are equal for all three, the way of working differs completely due to the collaboration with different parties, cultures and sources. Therefore they are shown separately. Afterwards, demand and supply information is combined and the critical part planner generally makes a proposal regarding the matching. All DnS' of all critical parts are checked and adjusted to align decisions regarding the critical path. The DnS file is sent to all stakeholders, that can be divided in active and passive receivers. The active stakeholders actually give feedback that is implemented, while the passive stakeholders are solely notified. The output of the process is input for both the plan round as the allocation process, described in Chapter 5.

7.2 Test plan

To MAP tool, the MAP method and allocation policy are validated in this chapter with planners. A scientific approach is used to conclude on its usability. Usability is defined as "the effectiveness, efficiency and satisfaction with which specified users achieve specified goals in particular environments" by the International Organization for Standardization (ISO). Therefore, a framework for usability testing is used to enable a structured approach, including goal, user and environment descriptions. The book of Barnum (2010) is taken as a point of reference to define the steps described in the this section.

7.2.1 Design

The methodology can be characterized as 'informal usability testing, because it does not take place in a special testing facility (Barnum, 2010). The tool can be further developed and adjusted to meet user requirements. Therefore the main focus is on the capabilities of the tool. Barnum (2010) indicate several elements that need to be decided upon before the actual test can take place. Those elements are elaborated below.

Goals The goal is to validate the usefulness and applicability of the MAP method at ASML, scoped on the SCP department. The test is focused on implementation at ASML and therefore to identify possible improvements. The research questions are defined as follows:

1. What are additional insights compared to the current process?
2. Where and how can the MAP method be useful in the CPP process?
3. Is the implemented allocation rule feasible?
4. What are desired improvements for the tool?

Methodology An in-person interview, 1-to-1 meeting in the field, which implies going to the user in his or her environment, is the basis for this study. The type of testing is defined as a formative study, as it involves evaluating a product during development. As mentioned before, focus is on the capabilities of the tool and not the user interface. However, the user friendliness is taken into account in the evaluation to identify potential improvements. Three meetings of one hour per person are held in a closed room. The first meeting discusses the method with use of case X, the next meeting case Y is elaborated upon and the last meeting case Z is discussed.

Users As the scope is focused on the critical parts of the SCP department, three critical part planners and one expert are the users of interest. The expert has numerous years of experience in the field of CPP at ASML. They are spoken to independently to avoid biased answers.

Scenarios As indicated above, three different cases are discussed each meeting. For the last two cases, several scenarios are used to guide the test. The scenarios are based on tasks that are related to the test goal and can be found in Appendix L.

Evaluation During the test, notes were taken. When all three sessions were completed, questionnaires were answered. These can be found in Appendix K. Both the notes and open questionnaire are qualitative feedback methods. To evaluate the usability of the tool, the closed questionnaire, and thus quantitative method, of Brooke et al. (1996) is applied. This survey is widely accepted. The so-called system usability scale can be found in Appendix K.

7.2.2 Requirements

Although we have not designed ChainMap ourselves, we do want to evaluate its design and usability. This is done by formulating requirements that can be reflected upon after performing the usability testing. Four types of design requirements can be distinguished, according to the definitions of Van Aken et al. (2012); functional requirements, user requirements, boundary conditions and design restrictions. The latter two are out of scope of this analysis, as these play the most important role during the development phase, which has passed. However, *functional requirements*; "performance demands on the object to be designed", and *user requirements*; "specific requirements form the viewpoint of the user" (Van Aken et al., 2012), are relevant. The requirements are formulated with an expert of the CPP process, see Table 7.1.

Table 7.1: Overview requirements for usability study

Category	Requirement
Functional	Correct and up-to-date SAP data is used, under the assumption that SAP data is correctly maintained
	Necessary data can be loaded in the tool easy and within 10 minutes
	Tool should show insights that cannot be obtained in the current process
	Allocation rule must reflect ASMLs way-of-working
User	Understandable and indicated by users as easy to use
	The tool can be used at a specified point in the current process

7.3 Results

This section discusses the insights gained from the user tests with critical part planners. The research questions formulated in the *test plan* of Section 7.2 are discussed separately. The questions that guided the construction of results are considered in Appendix K.

What are additional insights compared to the current process? The MAP method and supporting tool have two main advantages compared to the current process and tooling. The first advantage relates to the conclusions of Chapter 6. The ability of the MAP method to determine the impact of shortages on an end-item level is highly appreciated. The consequences of the current supply state, assuming a certain allocation, can be seen clearly. As concluded in Chapter 6, MRP shows shortages on the (bottleneck) item level. Estimating the impact is currently done manually, and mainly for a short horizon. The MAP method is beneficial, because it considers the total length of the planning horizon in its calculation. It confronts the user with the consequences of their decisions made. The second main advantage is the speed of the calculation. The calculation time of the method is negligible as it takes seconds, which is an enormous improvement compared to manual calculation. The fast calculation enables testing and comparing with different input parameters. This is specifically useful for scenario testing. Another additional insight is the visual overview of the network (e.g. a specific module) under consideration. However, in case the network is complex, the overview becomes less transparent.

Where and how can the MAP method be useful in the CPP process? The method can be used for multiple tasks considering the tasks of a critical part planner in Figure 7.1. First of all, at the start of the planning process the tool clearly shows the deltas in the plan. This is a starting point for performing analyses related to demand and supply. The second task in which the tool is useful is during the matching of supply and demand. This task is decomposed in Figure 7.2. The 'test scenario' step is currently done manually with spreadsheets and takes a considerable amount of time. If the tool is used in this step, it benefits from the two previously identified advantages: impact and speed. It improves the understanding of the consequences of a scenario, enhancing decision-making. In this way, the MAP tool and method can support the decision-making in this phase and can impact the output. It must be noted that the MAP tool can clearly improve decision making, although the output of the tool will not be directly implemented by the planners. This implies that planners do not the implementation of a complete material constrained plan. They rather prefer to implement a (partly) infeasible plan for two reasons. First, it shows the infeasibility of the plan to all demand and supply stakeholders to challenge them to resolve shortages. Second, postponed allocation increases flexibility of end-item planning. As mentioned earlier, constraints are not completely fixed at ASML, which also holds for material constraints. Allocation of bottleneck items implies that it is decided which parent-items do *not* receive a bottleneck item, and at which timing it will receive an item. Hence, the supply of other child-items to assemble that parent-item, is postponed. Flexible constraints can result in a situation where the supply of bottle neck items increases within lead time. However, other child-items need to be present to assembly an extra parent-item. Extra output outweighs obsolete inventory in this situation.

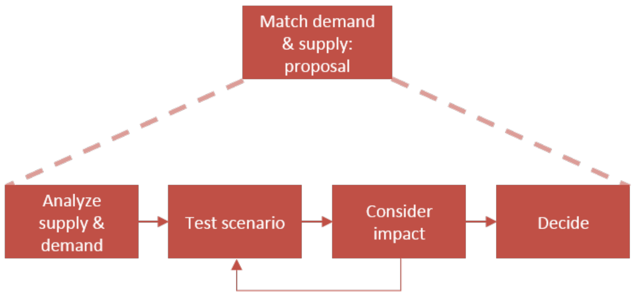


Figure 7.2: Task decomposition "Match demand and supply"

Is the implemented allocation rule feasible? The allocation policy implemented in the MAP tool is not completely supported. Planners value the ability of the MAP method to show shortages on an end-item level, but they would like to analyze different scenarios. They prefer to be able to manually adjust or override decisions constructed by the allocation policy. This is in accordance with ASMLs currently used 'flexibility allocation rule'. Specifically, this implies that priorities can change from week to week for the length planning horizon, per week. On the one hand, manually inserting priorities in the MAP tool takes time, which decreases the power of the method. On the other hand, when the allocation policy is not accepted by users or experts, it looses its complete value. Hence, it is of utmost importance to analyze the acceptance of the allocation policy for the MAP tool to be beneficial in the current planning process.

What are improvements for the tool? Aside from the allocation policy, several adjustments have been suggested. These relate to the *graphical user interface* (GUI) of the MAP tool. The most important improvement is the adjustment of the main interface. Currently, it only shows the planned order releases of the (selected) items. However, the test has shown that the experts prefer an overview of the end-items, including priorities, cumulative demand and supply, and shortages during the planning horizon. Another improvement is that other parameters can be changed from the item-specific screen, such as lead times and priorities.The last important improvement is the actual implementation of the tool. The manual transformation from SAP data to the required format is time consuming and inefficient. A tool should be developed to automate this process.

Overall, it is concluded that the insights derived from the MAP method are highly appreciated by the experts. Although the users wish immediate implementation of the tool, the identified adjustments are required to satisfy their current needs. This brings us to the requirements mentioned in Table 7.1. The requirements focus on the usability of the MAP tool in the current CPP process. All requirements can be satisfied by three adjustments. First, the GUI of the tool should be reviewed to align the interface and the needs of planners. Other summary overviews are desired, including an adequate visualization of the priorities. Second, the allocation policy should be adjusted to satisfy the requirements of the planners. At the moment, the FP and RCRO policies are not adjustable. The adaption is considered necessary to a certain level, to ensure that the acceptance of the current users is taken into account. Thirdly, an additional tool should be developed that translates ERP data easily to the format required by the MAP tool. Issues encountered are listed and can be taken into account.

7.4 Discussion

It can be stated that the MAP method is valuable as a decision-support tool for critical parts planning, based on the results of both the quantitative and qualitative analyses. MAP generates a material-feasible plan, in contrast to MRP. Nonetheless, ASML does not prefer to implement the output completely, independent of the allocation policy. Their main reasons include maintaining highest flexibility and to clearly exhibit shortages. However, high flexibility is accompanied by low stability.

The use of an allocation policy has shown to be an interesting consideration. The allocation rule has a considerable impact on the performance of the MAP method, mainly due to low volume of demand. This showed in both the case study in Chapter 6 and the usability study in Chapter 7. The (manual) flexible priority allocation desired by ASML is intuitively not optimal, because priorities are dynamic and decided upon by human planners. It is known that human decision-making differs from rational decision-making. Humans use more contextual information and might be biased (Tversky and Kahneman, 1974). Literature has focused on (rational) allocation policies in a stochastic environment, discussed in Chapter 3. A rolling horizon analysis in Chapter 6 discussed a comparison of the RCRO rule with realized orders. Despite the limited horizon and assumption, the MAP method generated output came close to the realized output. This analysis asks for a thorough comparison of the MAP output versus the realized output. A search in literature yielded no research on the comparison of the performance of humans versus rational policies in a high-complexity environment, to the authors knowledge. Hence, the question arises if human planners perform better than an algorithm, such as MAP, in a complex environment with stochastic demand.

