Eindhoven University of Technology

MASTER

Determining safety buffer requirements against supply side uncertainties at ASML

Laçin, B.S.

Award date:
2011

Veldhoven, June 2011

Determining Safety Buffer requirements against supply side uncertainties at ASML

by
Bedir Siyar Lacin

BSc Industrial Engineering— INPG 2011
Student identity number 0729395

in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

Supervisors:
Prof.dr. A.G de Kok, TU/e, OPAC
Dr.ir. Zumbul Atan, TU/e, OPAC
Mehmet Atan, ASML
Fred Janssen, ASML
Rogier de Kok, ASML

TUE. School of Industrial Engineering.
Series Master Theses Operations Management and Logistics

Keywords: Safety buffer, Safety stock, Safety Time, Random yield, Lead time variability

I. Abstract

This thesis describes possible safety buffer determination methodologies to cover the uncertainties that are originated from the supply side of a multinational high-tech company in the form of defected items and late deliveries of the scheduled orders. Single-item single-echelon pragmatic formulas are developed to determine the safety stock and buffer times against the defected items and late deliveries respectively. A simulation model is developed to validate these methodologies, compare it with the current way and give some managerial implications.

II. Executive Summary

The research under consideration is conducted at ASML. ASML designs, develops, integrates, markets and serves advanced lithography systems that are critical to the production of integrated circuits or microchips. Thanks to its continuous improvements and achievements in the last 25 years, ASML became the technology leader in its sector. Currently it has become the biggest supplier of lithography systems with an over 70% market share.

Managing and controlling the supply chain of ASML is really complex due to the unique characteristics of its supply chain and market. Some of them which are related to this project are as follows:

- The lithography market is fluctuating and has frequently downturns and upturns which makes it difficult to forecast the customer demand and forces ASML to have a flexible logistic structure.
- Around 90% of all items used in the ASML lithography systems are outsourced to the suppliers, which makes ASML dependent of them.
- Some of the buy parts are really expensive, i.e. they can be over € 1 million.
- The production of these buy items and modules is complex and requires great attention which makes the production lead times variable and yield rate random.

This project is done to cover the uncertainties on the supply part of logistic control at ASML. This coverage uncertainty takes the form of safety stock and safety time parameters which will be an input to the planning system of ASML. During the investigation of the current supply chain, two types of supply uncertainty have been detected that can affect the performance of the logistic system:

- Defected buy items inside the ASML factory
- Tardiness of the supplier order deliveries

First, we carefully analyze the current situation to be able to understand the problem. Data analysis enables to quantify the size of the problem and analyze the current performance of the safety buffer settings in ASML. Several interviews have been held with the defined stakeholders in order to understand the process and underlying causes of the problem and finally a survey is handed out to the material planners to validate the findings and understand the problem in detailed. We found that the main drawbacks of the current safety buffer methodology in ASML are:

- Safety stock proposals of MACP (current safety stock methodology against rejects) are not reliable and not used by the Material Planners. The main reason of this situation is that safety stocks are calculated based on the contaminated reject data which includes the batch and incident types of rejects.
- Current safety stock calculation cannot satisfy the required predefined service level since the calculation is only based on the mean of the reject rate; in fact achieved service level also depends on the standard deviation of the reject rate.
- Planned delivery lead times are set without taking into account the current performance of the supplier.
- There is no feedback mechanism to report the effectiveness of the current safety stock levels and lead times.

For ASML, it is really important to reach predefined service levels and minimize the effect of uncertainties to the production with proactive actions. Based on the problems listed above and the request of the company, the following project definition is formulated:

"***Develop a methodology to determine the buffer requirements of ASML for all buy and buy under buy parts to compensate for supply uncertainty, namely supplier lead time variability and defective items. Compare this methodology with the current way of working in terms of service level and cost, and develop a tool based on this methodology.***"

After the detailed analysis of the problem and project definition, the To-Be process is defined and requirements of the prospective solution are discussed. Then literature analysis is done to be able to gain some theoretical knowledge and find applicable methods from the literature to apply to the ASML. Unfortunately, we couldn't find any applicable method directly from the literature; however the methods of Inderfurth (2011) and Hopp & Spearman (1993) are restructured in order to calculate the safety stock and time respectively. Under some assumptions the distribution of the random variables, reject rate and order lead time tardiness are found so that proposed methods can be used and implemented.

A simulation model is designed to be able to compare and validate the different methodologies of safety buffer calculation. The analysis shows that proposed methods always guarantee the predefined service level (chosen as 95%); moreover two different algorithms are created in order to calculate the safety stock in a more accurate way. The main conclusions from the simulation studies follow as:

- Proposed safety times based on mixed Erlangian distribution are performing close to the target service level in most of the case; whereas safety times based on exponential distribution achieve higher target service level than needed which increases the average inventory.
- Current way of calculation (MACP) is not capable to satisfy the high target service levels such as 90 or 95 percent. Furthermore its performance is getting worse for the items which have higher variability of reject rate and longer lead time.
- Proposed method for the safety stock always reaches the target service level, however it is performing higher service level than the target (95%) in the long run due to the low consumption rates. So an updated algorithm is developed which reaches the 95% target service level in the long run.
- Using repair lead time concept for the items which have a high consumption rate, longer lead time and expensive can bring substantial savings in terms of average inventory cost.
- Demand uncertainty may affect negatively the achieved service level required for the rejected items; however the additional investment to cover this uncertainty can be huge in some cases and may not be financially feasible.

Finally, some recommendations are given to the ASML to implement the method easier, which concern gathering data and updating the distribution parameters. This project can be considered as a starting point to determine the buffer requirements in ASML against uncertainties. It is really important to consider this topic more deeply in the future studies which may take also into account the demand uncertainty or create a multi-echelon structure to determine the safety buffer requirements.

III. Preface

The report you are about to read is the result of my graduation project in completion of the Master of Science degree in Operations Management and Logistics at Eindhoven University of Technology. This graduation project has been carried out from January 2011 to June 2011 at ASML Netherlands BV. This report symbolizes the end of a very important and pleasurable phase in my life and the start of a new chapter in my life.

Until the last day of my project, this has been an enjoyable and challenging environment. It has been very interesting to talk to many people in the organization and I very much appreciate the willingness and enthusiasm that all my colleagues showed. Therefore I would like to thank all ASML colleagues that have been involved in this project especially Roy Arts and Lionel Yang.

Specifically I would like to thank to Atan Family. I owe special thanks to Mehmet Atan who is my first supervisor in the company and I believe that I am the luckiest person in the world to have such a first mentor. Also I thank Zumbul Atan for her critical remarks about my methodology, simulation model and report. I will feel really honorable if they give my name to their first prospective child.

I feel myself again really lucky to have the smartest teacher in Tue as a first supervisor who is Prof. A.G. De Kok. It is really difficult to express you in words but I am sure that you are the best teacher I have ever seen. Besides that I want to thank Fred Janssen for his support in the development of my algorithm and lessons about the distributions. Also I owe many thanks Rogier de Kok for giving me the opportunity to do this project and for his critical remarks and suggestion at the right moments in time.

I received much support from family and friends during this master study. Therefore I want to thank everybody who has in one way or another been involved. Last but not least, I would like to express many thanks to my mother, who always supported me in every case and prayed for me every day. Without her, I could not have been able to achieve this satisfying result in the first place.

Bedir Siyar Lacin

June 2011

Table of Contents

1. Introduction

This report is the master thesis of the master program "Operations Management and Logistics" in Eindhoven University of Technology (TU/e). This project is carried out at Advanced Semiconductors Manufacturing Lithography (ASML) and has duration of 6 months. This section describes the introduction of the company and logistic structure of it more specifically.

1.1 Introduction to the Company

ASML was founded in 1984 and is the world's top provider of lithography machines for the semiconductor industry, who is dedicated to manufacturing complex machines that are critical to the production of integrated circuits or microchips. ASML designs, develops, integrates, markets its systems and provides after-sale services, which continue to assist their customers by reducing the size and increasing the functionality of microchips. In 2009, ASML has had a market share of around 68% (see Figure 1, based on revenue) with total revenues of 1.6 billion euro.

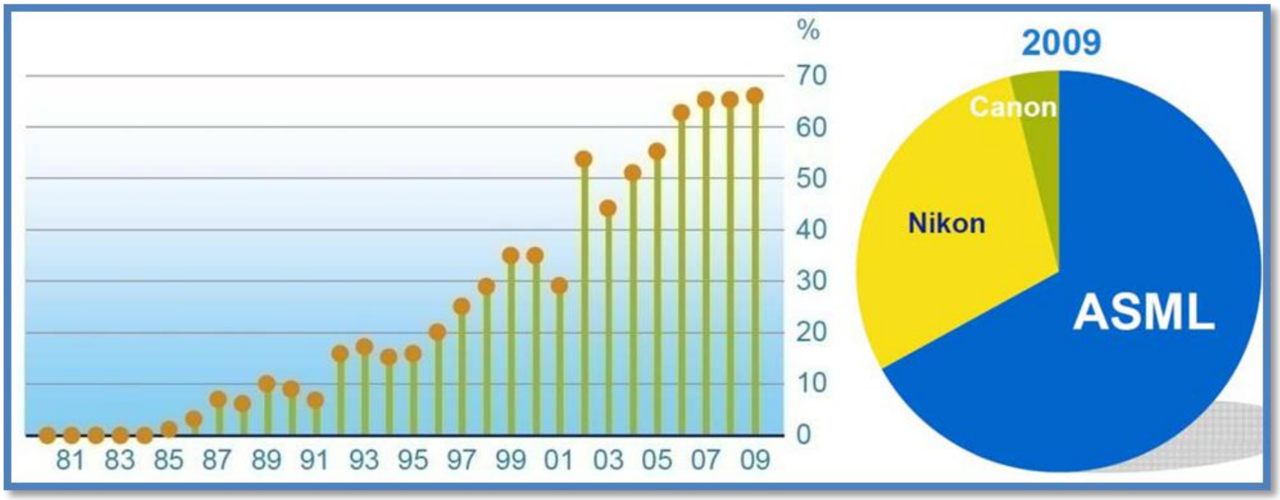


Figure 1 Market Share of ASML

ASML's corporate headquarters is established in Veldhoven, the Netherlands. Manufacturing sites and research and development facilities are located in Connecticut (USA), California (USA), and Veldhoven (the Netherlands), whereas technology development centers and training facilities are located in Japan, Korea, the Netherlands, Taiwan, and the United States. Additionally, ASML has sixteen local offices in sixteen countries to provide quick service to its customers. ASML has a large customer base, with amongst others, IBM, Samsung, TSMC and other major chip manufactures. Around 83% of the sales were in Asia and 17% in the United States in 2009.

1.2 Logistic System of ASML & Related Challenges

ASML commits itself to provide customers with leading-edge technology at the earliest possible date and high quality customer support to the specific requirement of its customers. Logistic structure of ASML is one of the key factors to reach this goal so it must be designed and controlled in the best way. The logistic system of ASML faces three types of demand streams. These are:

- *Demand of the new systems*: New systems that are ordered by different customers such as Intel, Samsung or TMC. This part consists of factory options (FO) which are the components that customer can choose based on its requests of the ordered system.
- *Service parts*: These parts are ordered from the Local offices of ASML and are used to repair and for the maintenance of ASML systems in the field.
- *Field upgrades*: These are upgrades for systems that are already installed at customer side to enhance their performances.

ASML has about 600 suppliers, some of which are really critical, including leading high tech companies such as Agilent, Carl Zeiss SMT, Cymer and VDL Groep. ASML outsources the manufacturing of materials as much as possible to focus on its core competence which is designing and integration of machines.

Within ASML, the production process starts with the assembly of production modules in different work centers, which is called as ASSY. Usually each work center is responsible for the production of one module and independent from other work centers. Afterwards, these ASSY modules are assembled into a machine which is called as “FASY” (Final Assembly). ASML plans the quantity of each machine that should start in FASY according to the forecast done in the Machine Start Plan (MPS) since FASY is the first operation after the Customer Order Decoupling Point. After FASY is finished, operation called “Test” is done in which machine is tested and important configurations are done. After these operations, machine is disassembled (Pre-pack) into the parts which are packed to be shipped to the customer. Finally, the machine is installed at the customer site which is called as “Installation”. Figure 2 presents a schematic of the supply chain of ASML.

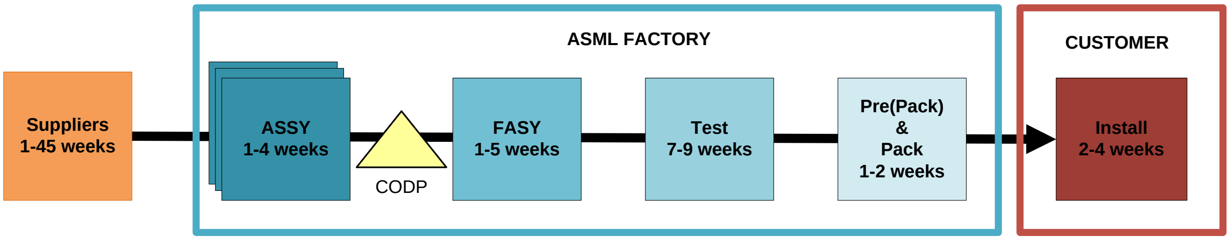


Figure 2 Supply Chain of ASML

Managing and controlling the supply chain of ASML is really complex due to the unique characteristics of its supply chain and market which are summarized below and will be elaborated in the next sections.

- Customer order lead time is longer than the total integral cycle time which consists of procurement and manufacturing lead time. That makes ASML to plan the part of the supply chain (upstream of CODP) based on the forecast.
- It is very difficult to forecast the customer demands of lithography systems since each system is customer-specific.
- The lithography market is fluctuating and has frequently downturns and upturns which forces ASML to have a flexible logistic structure.
- Some of the buy parts are really expensive, i.e. they can be over € 1 million.
- The product life cycle is short, around 2 years.
- There are many engineering changes (EC’s) over the life cycle of a product.
- Around 90% of all items used in the ASML lithography systems are outsourced to the suppliers, which makes ASML dependent of them.
- The production of the items and modules is complex and requires great attention which makes the production lead times variable and yield rate random.

This project is done to cover the uncertainties of the supply part of logistic control at ASML which will be an input to the planning system of ASML. The uncertainties that are originated by supply part of ASML will be discussed in detailed in the next section.

2. Supply side uncertainties of ASML

Several different types of supply uncertainty have been described in literature. Mohebbi (2004) indicates that, uncertainty is the result of variability in (delivery) lead times. Another important supply uncertainty factor described in literature is yield rates. Bollapragada et al. (2006) incorporated this uncertainty factor in their research. During the investigation of the supply chain organization, several supply uncertainties which can influence the current performance of the supply chain at ASML have been distinguished.

The supply uncertainty factors can be divided into two main types:

- Rejects inside the ASML factory
- Supplier delivery unreliability

2.1 Defective Items in the Production

The ASML production site can be considered as an assembly factory where most of the components are purchased and assembly of these components is done at the factory. These components can be detected as "defective" and rejected during the assembly. There may be several reasons for these defects such as vendor, production, people or technology. Defective items can be either internally repaired or send back to supplier to be repaired or scrapped. The operational flow of the defective items is shown in Appendix A. Yes or No codes determine the status of the defective item. These are summarized in table 1.

Code	**Definition**
No	No Materials Returned
Yes	Materials Returned General
Yes1	Analyze and repair after a valid quote
Yes2	Upgrade after valid quote
Yes3	Repair and upgrade after valid quote
Yes4	Material status is unknown
Yes5	Materials don't come back (Scrap)
Yes6	Materials need to be cleaned

Table 1 Status of the defective items

As it can be seen from Appendix A as well, when there is a defect and no stock in the factory, production can stop if the item is really critical for the operation, i.e. it is impossible to continue the process without this specific item. If the item is not critical, workers can continue to work without that item by working around (or other solutions such as using dummy item), however these solutions increases production time in most of the case.

The difference between the moment that the item is sent back to the supplier and the moment that the item is repaired and received to the ASML warehouse is referred as "repair lead time". Note that repair lead times depend on the YES type and the item, for this reason it can't be specified as an average time for the repair process however associated average times for the other type of processes are found and shown in Appendix A.