It is suggested that a distinction between short-term and long-term planning should be made regarding allocation policies. However, this distinction holds a fine line. In a short-term allocation decision, the knowledge of experts is deemed to outperform an algorithm. Intangible costs and considerations can be taken into account. Additionally, the short-term plan has a lower uncertainty. However, on the long term, an automated allocation strategy is beneficial. Demand and supply are stochastic and uncertainty is higher. An algorithm guides decision-making. A (limited) option for manual override could be a solution, as it might increase the acceptance and trust of the MAP tool. As mentioned by Lee and See (2004), trust appears to be an important criterion in use of systems in situations with uncertainty and complexity. Further research to the performance of an automated allocation policy on the long-term is recommended. Not only in a low volume and high complexity environment, but also in other areas.

Even with an adjustable allocation rule, the MAP tool is considered to have added value for CPP. Manual adjusting would reduce the saved time compared to an ‘automated’ allocation policy. Nonetheless, the fast calculation of scenarios is very beneficial. Therefore, it is concluded that the tool and method can support decision-making in critical part planning. Both in the weekly monitoring as as input for the monthly plan round, the MAP tool gives important insight and support decision making.

Finally, the limitations of the case study should be noticed. A bias can arise due to the subjectivity of the users involved in the test. The impact of the bias is limited by increasing the number of users, cases and sessions. Another limitation is the assumption of complete correctness of the ERP data.

7.5 Conclusion

This chapter concludes on the applicability and implementation of the MAP method and tool in a critical parts planning which is part of SCP. It can be concluded that the MAP method adds value, but the allocation policy demands clear considerations. A differentiation in allocation decisions is recommended between the short and longer term horizon regarding allocation decisions. Manual allocation is considered to be better on the short term, and the MAP method delivers substantial benefits on the medium to long term. It would be interesting to compare the performance of human planners with an allocation policy in a complex environment with low volume demand, as is the case at CPP. This is emphasized as a recommendation for further research. All in all, the MAP method generates a better understanding of the supply state, which leads to better decision-making in planning supply and demand.

Part III

Conclusion and reflection

8 | Conclusions and recommendations

The conclusions from this research and practical recommendations for ASML are discussed.

8.1 Conclusions

This research analyzed the applicability of material availability planning in a low volume environment. This section concludes the research by providing an answer to the defined research questions. Furthermore, additional insights are discussed. Based on the problem statement, the following research question was formulated: *How to design MAP such that it is applicable in a low volume environment?*. The research questions are discussed one by one.

What are the characteristics of the MAP method? As this research focuses on the MAP method, this method is compared with the widely adopted MRP method. The main difference between the MAP and MRP method is related to the MPS. In the MRP method, the MPS is used as in input. This is often already smoothened or adjusted compared to the actual demand dates, typically this is done manually. This MPS does not have to be feasible in the MRP method. The MAP method uses the actual demand as an input and generates a material feasible MPS as an output. Hence, the MAP method deals with material availability if shortages occur. In order to do this, it is essential to have an allocation policy which allocates available supply.

Which adaptations need to be made to the MAP method? Literature does not provide an allocation policy that is suitable in the considered situation: a low volume environment with unknown demand at the moment supply is allocated. Consequently, an experimental analysis is performed. Seven allocation policies are defined based on literature and the ASML context. Two performance measurements are defined: the fill rate and the total inventory. It is concluded that both the RCRL and RCRO perform best across all experiments. The SL and CLRO policy generally performed considerably less, while the ROT, CLRL, and FP policy behave moderate. The FP policy shows most variability in realized fill rate of end-items, while the RCRL is most smooth. As foreseen, the performance of the policies is highly dependent on the amount of safety stocks. Two allocation policies are implemented in a provided MAP tool. Resulting form the numerical analysis, the RCRO policy was selected. Additionally, the FP policy was included, because it best reflects the allocation procedure of ASML.

How is the current planning process designed at ASML? The general planning process of ASML is extensive and covers multiple departments. This study scopes on the role of the supply chain planning (SCP) department. This department is responsible for the monthly creation of a supply plan, which is made in collaboration with all relevant stakeholders. This is done with a process called the plan round. The SCP input of the creation of the plan round can be divided in end-items and critical parts. The latter is particularly interesting, because these items have high shortage risk. Therefore, the focus of this research is on the applicability of the MAP method on critical parts planning (CPP). The planning process of CPP aims to create a complete overview of all supply and demand for a specific critical part.

What are the results of using the MAP method if applied to a case study at ASML? The provided MAP tool is used to analyze two cases based on assemblies of ASML. These cases can be related to critical parts. The case study confirmed that MRP generates an unfeasible supply plan. Shortages are only shown at the bottleneck item, while there is no impact on the supply of other items. The MAP method determines the impact of the shortages throughout the chain, based on the current supply chain state and used allocation policy. Hence, it shows the shortages in the output of end-items. The case study shows the differences between the impact of the FP and RCRO policy. The FP policy strictly allocates stock in a fixed sequence based on priority and the RCRL policy divides stock more equally. Furthermore, the output of the MAP method is analyzed in a rolling horizon. The output as calculated by MAP is determined for 10 weeks in a row based on the supply state of the first week. It is compared with the realized output for a number of items. A number of assumptions is considered, such as that scheduled receipts do not changes. It is shown that the MAP method performs considerable, despite the assumptions. It can be concluded that the MAP method is applicable in a low volume environment. The results of the quantitative case study are further analyzed by means of a usability study with potential users of the MAP tool. These are the critical part planners at the SCP department. The speed and insights on the impact of shortages on end-items is evaluated as highly valuable. Preferred changes to the GUI of the MAP tool are collected. Although the MAP method generates a feasible plan, ASML does not prefer to implement this completely, independent of the allocation policy used. First, it is preferred to show shortages explicitly to challenge all stakeholders. Second, it reduces flexibility in the current situation. Constraints are often flexible at ASML, which also holds for material constraints. Hence, postponing allocation until the last possible moment is preferred. For this reason, the biggest added value of MAP in the current situation is as a decision-support tool. An interesting insight is that ASML prefers a (manual) flexible allocation policy. This differs substantial from the implemented (rational) FP and RCRO allocation policies. Planners prefer to manually adjust priorities to test different allocation scenarios above the use of an allocation policy.

How to implement the MAP method at ASML? As mentioned above, the focus is on CPP. Manual allocation would decrease the speed of the tool, and hence decrease its added value. Nonetheless, it is concluded that the MAP method is highly useful. This is because the main insight that can be provided with the MAP method, the consequences of shortages, cannot be obtained with current tooling. Therefore, it is concluded that the MAP tool can be implemented immediately, if certain adjustments are made. It is suggested to differentiate between short-term and medium-term decision-making regarding allocation. It is assumed that manual allocation decisions are better on the short-term, but that an allocation policy should be considered regarding the medium-term. This is due to the increased uncertainty on a longer horizon. The case study show the initial results of using MAP at CPP, but the cases are representative for ASML in general. Therefore, other areas can be considered after experiences from CPP.

This research takes a step-wise approach in analyzing the applicability of the MAP method in a low volume environment. From a general comparison between the MRP method and MAP, to an experimental analysis of allocation policies, to a practical case study, to the actual applicability in usability test. Finally, the case study proves that the MAP method is applicable in a low volume environment. The allocation policy used has a considerable effect on the impact of end-items, due to the low value. Hence, it should be considered carefully. It is shown that the MAP method generates a better understanding of the supply state, which can lead to better decision-making. Overall, it is concluded that material availability planning in a low volume environment is both promising from a literature as a business perspective.

8.2 Recommendations

Several recommendations for ASML are formulated, and are related to an improved decision-making regarding planning.

First of all, it is highly recommended to implement the MAP method and embed it in the critical part planning process for the medium to long planning horizon. Even if the allocation policy implemented does not exactly reflect the desired allocation procedure, it still generates insights that currently cannot be retrieved: the impact, i.e. quantitative shortages on the end-item level. The (automated) allocation policy additionally reduces the time spend on allocation decisions for the medium to long planning horizon. Currently, this is done manually, which can take a considerable amount of time.

It is recommended to actually implement the MAP tool, on the condition that adjustments are made. First, the GUI of the tool should be adjusted to align with the needs of planners. Second, an additional tool should be developed that translates the ERP data easily. Third, for now the tool will only be accepted if the allocation policy is changed. A manual override option should be added to satisfy the current needs of planners.

Furthermore, it is recommended to analyze the performance of the MAP method with the performance of human planners. Several allocation policies can be taken into account. Although ASML emphasizes its desire for flexibility, this also results in decreased stability and thus nervousness. A balance is necessary for the best performance. Using a material availability method such as MAP completely will increase stability and would lead to a substantial reduction of the necessary time spend on planning. Remind that another alternative for constraint-based planning is linear programming, however out-of-scope in this research. Hence, it would be very interesting to compare MAP with human planners. If the MAP method performs satisfactory, enormous improvements can be made. However, an extensive data-driven analysis over a longer period of time is necessary. Sufficient data should be available. Moreover, the performance indicators that measure performance should be considered carefully.

Finally, data from the ERP system is used to assemble these cases. The correctness of this data strongly influences the performance of the method and tool. Therefore, it is recommended to continue to focus on data integrity.

9 | Reflection

This chapter reflects on the performed research. The first section describes how the research contributes to academics. Hereafter, the section discusses the limitations of this research and the last section provides suggestions for further research.

9.1 Contribution to literature

This research contributes to current literature in multiple ways. An interesting contribution is the experimental analysis of allocation policies in a low volume environment with unknown demand at the moment supply is allocated. To the authors knowledge, this has not been researched before. Furthermore, a large number of allocation policies is taken into account in a general setting including a demand forecast.

Additionally, the rounded CAS policy with run-out time or random leftovers has been introduced. It is demonstrated that this policy performs outperforms the other integer-feasible policies analyzed. This analysis was executed in an experimental and general setting, and therefore triggers further research.

Furthermore, this study shed a light on allocation policies used in business practice in a low volume environment, although only company is considered. It is shown that this is mainly guided by human decision-making, which is different than described in literature. In the evaluated case-setting, the allocation policy was only evaluated as useful if a manual override is added.

Finally, the gained insights are applicable to a variety of sectors apart from the high-tech sector. Similar situations, implying MRP planning in combination with shortages, can be found in other companies that face a low volume demand. They can benefit from the research as well.