2.2 Tardiness of the scheduled receipts

ASML is using a Material Requirements Planning (MRP) system which is essentially a deterministic model, where all lead times are fixed and known. However both in-house production time and supplier lead time are variable and stochastic. These uncertain lead times can have a significant impact on overall system performance. Note that variability of in house production time is out of scope and will be taken as fixed in the modeling of the system. This problem is tried to be solved by embedding safety times into the production times and currently 2 other master theses are being held to set these safety times. The reasons of variable supplier lead time can be such as:

- Supplier planning issues: Supplier makes a wrong plan and cannot send the part at the required time.
- Supplier shipping / Transport Issues: A disruption occurs during the transportation which increases the lead time.
- Supplier Issue Quality: At the end of production of the item, it is detected as defective and cannot be sent to the ASML.
- Other disruptions at the supplier that causes late delivery.
- ASML can change the delivery date of the order, i.e. wants supplier to send items earlier than original due date, because of the sales order changes of ASML. This situation can lead to later delivery than expected.

2.3 Current safety stocks setting methodology against defects

Safety stocks are needed to minimize the lost production hours as a result of rejects. This calculation is done by the program named “MACP”. MACP calculates the safety stock for each product based on the following formulation:

- $PstSupRej = Number\ of\ rejected\ parts\ in\ last\ 6\ months$
- $PstCons = Consumption\ amount\ in\ last\ 6\ months$
- $RejRat = \textbf{Reject rate} = {}^{\mathbf{PstSupRej}}/_{\mathbf{PstCons}}$
- $FutReq = Future\ requirements\ next\ 6\ months$
- $FutRcp = Consumption\ period\ next\ 6\ months\ (How\ many\ weeks?)$
- $AvgReq = Average\ requirements\ per\ week = {}^{FutReq}/_{FutRcp}$
- $ExpRej(week) = RejRat\ x\ AvgReq$
- $SS = Lead\ Time\,(week) x\ ExpRej$

The MACP program is run once in 3 weeks by taking the needed input from the SAP. After the calculation, safety stock proposals are sent to the Material Planners to be reviewed and approved. If the proposal is to increase safety stock for an item, the Material Planner has to check whether the reject data contains batch defect or incident. Furthermore, the proposed safety stock value must be acceptable in terms of money. If the proposal is to decrease the safety stock for an item, Material Planner has to check whether this item is a buy under buy part since there is no demand visible for buy under buy parts in SAP which makes MACP to propose zero safety stock for these items despite that they may have reject in the past. Note that buy under buy part is the predecessor of the buy part in the BOM.

Finally, it is the decision of Material Planner to change the safety stock independent of the MACP program. From this point of view, it could be said that MACP is a decision support tool to the Material Planners to set the safety stocks against defects. Note that this process sets the safety stocks at the warehouse level whereas it is the decision of the Material Handlers to allocate these stocks to the work centers based on the discussion between people from production department. Current procedure of safety stock setting is shown in Figure 3.

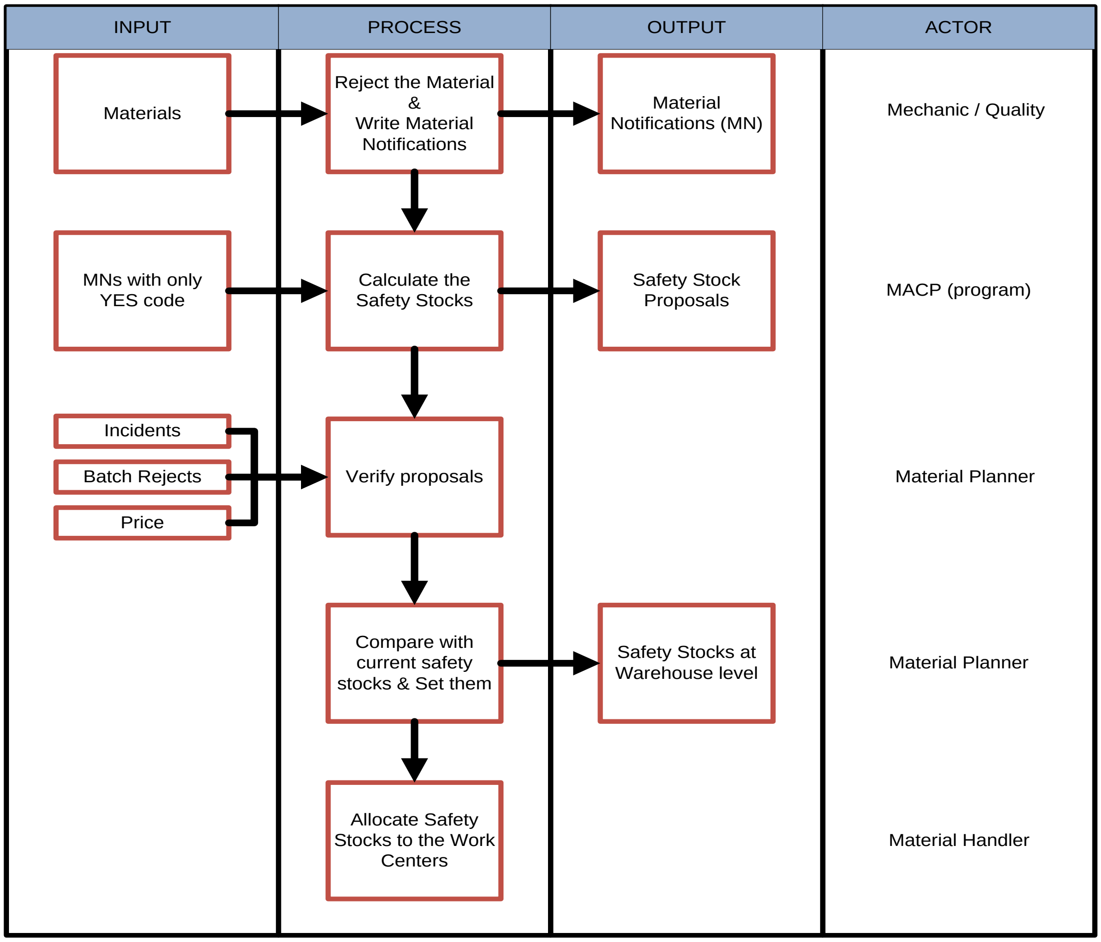


Figure 3 AS-IS procedure of safety stock setting at ASML

2.4 Current safety times against lead time variability

Safety time is an input to MRP and can be defined as an additional time that a purchase order is released earlier to cover lead time uncertainty. However, safety times for the buy parts in ASML are not calculated by taking into account the recent performance of the supplier which may change over time. Lead time setting is based on the agreement between ASML and supplier. For items which are more expensive than 10.000€ and classified as A type in the ABC categorization, zero safety time is proposed. For remaining items, 5 days fixed safety time is put in addition to the product delivery time. However items which are cheaper than 10.000€ can have zero safety time due to the agreements between the supplier. It is important to note that these safety times are embedded into the Master Data to be used at MRP. It is not up to Material Planner to change these safety times.

2.5 Performance of the current safety buffer levels against the supply uncertainties

Performances of the suppliers in terms of delivery reliability are analyzed for a specific time period and analysis shows that 304 shipments are late in 14 subsequent weeks (from 10.43 to 11.07) and 300 hours are lost because of these late shipments which causes 160 hours delay in the FASY. Since FASY is downstream of the customer decoupling point, such delays in FASY can easily affect the machine delivery date.

Second analysis is done to show the effect of quality problems inside the factory. 46 takts (8 hour units in ASML terminology) are lost at FASY because of quality related problems for a period of 4 weeks (11.01 – 11.04) and moreover according to the production people, no safety stock was available to prevent such situations. Note that even if there were enough safety stock, that doesn't mean that those lost 46 takts could have been recovered, since in some cases there is a time elapse between the starting to use the item and finding out that it is defective. But it is still obvious that there is an improvement opportunity if the safety stocks were set correctly.

Since MACP is a decision support tool and the final decision to change safety stocks is given by Material Planners, it is investigated whether Material Planners are using the proposals of MACP or not. Analysis shows that Material Planners do not set the safety stocks as proposed by the MACP most of the time. These two analyses show that the current way of calculating the safety stocks are not enough to cover the uncertainties mentioned above and don't represent the reality.

2.6 Problem Formulation

As explained above, current safety buffers do not cover the supply uncertainties which are defined as defects and lead time variability. The current calculation methods of safety buffers described in the previous section have several drawbacks. The main drawbacks are:

- Safety stock proposals of MACP are not reliable and are not used by the Material Planners. Interviews with Material Planners reveal that Safety stock proposals of MACP are not used because it contains a lot of reject data which is batch defect or incident which inflates the safety stock level proposals. Also most of the time Material Planners contact with the supplier to learn the reason of the defect and when they are sure that there is a reasonable explanation of the reject, they ignore the safety stock proposals. This situation shows that future decisions about safety buffers (calculation method) are not based on the correct past data.

- Demand is invisible for buy under buy parts, which makes it impossible to calculate the safety stock levels for them. It must be possible to deduce this demand from BOM's within a modified MACP tool.
- Current safety stock calculation cannot satisfy the required predefined service level since the calculation is based on averages in fact the service level also depends on the standard deviation of the reject rate. Moreover it only takes into account the defect rate and lead time, in fact interviews and analyses shows that there are other important variables that can affect the calculation such as price of the item, criticality of item in the view of operation continuity, status of the part (under development or no development anymore), reliability of the supplier in terms of lead time and capacity of the some suppliers.
- Planned delivery lead times are set without taking into account the current performance of the supplier, i.e. variability.
- There is no feedback mechanism to report effectiveness of the current safety stock levels and lead times.
- Molinder (1997) shows that safety time can also be an option for the defective items whereas safety stocks can be used also for the supplier lead time variability. However the current methodology in ASML is not able to take the benefits of safety stock and time combination, instead it makes a clear cut that safety stocks are only used for defects, on the other hand variability in the supplier lead times are covered by safety times.

Hence, the main problem that ASML is facing defined as:

"ASML is using a safety buffer calculation methodology against supply uncertainties that is unreliable and has drawbacks that cause problems with respect to service levels and costs."

3. Project Formulation and Scope

This chapter includes the definition of the project based on the problem formulation described at the last chapter. Afterwards, project scope and deliverables are formulated. Lastly input and output specifications of the model are explained to realize the general framework of the to-be process which is discussed in section 3.1.

3.1 Project Formulation

For ASML, it is really important to reach predefined service levels and minimize effect of uncertainties to the production with proactive actions. Based on the problem definition and request of the company, the following project definition is formulated:

"***Develop a methodology to determine the buffer requirements of ASML for all buy and buy under buy parts to compensate for supply uncertainty, namely supplier lead time variability and defective items. Compare this methodology with the current way of working in terms of service level and cost, and develop a tool based on this methodology.***"

A design of the new safety stock setting procedure is shown in Figure 4. The main differences between the AS-IS process are the calculation method and reject data collection procedure.

As it is discussed in the section 2.3, the calculation method takes an input of the contaminated past data which includes batch defects and incidents. Moreover, it includes all the rejected materials that sent back to supplier. However, some of these materials are rejected because they are upgraded and will not be used any more. In this case even if there is a safety stock, they will be useless as well. These items are coded as Yes2 (refer to Table 1) in the Material Notification.

To overcome these problems, it is decided to submit all the reject data without Yes2 codes to the Material Planners before the calculation of safety buffers. It is the responsibility of Material Planners to filter the data with incident and structural rejects by contacting with suppliers and making investigation on Material Notifications. Afterwards, the new calculation tool will take only the structural reject data as an input and make the calculation of safety stocks (at warehouse level) and times based on the correct past data. Another important feature of the new method is to calculate safety stocks and times simultaneously.

Finally, Material Planners will make the final decision of safety buffers since every material has some unique characteristics that are known by Material Planners. These characteristics can affect the safety buffer of an item and in fact the model can not reflect the outside world with %100 match. Note that Material Handlers are again responsible of allocation of the safety stocks to the Work Centers.

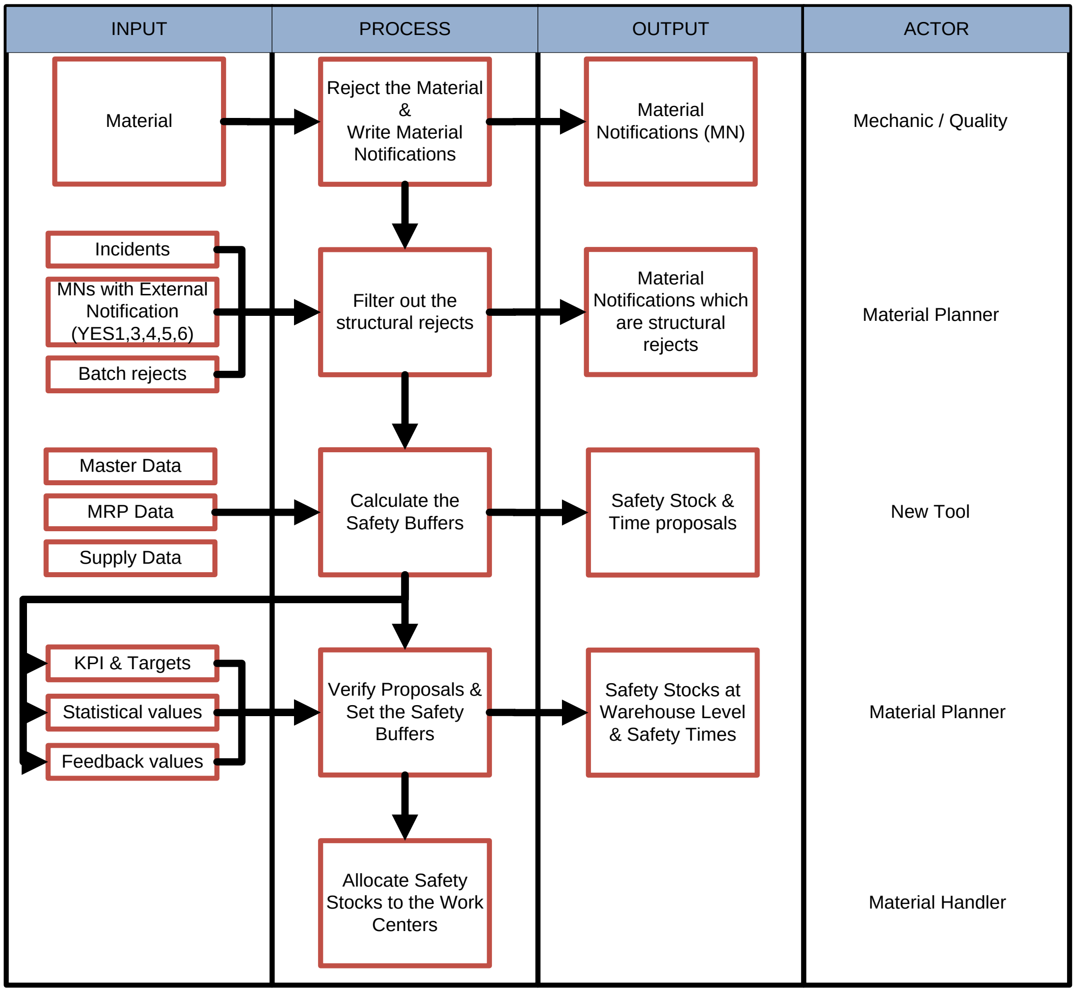


Figure 4 To-be process of setting safety buffers

3.2 Project scope

The most important difference between the new safety stock setting procedure and current one is the calculation methodology which is based on statistics and includes other important variables besides the reject rate and lead time. Moreover this methodology is embedded in a tool which will calculate the safety buffers with the given parameters. To reach these goals, the project boundaries are set; these are summarized below with the reasons behind:

3.2.1 In scope:

1. *The calculation methodology* to determine the buffer requirements of ASML against supply uncertainties.
2. The following parts of the supply chain
    a. *All buy parts*. The tool must be capable to give safety buffers for the entire buy parts.
    b. *All buy under buy parts* which are found as defective and can be ordered from the supplier in case of defect. Only safety stock proposals are needed for buy under buy parts since they are not ordered from the supplier in normal case.
    c. *ASSY and FASY & Test process step*. These two production steps are taken as a black box and separated, since Yang (2009) makes the analysis of the production unit (PU) selection and shows that FASY & Test and ASSY are the two production units of ASML factory. The main reason to define PU's in the production control is to reduce the complexity of logistic planning and control.
3. *Demand of the new systems*: It is the policy of ASML that Material Notification is written only for items that are detected as defective inside the ASML factory. When there is a defect outside the factory which can occur for the service parts and field upgrades, that defect is not written to the Material notification list. Demand of field upgrades and service parts are taken out of scope for this reason, whereas only demand of the new systems are taken into account and will generate the requirements of the items.
4. *Engineering changes*: A system faces many Engineering Changes (ECs) within its life cycle (around 80 clustered changes per week); so engineering changes must be taken into account to represent the situation of ASML.
5. The method has to give safety stocks and times for the buy parts whereas only safety stocks for the buy under buy parts.