9.2 Limitations

The current research is subject to several limitations. Roughly speaking they can be divided in limitations related to the experimental analysis and limitations related to the case study. Regarding the experiment, several assumptions have been made. These include deterministic lead time, no lost sales, and a certain forecast accuracy. However, in reality these are not so 'simple', which limits the research.

The fixed priority allocation rule implemented in the tool cannot be generalized unfortunately. This implies that if another network is reviewed, the performance should be assessed carefully. The rule should be adjusted to be applicable in any network.

Several practical assumptions have been made in the case study that can impact the results. Due to the long process times, not all assembly items are ready when the assembly has started.

If this is the case, a scheduled receipt is postponed just outside lead time. However, this impacts the number of parts in the system and therefore influences the output.

The cases constructed are carefully analyzed in collaboration with an expert from ASML. It is aimed to include the critical path. However, specifically regarding case Z, it cannot be excluded that a part that is not included in the network was the bottleneck in a certain week. Hence, it cannot be guaranteed that the actual critical path was included in the network during the 10 week analysis. This is not known, because this data was not available. This can impact the demand dates.

Finally, only one company and a limited number of people were included in the usability study. Although the cases are constructed carefully, they cannot just simply be generalized.

9.3 Future research

Several directions for future research follow from this study. First, linear programming is another alternative for constraint-bases planning. It would be interesting to compare the performance of both methods in a low volume environment.

Furthermore, the numerical analysis can be expanded. A number of assumptions have been made, such as a certain forecast error, the determination of safety stocks and deterministic lead times. Furthermore, only a two-echelon network is studied. Extending the study by the relaxation of assumptions is a good approach to see if the results hold. Additional research can also focus on the impact of extended parameters (e.g. lead times, performance indicators) in a low volume and integer formulated environment. In addition, analyzing the impact of lost sales is interesting as well.

Only a limited number of allocation rules has been tested. Although the policies have been derived from literature, more policies exist and more policies can probably be researched. It would be interesting to take other integer-suitable policies into account and compare them with the rounded CAS policy. An example is the linear allocation rule of Diks and De Kok (1998).

Finally, it is highly suggested to further research the performance of the MAP method compared to the performance of human planners. This is already mentioned in Chapter 8, but it is also relevant for research insights. In Chapter 6, the rolling horizon analysis performed touches this direction, but it should be expanded considerably. To start with, multiple companies in a low volume environment should be analyzed to determine if manual allocation is common. Then a research can be performed to compare the results of the MAP method and the human planners. However, sufficient data must be available and the performance measures should be defined precisely. Several allocation policies can be taken into account. This could lead to very interesting insights.

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Appendix

A Company background

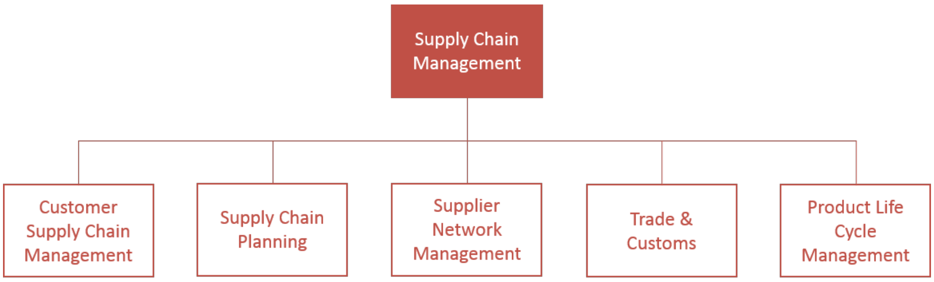


Figure A.1: Organizational chart Supply Chain Management (SCM)

B Research background

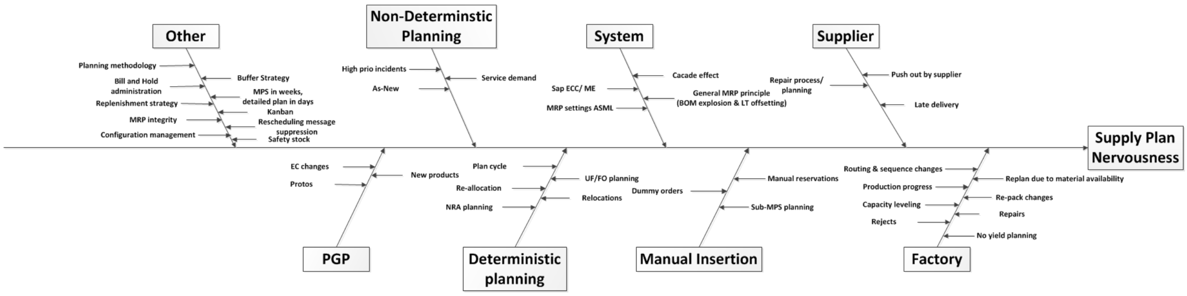


Figure B.1: Ishikawa with causes of supply plan nervousness (by ASML, 2018)

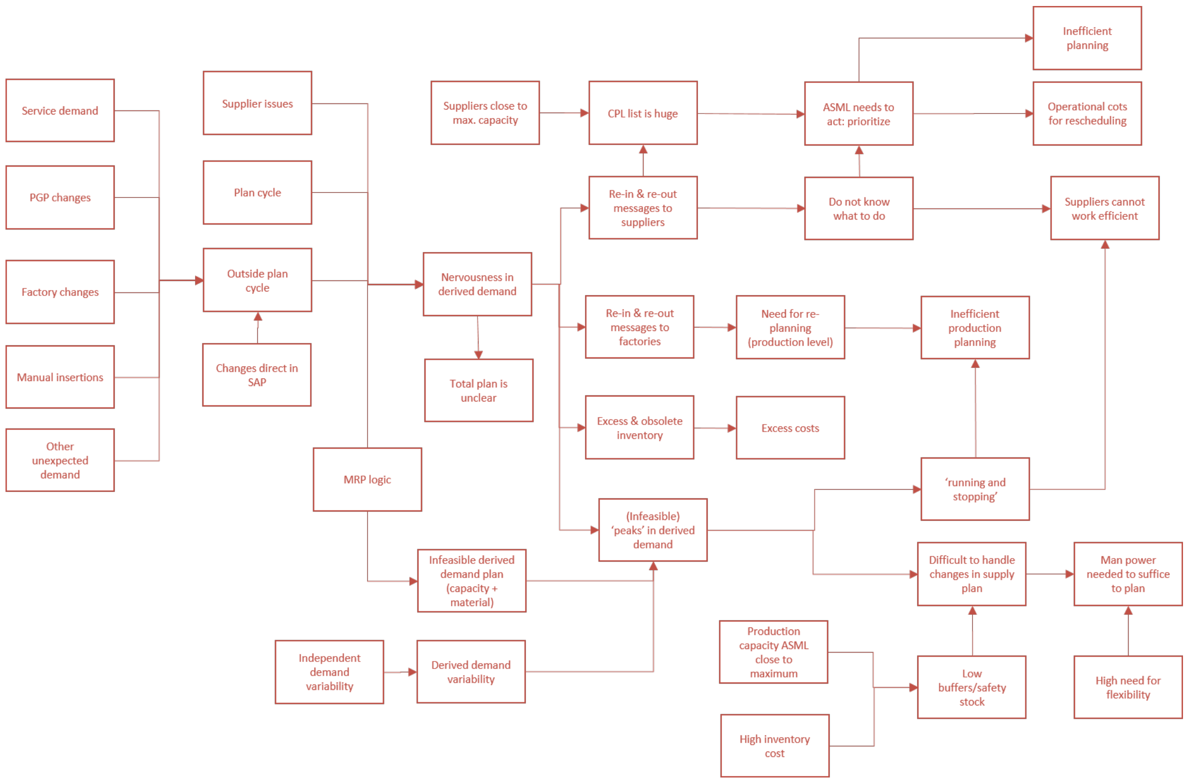


Figure B.2: Cause & effect diagram

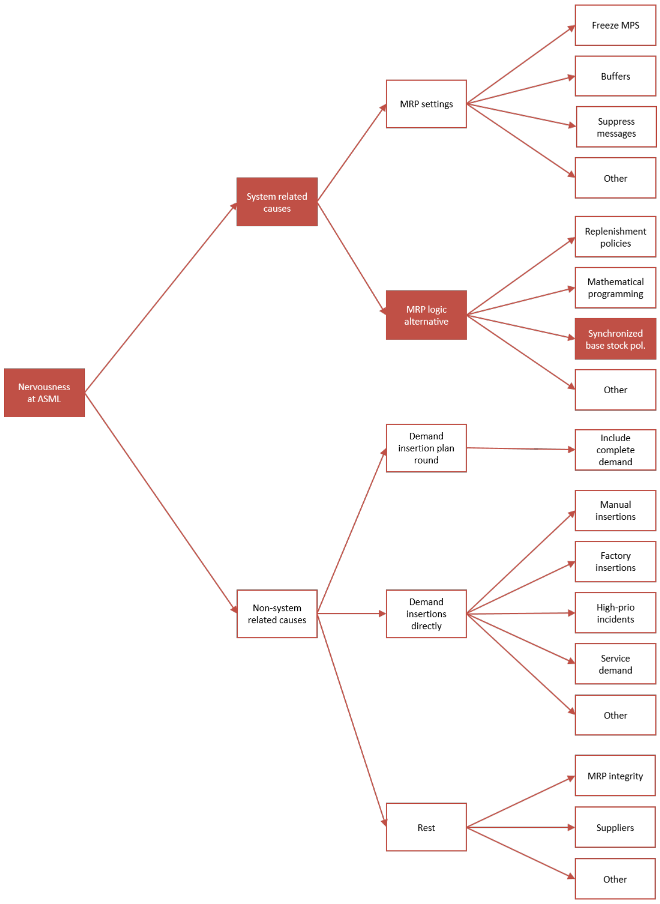


Figure B.3: Decision tree

C Planning process at ASML

This appendix presents an elaborated swim lane diagram of the planning process at ASML. Figure C.2 represents the swim lane where each node represents a decision (or action) function. Each decision function is afterwards explained using the IDEF0 method, see figure C.1. CSCM refers to the customer supply chain management department, SNM refers to the supplier network management department, CP refers to central planning department and SCP refers to the supply chain planning department.

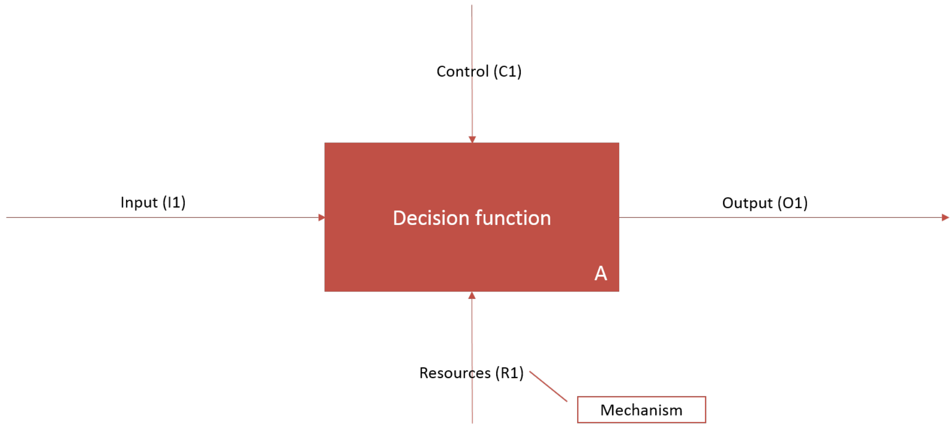


Figure C.1: Description of the IDEF0 modeling method

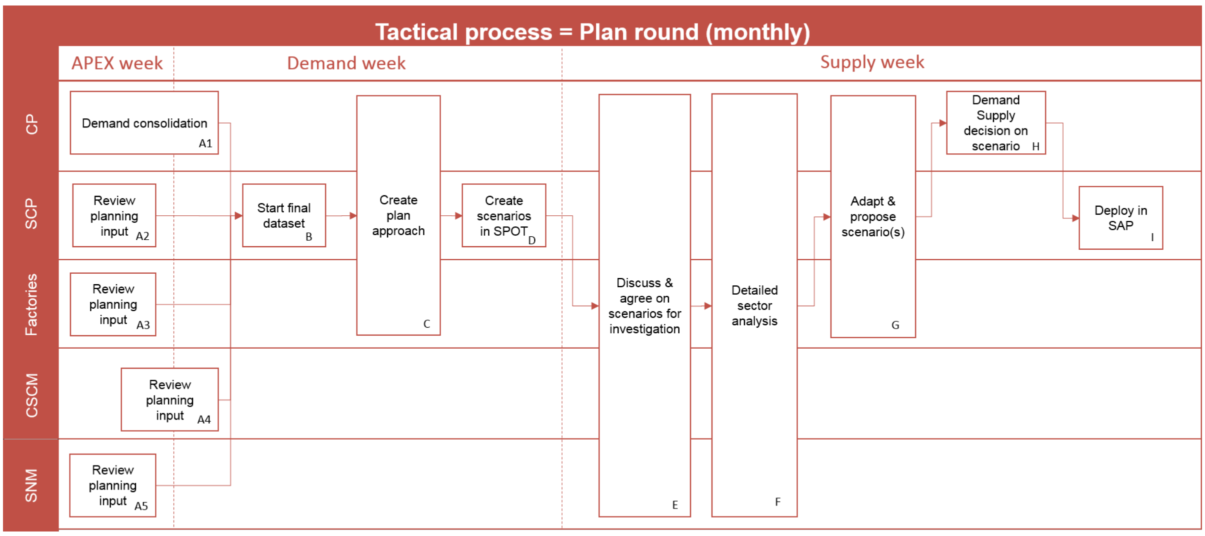


Figure C.2: A swim lane of the plan round process

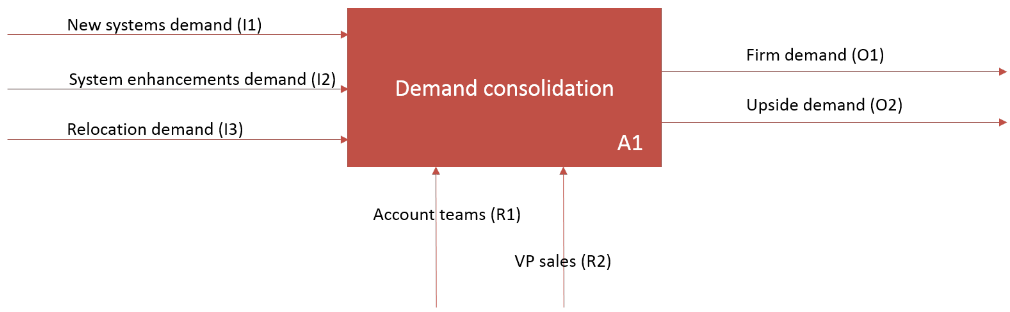


Figure C.3: Swim lane: A1

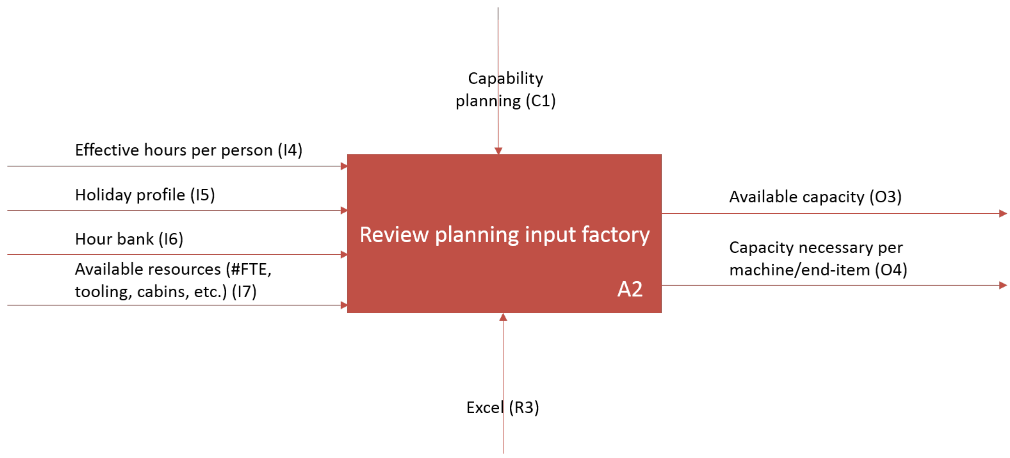


Figure C.4: Swim lane: A2

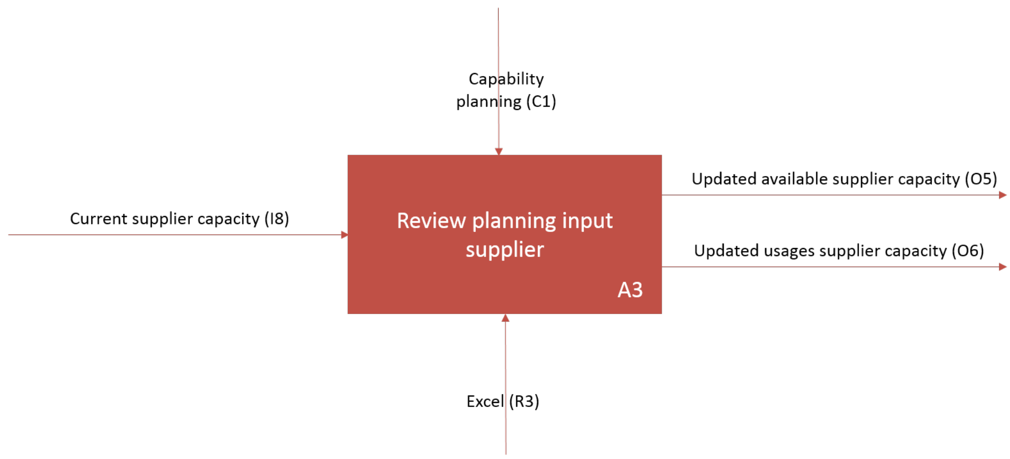


Figure C.5: Swim lane: A3

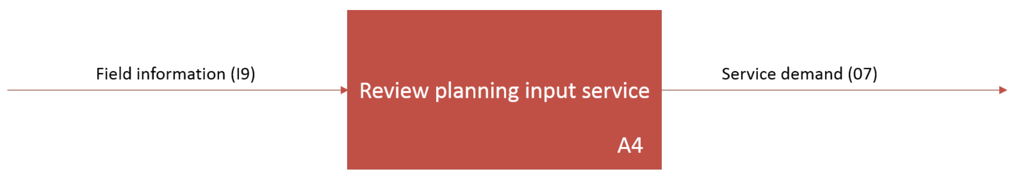


Figure C.6: Swim lane: A4

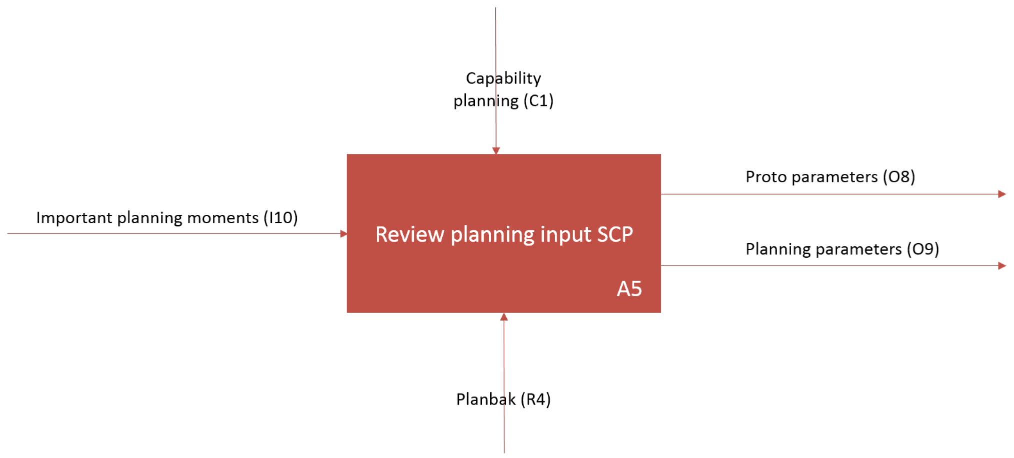


Figure C.7: Swim lane: A5

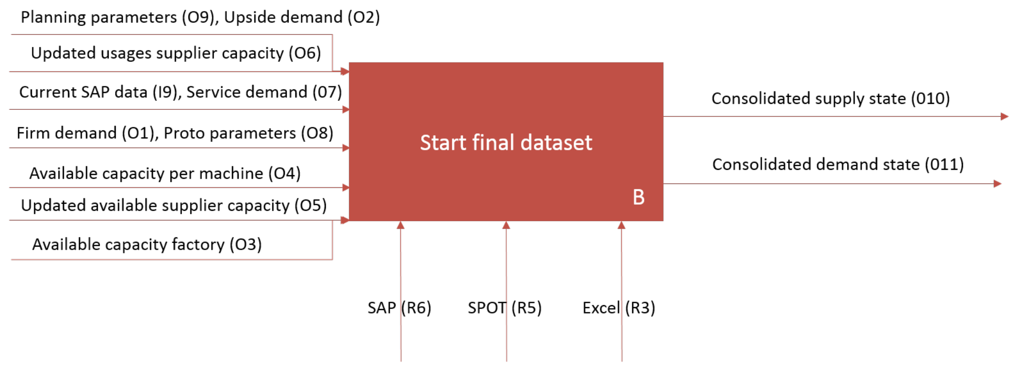


Figure C.8: Swim lane: B

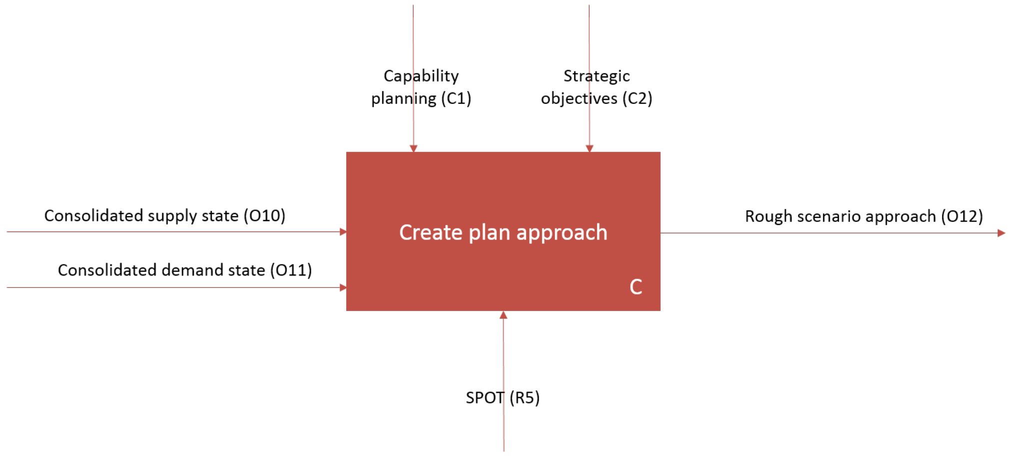


Figure C.9: Swim lane: C

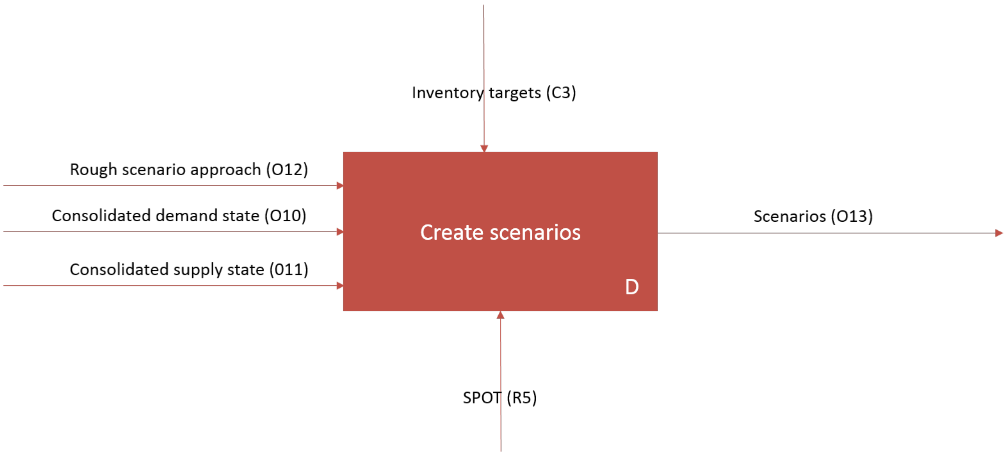


Figure C.10: Demand week: D

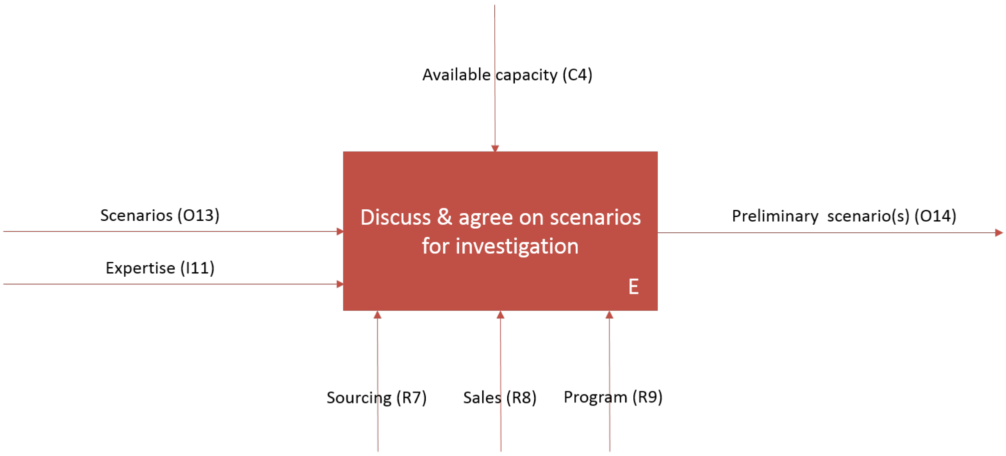


Figure C.11: Swim lane: E

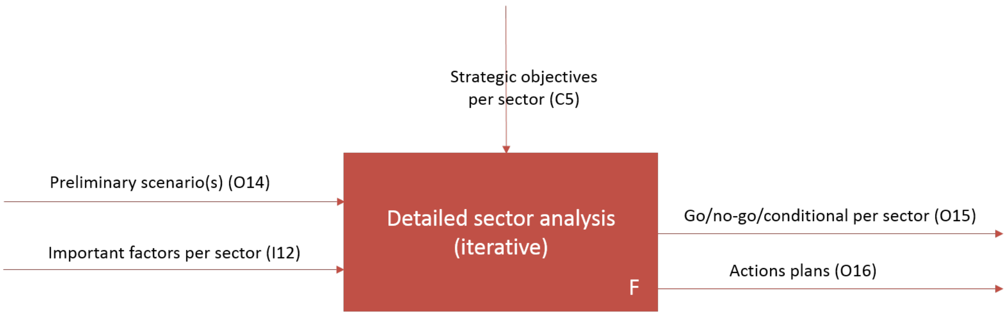


Figure C.12: Swim lane: F

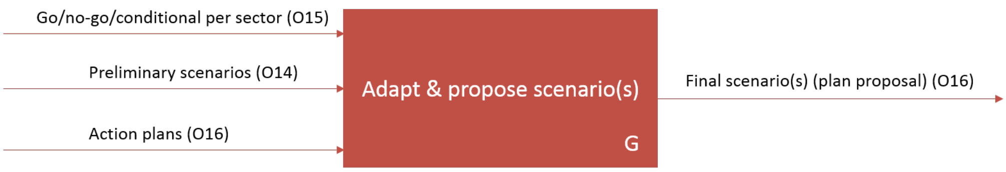


Figure C.13: Swim lane: G

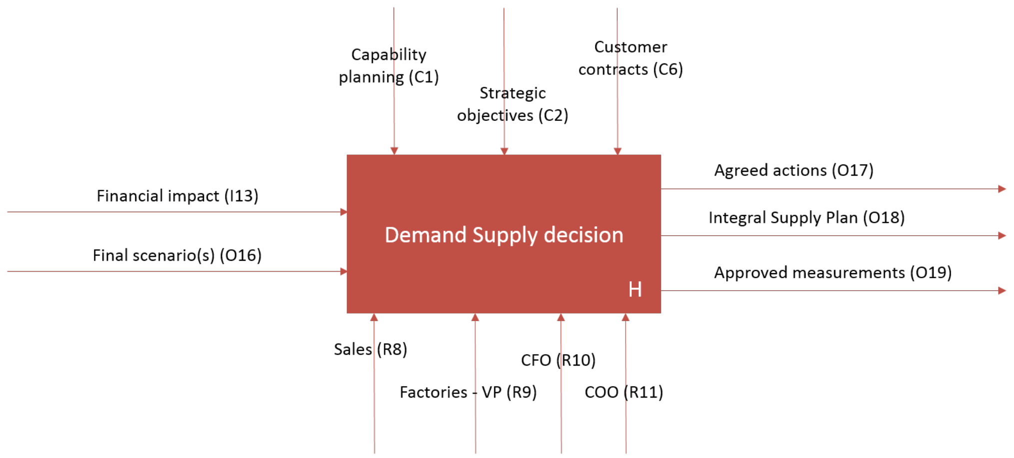


Figure C.14: Swim lane: H

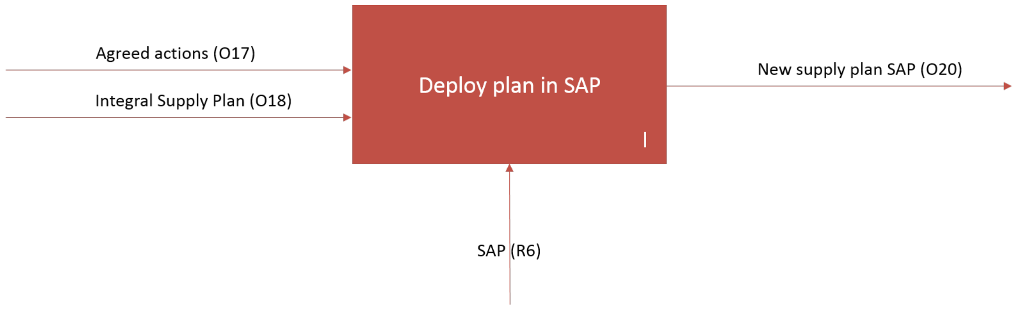


Figure C.15: Swim lane: I

D Variables

Table D.1: Definition of variables

Variables	Description
General	
$\mathcal{M}$	set of all items
$\mathcal{N}$	set of all end items, i.e., items sold to customers of the value network, $\mathcal{N} \in \mathcal{M}$
C_i	set of immediate successors or parent set of item i, $i \in \mathcal{M}$
P_i	set of immediate predecessors or child set of item i, $i \in \mathcal{M}$
F_i	set of end items delivered by item i, $i \in \mathcal{M}$
Parameters associated with item $i \in \mathcal{M}$	