3.2.2 Out of scope

1. *Individual ASSY work centers*: The reason of taking this part out of scope is discussed in section 3.2.1.

2. *Variability in demand*: This is the request of the company since ASML wants to solve the problems of fluctuations in the demand with another way, namely; by changing the delivery date of the buy items (re-in vs. re-out) and swap packages. We refer to Yang (2009) and Buijssen (2010) for detailed information about these issues. However, it is not possible to separate demand and supply uncertainty in the real life. So besides the deterministic demand case, a safety buffer methodology which takes into account demand uncertainty will be developed.
3. *Variability of in house production time:* This issue is discussed in section 2.1.
4. *Capacity of the suppliers:* Interviews with the Material Planners reveal that capacity is not an important parameter that can affect the safety buffer of the item since ASML has the power to request a capacity increase at the supplier for a specific time period.
5. *Effect of batch ordering on the price*: According to the Material Planners, this issue is not so common and also it is hard to determine the price of the item with the changing batch sizes.

3.3 Project Deliverables

The deliverables of this project are following

- Operational safety buffer determination tool

This tool will be developed to set the safety time and stock with the given predefined service level. Besides the buffer requirements, it will show the required investment and anticipated service level for each part for different safety stock values. In this way, it can give insights to the Material Planners when they are confronted with the proposals of the safety stock. The report will contain specifically:

  - Input and output specification
  - Mathematical model, i.e. the methodology to set buffer requirements
  - Solving the model with an appropriate tool described above
  - Validation of the tool and comparison of it with the current way
  - Conclusion, implementation and recommendation

3.4 Output specifications of the model

Output requirements of the model are divided into 3 following sections:

- **Safety buffer requirements**

This part shows the main outputs of the tool which are the required safety stocks and safety times to reach the predefined service level for each part.

- **KPIs & targets**

This section displays the anticipated service levels for each part for different safety stocks and associated costs. Actually these two outputs show the tradeoff between the costs and service level which is an important issue to be considered at the final decision of setting safety buffers.

- **Statistical & Feedback values**

This part shows the results of the distribution about the rejects and the lead times. It will give some statistical data about rejects and lead times to help the final decision maker to set the safety buffers. Moreover the model will be designed in a way that it will give outputs about the previous safety stock propositions and number of defects occurred for each part since the previous period so that Material Planner can make comparisons between the previous and current period.

Safety buffer requirements	Explanation
Safety stock	Safety stock levels for each part
Safety time	Safety time for buy parts only

KPI & Targets	Explanation
Cost of Safety Stock	Total value of inventory due to safety buffer
Anticipated service level of the item	Anticipated Percentage of the jobs that start on time

Statistical & Feedback Values	Explanation
Statistics of defects	Distribution of reject rate of the item
Statistics of lead times	Distribution of the order lead time tardiness of the item
Previous Safety stock	Safety stock propositions of each part for the previous period
Previous defect data	Number of defects occurred for each part since lead time of that item

Table 2 Output specifications of the model

3.5 Input descriptions

To be able to satisfy the requirements of the model described in the project deliverables, the input of the model is specified in this section. The inputs are addressed below and consist of three categories: (1) Master Data, (2) MRP Data and (3) Supply Data.

- **Master Data**

Master data are the parameters which are used for items, production units and links between them. On the item level, a 12NC is needed for referencing the costs and the lead times. The BOM structure is used to calculate the requirements of the items, so for example to produce one item a, it is required to have one item b and two items c. Lead times are defined as a time in which the released work order is produced.

- **MRP Data**

MRP Data contains the inputs which basically include the demand data that generates the future consumption of each item and can be changed every period. Note that Sales orders and forecast data will be handled as one input at this point.

- **Supply Data**

This part includes the data which represents the stochasticity of the supply side that make disruptions at the ASML factory. Specifically, these are the rejects that are sent back to supplier and the variable supplier lead times. Moreover, the decision maker has to set a service level for each part which will be discussed later. In this context, service level is defined as the percentage of the process that starts on time, in which the specific part is used. Note that the tardiness of lead times are taken into account instead of the actual lead times due to the fact that the former case will not reflect the lead times correctly. Because ASML can change the order dates (re-in and re-out) and thus the lead times of the orders. Then it is more appropriate to calculate the lateness of the supplier and put it as an input to the model. Moreover as it is discussed at section 2.1 that repair lead times are variable and can’t be determined easily. However it is logical to use artificial repair lead time and analyze whether it is beneficial to use it or in which cases repair lead time is effective. The calculation methodology will be discussed later. All the inputs are defined in the Table 3.

Master Data	Explanation
Bill-Of-Materials (BOM)	The relations between parent and child items

Cycle Time/In-house Production Time	Time to produce or assemble an item
Cost Price	Value of an item (standard cost price)
Buy/Buy under buy part	Item that is at the lowest level of BOM (buy) or predecessor of the buy item (buy under buy)
Planning Horizon	Horizon to be optimized
Supplier lead time	Agreed planned delivery time between the supplier for a specific part

MRP Data	Explanation
Sales Orders	Confirmed orders of new lithography systems
Forecast	Forecast of new lithography systems

Supply Data	Explanation
Tardiness of Lead Times of suppliers	Difference between the planned received date and actual received date
Rejects of items	Rejects that are sent back to supplier (YES1,3,4,5,6) and are structural
Predefined Service Level of each part	Percentage of the jobs that start on time
Repair lead time	Time to repair the rejected item which is sent to the supplier

Table 3 Input specifications of the model

4. Literature Study & Method Selection

In this chapter, it is aimed to give some crucial information about the buffer management literature firstly. Results of the literature review study will be presented for this reason. Then the analysis of possible solution methods will be discussed in the section named structure of the model. Finally, the selected methods will be shown and explained in detail.

4.1 Results of the Literature Review Study

To be able to find feasible models for setting safety buffers against supply uncertainties, the buffer management literature is analyzed with a special consideration of safety stock and time measures for supply uncertainty in MRP environment. It is identified from this study that safety stock is predominantly applied to buffer against supplier uncertainties, besides safety time and scheduling approaches such as rescheduling or frozen MPS which is opposed to buffering strategy. It is interesting to observe that researchers consider both demand and supply uncertainties simultaneously in most of the studies.

It is found out that most of the time researches come up with non-linear objective function in which associated solution procedures are somewhat more complex, both analytically and computationally. They use some heuristics to resolve this difficulty. Also Yano and Lee (1993) stress that manufacturing systems (under which multi-period models are classified) are very complex and since closed-form solutions are often unachievable, valid heuristics must be further studied and developed. On the other hand, some researches choose to use simulation method to solve the associated problems.

Generally, from basic to complex systems, the researchers consider single-stage continuous models with random demand and yield as a simple system and study on discrete time models for a single finished product with a single production stag, or multiple stages in series, or an assembly structure which can be considered as more complex systems. Recent literature focuses on more complex systems with multiple finished products, production processes that produce multiple quality grades, rework and multiple suppliers.

The papers which are found in the literature and considered applicable in this project are classified in Table 4. Most of the time, researchers focused on both demand and supply uncertainty together and unfortunately no researcher tried to optimize safety stock and time simultaneously, despite the fact that Cheng (1984) notes that safety lead times can be lowered with the presence of safety stock which can be argued to be a possible gap in the literature. Note that Molinder (1997) optimizes safety stock and time separately with a simulation and compare the associated costs.