a_{ij}	number of items i required to produce one item of item j
L_i	lead time of an order of item i
L^*_{ij}	sum of lead times a between item i and item j (both inclusive)
ST_i	safety lead time associated with item i
ST^*_i	sum of safety lead times between item i and j (both inclusive)
z_i	inventory level of item i
$\beta^{(t)}_j$	Target fill rate for item i
Variables for all $i \in \mathcal{M}$ and $t \geq 1$	
$D_i(t)$	forecast of demand for end item i at the start of period t
$I_i(t)$	net stock of item i at the start of period t
$IP_i(t)$	inventory position of item i at the start of period t
$EIP_i(t)$	echelon inventory position of item i at the start of period t
$SR_i(t)$	scheduled receipt of item i planned to arrive at the start of period t
$PO_i(t)$	work order of item i released at the start of period t
$EIP^*_i(t)$	echelon inventory position of item i immediately after allocation of available stock
$S_i(t)$	target base-stock level for item i
CSS_i	cumulative safety stock in the echelon of i
SS_i	safety stock of item i
$q_i(t)$	unconstrained order from item i at time t
$Q^{(i)}_j, Q_j$	order released for item j if item i would be the only predecessor of item j
Q^k_j	order released for item j from class k, if item i would be the only predecessor of item j
$rt_i(t)$	The run-out time of item i calculated at time t
$SO_i(t)$	Stockouts of item i at time t
$G_i(t)$	Relative fill rate gap of item i at time t
$LO_i(t)$	The leftover inventory or unallocated virtual available inventory of item i
$\beta_i(t)$	The realized fill rate of item i at time t

E Detailed description MAP algorithm

Derived from De Kok et al. (2005). The lead times, L_i, exclude the safety lead times, ST_i. It is assumed that the (safety) lead times are exogenous parameters and that $a_{ij} \in \{0, 1\}$). Every review period a work order is released for all items of the value network. No lot-sizing restrictions are assumed. The net stock of all non-end items is non-negative immediately after all orders have been released, so only feasible work orders for materials are released. It is assumed that the scheduled receipts arriving at the start of period t are consolidated in $I_i(t)$. Furthermore, it is assumed that demand forecasts not are satisfied from (planned) end-item stocks are backlogged.

$$I_i(t) \geq 0, \qquad i \in \mathcal{M}\backslash\mathcal{N}, \quad t \geq 1 \tag{1}$$

$$IP_i(t) = I_i(t) + \sum_{s=1}^{L_i-1} SR(t+s), \qquad i \in \mathcal{M}, \qquad t \geq 1 \tag{2}$$

$$EIP_i(t) = IP_i(t) + \sum_{j \in C_i} EIP_j(t), \quad i \in \mathcal{M}, \qquad t \geq 1 \tag{3}$$

The initial state of the system can be described as follows:

$$SR_i(t+s), \quad t = 1, ...L_i - 1, \quad i \in \mathcal{M} \tag{4}$$

$$D_i(t), \qquad t = 1, ...T \tag{5}$$

Both immediate work-order-release decisions and planned work-order-release decisions are generated. T is the planning horizon and assumed to be long enough to accommodate all immediate planning decisions:

$$T \geq \max_{i,j}(L^*_{ij} + ST^*_i) + 1, \quad i, j \in \mathcal{M} \tag{6}$$

It is assumed that (planned) events occur in the following order:

1. Facilities receive scheduled or planned items immediately at the start of a period;
2. They release work orders for each item immediately after this;
3. They fulfill customer-demand forecasts and internal work orders just before the end of the period.

Furthermore, it is assumed that scheduled and planned receipts arrive according to their planned lead times and that demand realizations equal demand forecasts. The state-updating procedure (until end of the planning horizon) is as follows:

$$SR_i(t + L_i) = PO_i(t), \qquad i \in \mathcal{M}, \qquad t \geq 1 \tag{7}$$

$$I_i(t+1) = I_i(t) - D_i(t) + SR_i(t), \qquad i \in \mathcal{N}, \qquad t \geq 1 \tag{8}$$

$$I_i(t+1) = I_i(t) - \sum_{j \in C_i} a_{ij} PO_j(t) + SR_i(t), \quad i \in \mathcal{M}\backslash\mathcal{N}, \quad t \geq 1 \tag{9}$$

To guarantee material feasible orders computations start with the most upstream items of the value network. Subsequent decisions are determined recursively, based on a combination of base-stock policies and linear allocation rules. The target base stock level S_i is equal tot the sum of the demand of all end-items k that are related to item i. Afterwards the cumulative safety safety stock in the echelon of i is defined.

$$S_i(t) = \sum_{k \in F_i} \left\{ \sum_{s=1}^{L^*_{i,k}+ST^*_{i,k}+1} D_k(t+s) \right\}, \qquad i \in \mathcal{M}, \quad t \geq 1 \tag{10}$$

$$CSS_i(t) = \sum_{k \in F_i} \left\{ \sum_{s=1}^{L^*_{i,k}+ST^*_{i,k}+1} D_k(t+s) \right\} - \sum_{k \in F_i} \left\{ \sum_{s=1}^{L^*_{i,k}+1} D_k(t+s) \right\}, \quad i \in \mathcal{M}, \quad t \geq 1 \tag{11}$$

If sufficient stock of item $i \in P_j$ is available to satisfy the order for an item j, it is satisfied. If a shortage occurs, because the total required quantity of item i exceeds its available stock I_i, consistent appropriate share (CAS) allocation policies Van der Heijden et al. (1997) are applied to allocate all available stock.

$$q_j(t) = \left(S_j(t) - EIP_j(t)\right)^+, \quad i \in \mathcal{M}, \quad t \geq 1 \tag{12}$$

The goal is to determine the quantity $Q_j^{(i)}$, which is the order released for item j if item i would be the only predecessor of item j. Two situations can be identified:

1. $\sum_{m \in C_i} q_m(t) \leq I_i(t)$, all orders for item i can be satisfied: $Q_j^{(i)}(t) = q_j(t)$.
2. $\sum_{m \in C_i} q_m(t) > I_i(t)$, where available stock I_i must be allocated.

For the second case, the following formulations are used to determine $Q_j^{(i)}(t)$:

$$EIP_j^+(t) = \begin{cases} S_j(t) - \dfrac{CSS_j(t)}{\sum_{m \in C_i} CSS_m(t)} \left(\displaystyle\sum_{m \in C_i} q_m(t) - I_i(t) \right), & i \in \mathcal{M}, \quad t \geq 1, \quad CSS_i(t) > 0 \\ S_j(t) - \dfrac{1}{\sum_{j \in C_i} a_{ij}} \left(\displaystyle\sum_{m \in C_i} q_m(t) - I_i(t) \right), & i \in \mathcal{M}, \quad t \geq 1, \quad CSS_i(t) = 0 \end{cases} \tag{13}$$

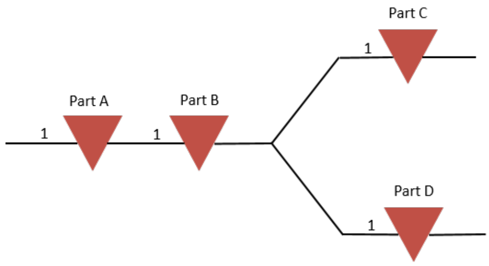
$$Q_j^{(i)}(t) = \frac{\max(0, EIP_j^+(t) - EIP_j(t))}{\sum_{m \in C_i} \max(0, EIP_m^+(t) - EIP_m(t))} I_i(t), \quad i \in \mathcal{M}, \quad t \geq 1 \tag{14}$$

Finally, the order released for item j is determined as following.

$$PO_j(t) = \max_{n \in P_j} Q_j^{(n)}(t), \quad i \in \mathcal{M}, \quad t \geq 1 \tag{15}$$

F Example rounded CAS policy

This section discusses the infeasibility of the CAS policy. It is shown how the released orders are calculated with the CAS method and why they need to be rounded down in case of shortages.



(a) Network including lead times

	ST	OHS	SR	Demand				
Time	-	0	1	1	2	3	4	5
item A	0	0	1	-	-	-	-	-
item B	0	0	3	-	-	-	-	-
item C	1	0	1	2	1	1	1	2
item D	2	0	1	2	1	1	1	2

(b) Current state and input parameters

Figure F.1: Network and supply state of case X

Case X is again used, with a slightly adjusted supply chain state. The network input parameters are shown in Figure F.1. Additional safety times are considered for item C and D. These are equal to 1 for item C and equal to 2 for item D. We discuss the situation at time 1 for part B, because the stock of part B needs to be allocated to item C and/or item D. Hence, $t = 1$ and this is dropped in further notation. The following information can be calculated given the information in Figure F.1. Variables are defined in Appendix D. First, we calculate the echelon inventory positions of item C and D.

$$EIP_C = IP_C + \sum_{j \in C_C} EIP_j = I_C + \sum_{s=1}^{L_C - 1} SR(1+s) = 0 + 1 = 1 \tag{16}$$

$$EIP_D = IP_D + \sum_{j \in C_D} EIP_j = I_D + \sum_{s=1}^{L_D - 1} SR(1+s) = 0 + 1 = 1 \tag{17}$$

Furthermore, the target base stock levels and cumulative safety stock of item C and D can be determined.

$$S_C = \sum_{s=1}^{L_C + ST_C + 1} D_C(s) = \sum_{s=1}^{1+1+1} D_C(s) = 2 + 1 + 1 = 4 \tag{18}$$

$$S_D = \sum_{s=1}^{L_D + ST_D + 1} D_D(s) = \sum_{s=1}^{1+2+1} D_D(s) = 2 + 1 + 1 + 1 = 5 \tag{19}$$

$$CSS_C = S_C - \sum_{s=1}^{L_C + 1} D_C(s) = S_C - \sum_{s=1}^{1+1} D_C(s) = 4 - (2 + 1) = 1 \tag{20}$$

$$CSS_D = S_D - \sum_{s=1}^{L_D + 1} D_D(s) = S_D - \sum_{s=1}^{1+1} D_D(s) = 5 - (2 + 1) = 2 \tag{21}$$

Consequently, we can determine the unconstrained orders of item C and D.

$$q_C = (S_C - EIP_C)^+ = 4 - 1 = 3 \tag{22}$$

$$q_D = (S_D - EIP_D)^+ = 5 - 1 = 4 \tag{23}$$

The available net stock of item B at time 1 equals $I_B = 3$. Hence, the sum of unconstrained orders equal $\sum_{m \in C_B} q_m = q_C + q_D = 7 > I_B = 4$. Now, the CAS method is applied by allocating the shortages of item B to item C and D. If a situation without safety stock is considered, the second part of Equation 13 is applied.