Paper	Objective	Decision Variables	Structure of the System	Planning Horizon	Uncertainty considered
Bollapraga and Morton (2006)	Holding and shortage cost with respect to service level	Order Sizes	Single item	Single Period	Uncertain demand and yield
Hoop and Spearman (1993)	Holding cost with respect to service level	Safety Time	Multi item - Single echelon	Single Period	Uncertain lead time
Hoop and Hegedus (2001)	Holding cost with respect to service level	Safety Time	Multi item - Multi echelon	Multi Period	Uncertain demand and production rate
Inderfurth (2011)	Holding and shortage cost	Safety Stock	Single item	Multi Period	Uncertain production rate
Molinder (1997)	Holding and shortage cost	Safety Stock and Time	Multi item - Multi echelon	Multi Period	Uncertain demand and lead time
Dolgui et al. (2009)	Holding and shortage cost with respect to service level	Safety Time	Multi item - Multi echelon	Multi Period	Uncertain lead time
De Kok and Gudum (2003)	Service level	Safety Stock	Single item	Multi Period	Uncertain demand
Bollapraga and Rao (1999)	Holding and shortage cost	Order sizes	Single item	Multi Period	Uncertain demand and lead time

Table 4 Classification of the papers found in the literature

Holding and shortage costs are the most common criteria that are used in the papers. Additionally, some researchers use also service level constraints besides the cost function. Finally, there is no article found which focuses solely on lead time variability and random yield problem.

4.2 Structure of the Model of the ASML Problem

Detailed analysis of the structure of possible solution methods is made in this section. The solution method needs to calculate the values of the safety buffer parameters, safety stock and time for each product that is defined in the input specifications of the model. The goal of this project is to develop a methodology for ASML that has a strong scientific basis and is valid according to the situation at ASML, i.e. can be implemented and used in the future.

Papers found in the literature are most of the time classified as single vs. multi period or single vs. multi echelon. So it is decided to start to create the structure of the model based on these classifications.

Schmitt et al. (2010) shows that if the firm is capable of planning proactively for future periods and the disruption risk is significant (the penalty costs for shortages are high and/or disruptions have a high probability of occurrence), the optimal base stock levels are underestimated by single period models. Authors note that the truncating approximation fails to recognize the need to stock multiple periods of demand for high newsboy fractiles, because it stocks for the current period only and ignores future disruptions. Moreover as it is discussed that ASML works in a really fluctuating environment which makes the single period models less reliable. In the light of these discussions, it could be said that a multi-period model must be used for the sake of reliability and optimization.

Even though the project considers the buy parts and buy under parts only, the associated system is a multi-echelon which means that in the case of a stock out situation on a certain level; production cannot be started until there is material available on the corresponding lower level in the structure. However it is found that researchers come up with nonlinear objective function for the multi period-multi echelon problems because of the complexity of the problem, which is difficult and time consuming to solve. Then they develop heuristics to resolve this difficulty which are based on several assumptions such as relaxing service level constraint or assuming that random process is normally distributed. Nevertheless these heuristics can't be applied to a lot of products and optimality of these heuristics is not guaranteed most of the time. Moreover, one can also propose that such a multi echelon model is not needed for a limited number of materials since the model will not consider all the materials in the supply chain, instead it will only consider the buy and buy under parts which are found as defective or associated lead times are variable. So it is decided to use single-echelon model for this problem which ignores the availability of the materials at the downstream.

According to the to-be process and input specifications, the model has to optimize safety stock and time simultaneously based on the reject and tardiness data. Based on these requirements, papers discussed in Table 4 are classified according to their models in Table 5. Table 5 shows that the only paper that could be used is Molinder (1997) which used simulation method to optimize the safety stock and time, however the author didn't optimize them simultaneously and also the paper doesn't include the model required for this simulation model.

Paper	Multi Period	Single Echelon	SS	ST	Random Yield	Uncertain Lead time
Bollapragada and Morton (1999)	N/A	X	E	N/A	X	N/A
Hopp and Spearman (1993)	X	X	N/A	X	N/A	X
Hopp and Hegedus (2001)	X	E	N/A	X	E	X
Inderfurth (2011)	X	X	X	N/A	X	E
Molinder (1997)	X	E	X	X	X	X
Dolgui et al. (2009)	X	X	N/A	X	E	X
De Kok and Gudum (2003)	X	X	X	?	E	E
Bollapragada and Rao (2006)	X	X	E	?	X	X
N/A=Not Applicable, E=Extendable, X=already have, ?=Unknown, SS=Safety Stock, ST= Safety Time						

Table 5 Classification of the papers based on their models

According to the specifications of the model discussed in chapter 3, the pragmatic formulas must be developed to calculate the safety buffers in order to implement the project. However, it doesn't seem possible to optimize safety stock and time with the simple formulas according to the literature review. Moreover, Whybark and Williams (1976) use simulation to study the efficacy of safety stock and safety time as buffers against quantity and timing uncertainty of demand and supply in single-stage, single-product systems. Their results suggest that safety stock is preferred for quantity uncertainty and safety time is preferred for timing uncertainty. Moreover Molinder (1997) confirms the results of Whybark and Williams (1976) with the simulation study. In the light of this discussion, it is decided to use *safety stock as a buffer against quantity uncertainty* which is random yield and *safety time for timing uncertainty* which is order lead time tardiness in this context. By this way, the complexity is reduced, and it is possible to use practical formulas which can be derived from the literature to calculate the buffer requirements.

4.3 Methods to Calculate the Safety Buffers

In this section, the most convenient and applicable methods for both safety time and stock will be selected from the literature separately. Then these methods will be restructured in order to be used and applied with respect to the context of ASML and specifications of the model. Firstly, selected method for the safety time will be discussed.

4.3.1 Selected Method for the Safety Time

According to the Table 5, Hopp and Spearman (1993), Hopp and Hegedus (2001), Molinder (1997) and Dolgui et al. (2009) discussed about safety time in their papers. Except Molinder (1997), all have developed specific methods to calculate the safety time in certain settings. However Hopp and Spearman (1993) derived the safety time formula for the multi period and single item setting which complies the specifications of the model. More in detail, the authors are concerned with establishing appropriate lead times (l_i) for purchased components with stochastic delivery times in this paper. They ignore the demand variability and assembly time; also assume that assembly cannot perform early. They further assume that the delivery times for each component i, i=1,2,3,….,n are independent random variables with continuous distribution functions, F_i, which is assumed as normal distributed with mean μ_i, variance σ_i, then it is convenient to write the lead time L_i with k safety factor as::

$$L_i = \mu_i + k \times \sigma_i$$

As it is discussed in Chapter 3 that the tardiness of the orders will be concerned instead of actual lead time; the formulation of Hoop and Spearman (1993) can be easily converted to the safety time calculation for our case. Then, safety time can be formulated based on the mean, variance of a specific distribution of the order lead time tardiness and confidence level (α):

$$ST_i = \mu_i + \Phi^{-1}(\alpha) \times \sigma_i \ (1.1)$$

Note that Φ^{-1} represents the inverse cdf of the specified distribution.

4.3.2 Selected Method for the Safety Stock

It is found in the literature review study that Bollapragada and Morton (1999), Inderfurth (2011), De Kok and Gudum (2003) and Bollpragada and Rao (2006) have developed specific methodologies to calculate the safety stock for the certain settings. However it is decided to use the method of Inderfurth (2011) who considers a manufacturer's stochastic production/inventory problem under periodic review and present a methodology for safety stock determination to cope with uncertainties that are caused by stochastic demand and yield variability. This method is selected due to the fact that Inderfurth (2011) develops pragmatic formulas which are the result of extensive review of the literature. The author determines safety stock for stochastically proportional yield with the following formula:

$$SST_t = k \cdot \sqrt{(\lambda + 1) \cdot \sigma_D^2 + \sigma_Z^2 \cdot \sum_{i=1}^{\lambda-1} Q_{t-i}^2 + \nu_Z^2 \cdot \mu_D^2}$$

Where;

$Q_t = \ Released\ order\ quantity\ in\ period\ t$

$SST_t = \ safety\ stock\ for\ period\ t$

$\lambda = \ production\ lead\ time$

$D_t = i.i.d.random\ demand\ in\ period\ t\ with\ expectation\ \mu_D\ and\ variance\ \sigma_D^2$

$Z = \ Random\ yield\ rate\ with\ mean\ \mu_z\ variance\ \sigma_z^2\ and\ coefficient\ of\ variation\ v_z$