$$EIP_C^+ = S_C - \frac{CSS_C}{\sum_{m \in C_B} CSS_m} \left(\sum_{m \in C_i} q_m - I_B \right) = 4 - \frac{1}{1+2}(7-3) = 2^2/_3 \tag{24}$$

$$EIP_D^+ = S_D - \frac{CSS_D}{\sum_{m \in C_B} CSS_m} \left(\sum_{m \in C_i} q_m - I_B \right) = 5 - \frac{2}{1+2}(7-3) = 2^1/_3 \tag{25}$$

It can be seen that more shortages are allocated to item D than to item C. This is because the safety stock of item D is larger than item C. Finally, we compute the order releases of item C and D. No imbalance (so $EIP_j^+ \not< EIP_j$) occurs in this example.

$$Q_C^{(B)} = \frac{(EIP_C^+ - EIP_C)^+}{\sum_{m \in C_B} (EIP_m^+ - EIP_m)^+} I_B = \frac{2^2/_3 - 1}{(2^2/_3 - 1) + (2^1/_3 - 1)} * 3 = 1^2/_3 \tag{26}$$

$$Q_D^{(B)} = \frac{(EIP_D^+ - EIP_D)^+}{\sum_{m \in D_B} (EIP_m^+ - EIP_m)^+} I_B = \frac{2^1/_3 - 1}{(2^2/_3 - 1) + (2^1/_3 - 1)} * 3 = 1^1/_3 \tag{27}$$

Remind that item C and D are homogeneous in terms of the network and the current supply state, except for the safety time. More shortages are allocated to item D, because its safety stock is larger than the safety stock of item C. Hence, part C receives a larger part of the available stock of B. However, both outcomes are infeasible and need to be rounded down.

$$\left\lfloor Q_C^{(B)} \right\rfloor = 1 \tag{28}$$

$$\left\lfloor Q_D^{(B)} \right\rfloor = 1 \tag{29}$$

$$LO_B = I_i - \sum_{m \in C_B} (Q_m^{(B)}) = 3 - 1 - 1 = 1 \tag{30}$$

Finally, the 'leftover' stock of item B is allocated according to the run-out rule or randomly. Only parent-items that have (unconstrained) demand left are taken into account.

G Calculating safety stocks in a simulation

This technique is extracted from Kohler-Gudum and De Kok (2002) and determines the safety stock while sustaining the target fill rate. The procedure is written down for one end-item i. We define t as the period number $(t = 1, .., L_r), L_r$, with the run length. Ψ_0 is an arbitrary choice of initial safety stock. X_t is the net stock at end of period t, while I_t is the net stock at beginning of period t. β is the target fill rate.

First we determine the minimum and maximum value of the net stock during the periods of the simulation. x_0 represents the minimum recorded net stock value and x_K the maximum recorded net stock value. Secondly, all X_t are collected and now we can determine the empirical probability distribution of $X_t(\Psi_0)$ for $k = 0, ..., K$.

$$p_k = P\{X_t(\Psi_0) \leq x_k\} \tag{31}$$

The fill rate can be determined as follows:

$$P_2 = \beta = 1 - \frac{\overline{B}}{\overline{D}} \quad \Rightarrow \quad 1 - \beta = 1 - \frac{\overline{B}}{\overline{D}} \tag{32}$$

Now using that $I_t(\Psi_0) \geq X_t(\Psi_0)$, we determine the following, taking x_0 as the minimum recorded value of $X_t(\Psi_0)$ and x_K the maximum recorded value of $I_t(\Psi_0)$ for $k = 0, ..., K$.

$$r_k = P\{I_t(\Psi_0) \leq x_k\} \tag{33}$$

We need to find the amount of average backorders $\overline{B}$ that satisfies the target fill rate. If x_k was the adjustment quantity, we calculate the average backorders as:

$$\overline{B}(x_k) = E_1 - E_2 = \sum_{i=0}^{k-1}(x_{i+1} - x_i)(p_i - r_i) \geq 0 \tag{34}$$

with

$$E_1 = E\left[(X_t(\Psi_0) - x_k)^-\right] = \sum_{i=o}^{k-1}(x_{i+1} - x_i)p_i \geq 0$$

$$E_2 = E\left[(I_t(\Psi_0) - x_k)^-\right] = \sum_{i=o}^{k-1}(x_{i+1} - x_i)r_i \geq 0$$

and $E_1 \geq E_2$

We define $x_{1-\beta}$ by $(1-\beta)\overline{D} = \overline{B}(x_{1-\beta})$, with $\overline{D}$ as the average demand. Hence, we would like to find τ satisfying $\overline{B}(x_{\tau-1}) \leq (1-\beta)\overline{D} \leq \overline{B}(x_\tau)$ with the corresponding $x_{\tau-1}$ and x_τ values, leading to $x_{\tau-1} \leq x_{1-\beta} \leq x_\tau$. Now we can find $x_{1-\beta}$ by linear interpolation (it is rounded to satisfy the integer constraint and target fill rate) and since X_t and I_t are translation invariant:

$$x_{1-\beta} = \frac{\left((1-\beta)\overline{D} - \overline{B}(x_{\tau-1})\right)x_\tau + \left(\overline{B}(x_\tau) - (1-\beta)\overline{D}\right)x_{\tau-1}}{\overline{B}(x_\tau) - \overline{B}(x_{\tau-1})} \tag{35}$$

$$\Psi^* = \Psi_0 - x_{1-\beta} \tag{36}$$

H Description of implemented allocation policies

Two integer feasible allocation policies are implemented in the MAP tool, the rounded consistent appropriate share policy with run-out time leftovers (RCRO) allocation policy and the fixed priority (FP) allocation policy.

H.1 The RCRO policy

This policy applies the CAS rule, but it is rounded to assure an integer result. Appendix F provides an example that demonstrates the way-of-working clearly and how leftovers are determined. The CAS policy allocates shortages according to the cumulative safety stocks. The cumulative safety stock includes all safety stocks on the path between an item and all the end-items it supplies. This implies that the parent-item with the highest relative safety stock, gets most shortages, thus a least percentage of the available stock. If no safety stock is taken into account, it is allocated based on the number of end-item each parent item supplies (including multiplicities). The leftover stock is allocated based on the size of the unconstrained orders of the end-items supplied by the item under consideration. This is roughly the sum of forecasted demand during lead times minus the stock forthcoming. This is ordered in decreasing size and consequently satisfied completely. Hence, if any leftover stock is left after satisfying the first end-item, the second is considered and so on. The unconstrained orders per end-item are finally translated to orders placed by each parent-item.

H.2 The FP policy

In the FP policy, end-items are manually assigned a priority. First, for the item under consideration, it is determined which end-items it supplies. These are prioritized first. The stock already forthcoming in the chain is allocated to end-items based on this priority. The unconstrained orders are consequently determined, which is done per end-item. Again, these are ordered in decreasing priority. The unconstrained order for the highest priority is completely fulfilled if sufficient stock is available. If any stock is leftover, the second highest priority is considered and its unconstrained order is fulfilled. This continues until no stock is left. The unconstrained orders per end-item are finally translated to orders placed by each parent-item.

I Networks case study

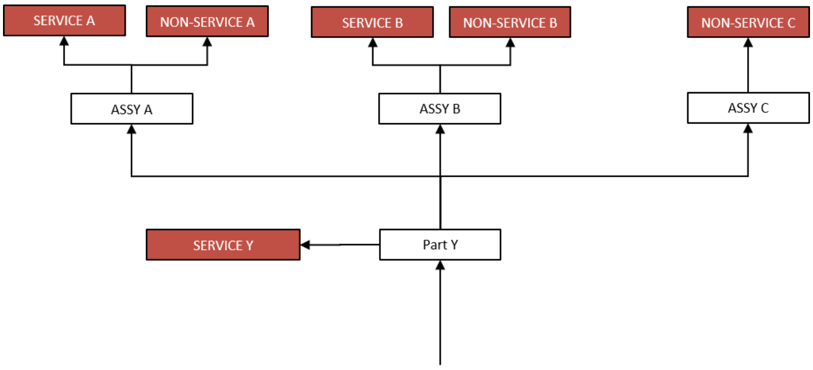


Figure I.1: Network of case Y

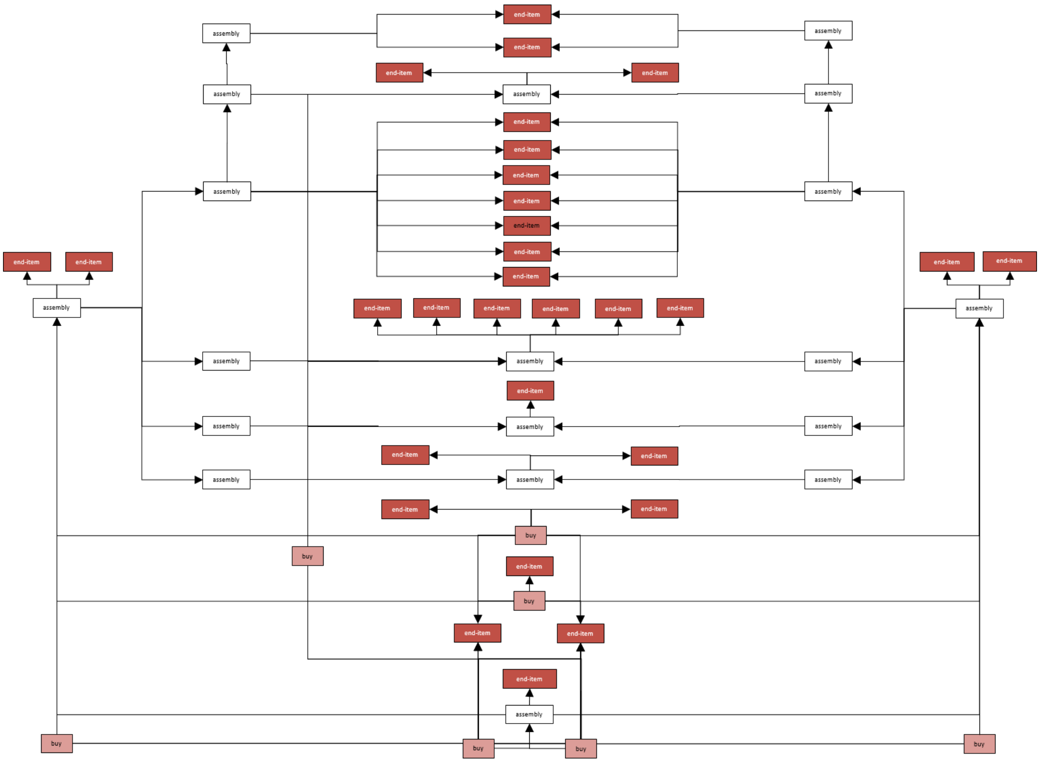


Figure I.2: Network of case Z

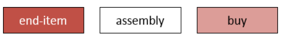


Figure I.3: Legend of networks

J Additional results case study

J.1 A one week analysis

Item	Priority	MRP	MAP-FP	MAP-RCRO
Part Y	-			
Assy C	-			
Assy B	-			
Assy A	-			
Non-service C	1			
Non-service B	2			
Non-service A	3			
Service B	4			
Service A	5			
Service Y	6			
Legend				