$\alpha = \ critical\ ratio\ (depending\ on\ holding\ and\ backlogging\ cost),\ \Phi^{-1}(\mathrm{\alpha}) = \mathrm{k}$

Before upgrading the formula to be able to use for ASML case, the reject process in ASML must be discussed. As it is discussed in Chapter 2, ASML can only know the amount of rejected materials when they are used in the shop floor, i.e. when there is a demand since there is not a quality checking process before the operation of that material. Because of that, the amount of rejected material at the specific period can be calculated by multiplying the yield rate with demand instead of scheduled receipts at that specific period. So the first change in the method of Inderfurth (2011) is to multiply the yield rate with demand instead of scheduled receipts. If yield were multiplied with the scheduled receipt, then safety stocks and repaired items would be subjected to the yield which will inflate the amount of the safety stock. Secondly, Inderfurth

(2011) takes into account the mean reject rate by multiplying Q_t (scheduled receipt) with YIF (yield inflation factor) which is $(1/(1-\mu_z))$. So the adapted formula must take the mean reject rate into account also since it is not an option to increase the order quantity in ASML case. In this section, the formula is developed against reject in which demand is assumed as deterministic. Subsequent section is devoted to stochastic demand case. In the view of these argumentations, safety stock formula for this case can be formulated as follows:

$$SS_t = \mu_z \times \sum_{i=1}^{LT} D_{t+i} + \Phi^{-1}(\alpha) \times \sqrt{\sigma_z^2 \times \sum_{i=1}^{LT} D_{t+i}^2} \quad (2.1)$$

Also the formula must be further developed which takes into account the repair lead time:

$$SS_t = \mu_z \times \sum_{i=LT-RLT+1}^{LT} D_{t+i} + \Phi^{-1}(\alpha) \times \sqrt{\sigma_z^2 \times \sum_{i=LT-RLT+1}^{LT} D_{t+i}^2} \quad (2.2)$$

Note that again Φ^{-1} represents the inverse cdf of the normal distribution. According to both formulas of safety time and stock, it is an absolute necessity to determine the distributions of the random variables which are yield rate and order lead time tardiness to be able to calculate safety stock and time. This process is described in the subsequent chapter.

4.3.3 Effect of Demand Uncertainty on Safety Stock Calculations

In the previous chapter, safety stock is calculated with the assumption that demand is deterministic. However this assumption is not practical due to the fact that demand is non-stationary in the ASML case, i.e. volatile which means that proposed safety stocks are not capable to secure the predefined service level in case of unexpected increase in demand. Based on this discussion, it could be easily said that the demand uncertainty should be also incorporated into the calculation to able to guarantee predefined service level. Note that proposed safety stock formula will be developed still to cope with reject rate despite the fact that the demand uncertainty is embedded into the calculation.

Before restructuring the formula, forecast error during the lead time of the item must be discussed in detail to be able to understand the process for the correct formula. We mean by the forecast error as the deviations of the forecast and actual demand. According to Enns (2002), forecast error is the combination of the demand uncertainty and forecast bias. Forecast error during the lead time is item specific and depends on the following factors:

- Where to use the item (before vs. after CODP)

- MPS frozen period
- Production Cycle Time (How long is the item far away from the CODP?)
- Planned Delivery Time of the item
- BOM (in which machine types to be used)

In order to visualize the process in detail, schematic process of the forecast error is shown in Figure 5. As it is already discussed, CODP is located at the beginning of the FASY process and MPS is done at the FASY level. That means the items which are used after the CODP, are consumed according to the real demand (confirmed sales orders). It is really difficult to change these sales orders and only some customers have the power to do that. However, it could be proposed that there is no demand uncertainty at this level.

MPS frozen period is the length of the period that ASML fixes the MPS and doesn't allow changes in it. However it is really difficult to freeze the MPS even for small period even due to the volatile environment of the semiconductor market. However, the changes in the frozen period are considerably less than the remaining MPS period.

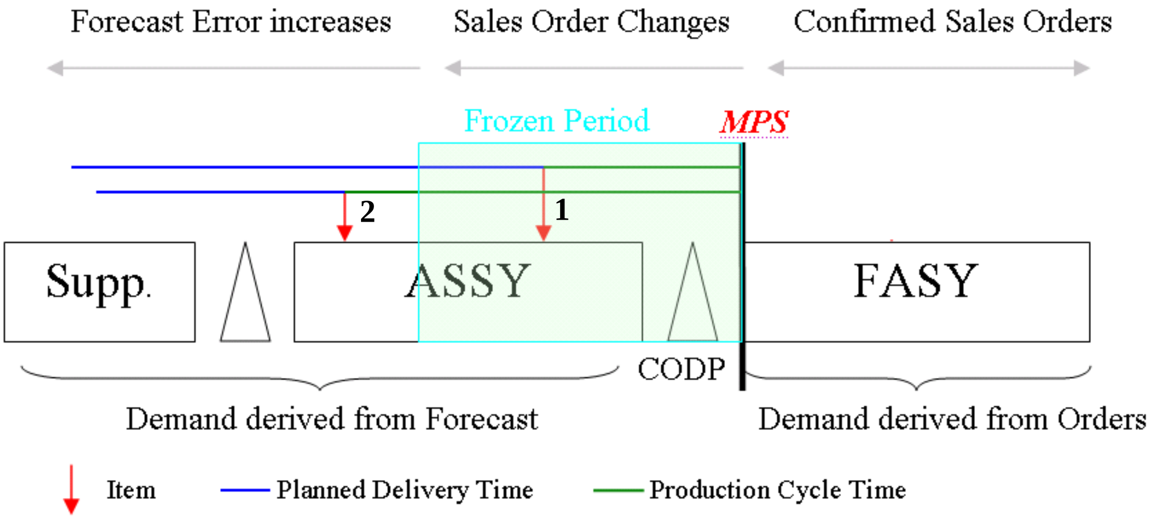


Figure 5 Schematic representation of the Forecast Error

In the light of the discussion from the previous paragraph, the forecast error over the production units changes according to Figure 6. Basically, the forecast error is zero after the CODP and it starts to increase in the frozen period, and the rate of the increase is greater for the periods besides the MPS frozen period. For the simplicity, two different standard deviations of the forecast error can be derived which are σ_l for the MPS frozen periods and σ_h for the unfrozen MPS periods.

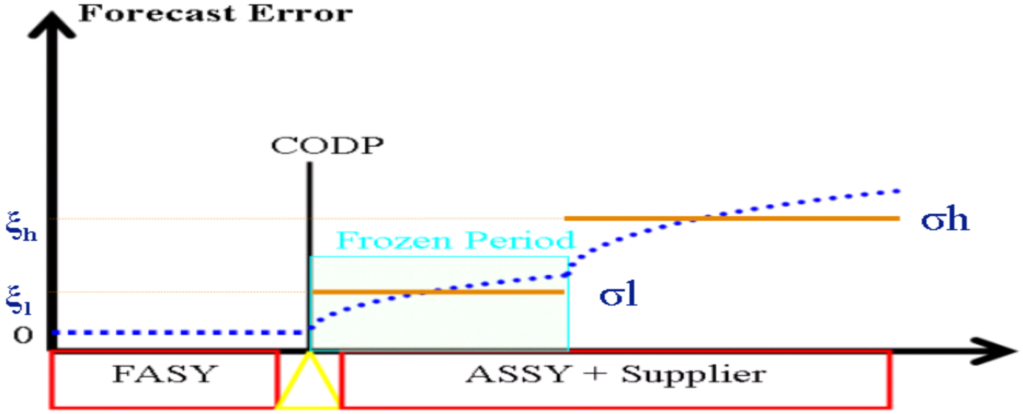


Figure 6 Evolving Forecast Error over Production Units

Lead time of the item and production cycle time of the successors of the item (time distance to the CODP) are determine the position of the consumption periods of that item. For example, item numbered 1 in the Figure 5 is consumed based on the end items from the frozen period and remaining MPS period. Likewise consumption amounts of the item numbered 2 are derived only from the MPS periods besides the frozen period.