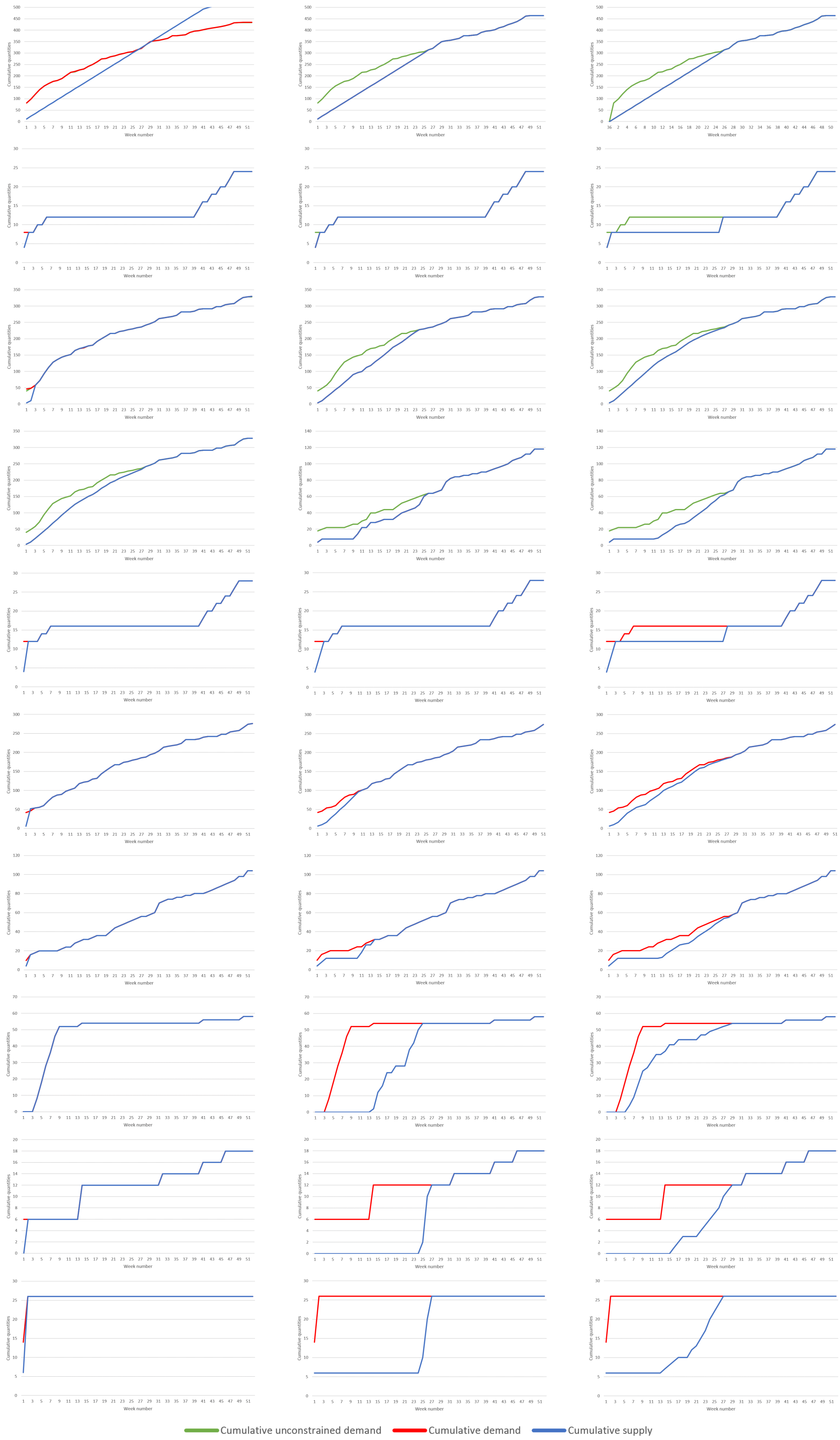
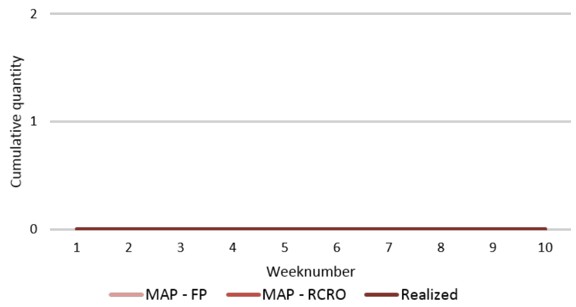
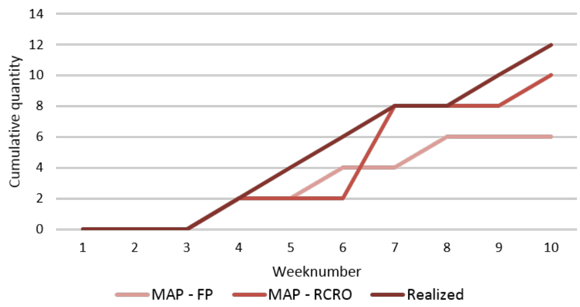


Figure J.1: MRP vs MAP for Case Y

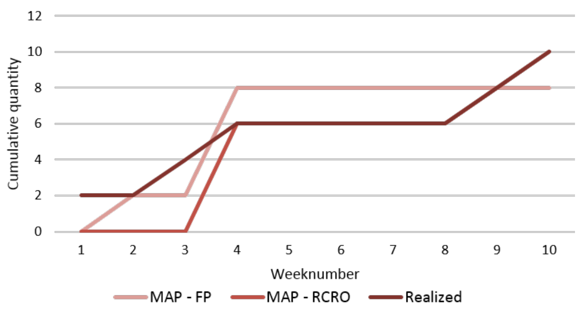
J.2 A rolling horizon analysis



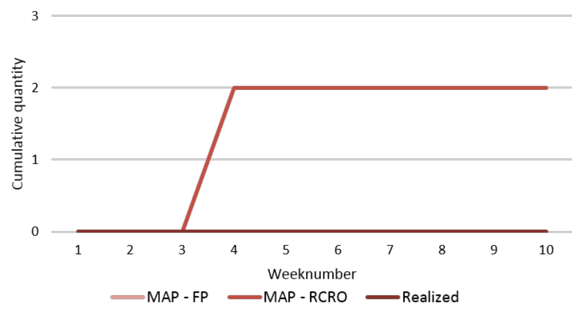
(a) Item ζ



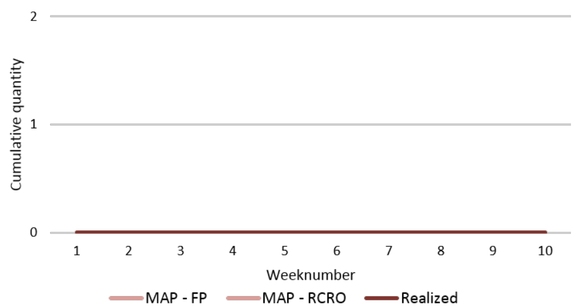
(b) Item ϵ



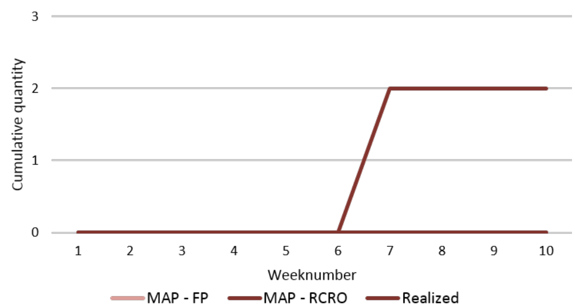
(c) Item η



(d) Item θ



(e) Item ι



(f) Item δ

Figure J.2: Cumulative finished orders generated by MAP-FP, MAP-RCRO and realized

K Questions usability test

K.1 System Usability Scale

Derived from Brooke et al. (1996).

		Strongly disagree				Strongly agree
1.	I would like to use this system frequently	1	2	3	4	5
2.	I found the system unnecessarily complex	1	2	3	4	5
3.	I thought the system was easy to use	1	2	3	4	5
4.	I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5.	I found the various functions in this system were well integrated	1	2	3	4	5
6.	I thought there was too much inconsistency in this system	1	2	3	4	5
7.	I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8.	I found the system very cumbersome* to use	1	2	3	4	5
9.	I felt very confident using the system	1	2	3	4	5
10.	I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

*Slow or complicated and therefore inefficient

K.2 Post-test questionnaire for usability test

1. Which elements or functionalities do you miss in current tooling?
2. What is the biggest added value of the tool according to you?
3. Which features/insights do you find useful and why?
4. Which features would you like to add to gain better insights?
5. How would you change the allocation rule and with what purpose?
6. Why or why not would you use this this as an actual planning method?
7. At which moment(s) during the CPP process can the method or tool be most useful?
8. Would you use the method or tool once or on an iterative basis?
9. What don't you like about the tool?
10. How would the tool support or hinder your tasks?
11. Would you like to use the method from now on?

disagree	1	2	3	4	5	agree

L Scenarios usability test

Scenarios present the tasks within realistic, goal-directed descriptions Barnum (2010). The following are elaborated upon with the users of interest. The tasks are constructed to cover all functionalities and insights of the tool.

Scenario 1
Your starting point is the current supply an demand status shown in the tool. You want to know if the current supply plan is feasible. How do you find out?

Scenario 2
The current supply plan is not feasible and you want to know which item(s) is/are the bottleneck.How would you find this?

Scenario 3
You have found the bottleneck item(s) and you want to know in which week(s) are the bottleneck week related to the item(s). What do you do?

Scenario 4
Furthermore, you want to know in which week all shortages are solved, how do you approach this?

Scenario 5
To be able to trace changes and explain shortages, you would like to know the supply and demand deltas compared to the last week. How do you gain this information?