It can be further said that each item is exposed to the standard deviation of forecast error during its lead time which depends on the factors that are discussed above. If this standard deviation is denoted as σ_d which is the combination of σ_l and σ_h, then the safety stock formula (2.1) can be restructured, follows as:

$$SS_t = \mu_z \times \sum_{i=1}^{LT} D_{t+i} + \Phi^{-1}(\alpha) \times \sqrt{\sigma_z^2 \times \sum_{i=1}^{LT} D_{t+i}^2 + \sigma_d^2 \times \mu_z^2 + \sigma_d^2 \times \sigma_z^2} \quad (2.3)$$

Unfortunately, it is not easy to calculate this variance for each product in practice, since it is also based on the end item type since end item which are sold frequently have a more reliable forecast process than the items which have an infrequent demand. Also it is believed that such an intensive research must be the scope of the buffer calculation methodology for demand uncertainty. However this safety stock methodology is tested in the simulation model (Chapter 6) with artificial values of σ_d whereas distributions of all other random variables are found in the next chapter.

5. Distribution Fitting

As it is already discussed in chapter 4, a specific distribution must be found for each random variable in order to calculate safety stock and time according to the proposed formulas. The distribution of the random process is really important since the distribution describes the statistics of the processes which are basically mean and standard deviation. First reject rate distribution is discussed, then distribution fitting to order lead time tardiness and demand rate is explained consecutively.

5.1 Distribution Fitting to the Reject Rate

Unfortunately, it is impossible to find a specific distribution of reject rate for each item since there are more than 2000 items which are rejected in the past and most importantly, there are not enough data to come up with a specific distribution for each item because of their low consumption rates. Hence, it is decided to make a Pareto analysis to find the items that constitute the 80 percent of the total value of the safety stock against defects and fit a unique distribution to each item, then classify the rest of the items and aggregate the data based on this classification to be able to fit a distribution.

To able to make a Pareto analysis, the results of the MACP (for the detailed information, see Chapter2) for the weeks 11.10 and 10.40 are analyzed and 65 items (over 1000) are selected which constitute the 80 percent of the total value of the proposed safety stocks.

Then the rests of the items are classified to 10 types based on the consumption and rejection rate. First items are classified according to their consumption rates and at the second level they are grouped based on their rejection rates. This kind of a classification is used since it is logical to expect that items which have similar consumption and rejection rate will have similar rejection rate distributions. If the items were classified in terms of their supplier or material type (electrical, mechanical, etc.), then the items which have really different rejection rates would be aggregated which would increase the standard deviation of the rejection rate for that class; moreover mean of the rejection rate would not reflect the correct mean. One can argue that classification can be continued at third level based on material type or supplier however then there is not enough data left to fit a distribution.

Classification of the items to fit distribution for the reject rate is shown in Table 6. The cut off points for the consumption are found by assumptions and cut off points for the rejection rates are found by the help of histogram, i.e. When the rejection rates for each classification are becoming intense in an interval, that interval is used as a classification. Note that rejection rates for A class items (consumption rate less than 0.1 per week, Table 6) are most of the time 1 or 0.5 so it is not logical to classify these items based on the rejection rates also. It is important to note here that only items which have a reject in its life cycle are analyzed to fit distribution for reject rate. If all the items were taken into account, it could be the case that an item must have a safety stock; even it is never rejected in the past, which is a costly process in the view of ASML and will make the calculation of safety stock to be considered as less reliable in the eyes of Material Planners.

	Type	Consumption rate (per week)	Reject Rate
1	A	CR<=0.1	all
2	Bl	0.3=>CR>0.1	Rr<0.3
3	Bh		Rr>=0.3
4	Cl	0.6=>CR>0.3	Rr<0.2
5	Ch		Rr>=0.2
6	Dl	1.0=>CR>0.6	Rr<0.1
7	Dh		Rr>=0.1
8	El	CR>1.0	Rr<0.025
9	Em		0.025=<Rr<0.1
10	Eh		Rr>=0.1

Table 6 Classification of the items for the rejection rate distribution

To fit distribution to the reject rates, firstly a number of items are selected for each classification according to total consumption and rejection amount of 67 weeks (04.01.2010-17.04.2011). Then consumption and rejection amount for each 67 weeks is found for each of these items. Afterwards, consumption and rejection amounts are summed for the items in the same classification and rejection rates for each week are found for each classification. Finally these rejection rates are used to fit into a distribution by the help of a program named Easyfit which is embedded into Excel.

Continuous type distributions are selected for the distribution of reject rate, since integer numbers are required for discrete type distributions. Also most common distributions are selected to be fit which follows as:

- Normal
- Exponential
- Weibull
- Gamma

These distributions are considered because it is easier to generate numbers based on them and use in the calculation of safety stock. Kolmogorov& Smirnov and Anderson-Darling statistical tests are used to assess the goodness of fit. However it is preferred to use Anderson-Darling test since Kolmogorov& Smirnov test gives more weight to the center of distribution than at tails and is distribution free in the sense that critical values do not depend on the specific distribution being tested. The Anderson-Darling test makes use of the specific distribution in calculating critical values. This has the advantage of allowing a more sensitive test. Significance level, α is chosen as 0.05 however if the hypothesis is rejected at that level, significance level is decreased until a specific distribution is fit. The results are shown in Table 7.

Type	Consumption rate (per week)	Reject rate	Number of items analyzed	Distribution
A	CR<=0.1	All	95	Normal (0,6681;0,32903)
Bl	0.3=>CR>0.1	Rr<0.3	60	Normal (0,19049;0,24983)
Bh		Rr>=0.3	30	Normal (0,4649;0,41447)
Cl	0.6=>CR>0.3	Rr<0.2	50	Expo (11,045)
Ch		Rr>=0.2	30	Normal (0,5005;0,32784)
Dl	1.0=>CR>0.6	Rr<0.1	140	Gamma (2,9496;0,01581)
Dh		Rr>=0.1	75	Gamma (2,5613;0,0973)
El	CR>1.0	Rr<0.025	80	Weibull (2,035;0,00986)
Em		0.025=<Rr<0.1	100	Weibull (3,12;0,05797)
Eh		Rr>=0.1	30	Normal (0,16456;0,08844)

Table 7 Distribution of reject rates for each classification

However it is identified during this analysis that selecting the specific distribution is too much sensitive to the data, i.e. small changes in the data will lead to different distributions. Moreover, more than one distribution becomes significant in some cases so it is not obvious which distribution to be selected. One can say, exponential distribution must be selected because exponential distribution depends on the first moment of the data (mean) then it is easy to implement and update. However right tail of the exponential distribution goes to infinity which can inflate the safety stock levels, moreover the data doesn't fit into the exponential distribution most of the time (see Table 7).

Based on the discussion in the previous paragraph, generic distribution must be found which can fit for all classifications. In the literature, there are some methods to fit distributions based on the two moments of the data which are mean and standard deviation. It is found out that unique gamma and mixed Erlangian distributions can be fitted to each positive random variable with given first two moments. Moreover the gamma and Erlangian density is always unimodal; that is the density has only one maximum. However According to Tijms (1994), for both theoretical and practical purposes it is often easier to work with mixtures of Erlangian distributions than with gamma distributions. Morevoer Mixed Erlagian distribution has 3 parameters which allow it to fit the data properly, note that gamma distribution has 2 parameters. Then the author proposed to use two moments by a distribution function of a Hyper exponential when the coefficient of variation larger than 1, and a mixture of Erlang distribution functions when the coefficient of variation is smaller than 1. Based on this procedure, the results are shown in Table 8.

Type	Consumption rate (per week)	Reject rate	Number of items analyzed	Distribution
A	CR<=0.1	All	95	**Erlang**
Bl	0.3=>CR>0.1	Rr<0.3	60	**Erlang**
Bh		Rr>=0.3	30	**Hyperexponential**
Cl	0.6=>CR>0.3	Rr<0.2	50	**Erlang**
Ch		Rr>=0.2	30	**Hyperexponential**
Dl	1.0=>CR>0.6	Rr<0.1	140	**Erlang**
Dh		Rr>=0.1	75	**Erlang**
El	CR>1.0	Rr<0.025	80	**Erlang**

Em		0.025=<Rr<0.1	100	**Erlang**
Eh		Rr>=0.1	30	**Erlang**

Table 8 Two moments mixed Erlangian distribution results for reject rate

5.2 Distribution Fitting to the Order Lead Time Tardiness

Distribution of the lead time tardiness is found in the similar way. Pareto analysis is done for the A class items (in ASML terminology; items which are expensive than 10.000€ considered as A class items). 300 A class items are found (over 2000) which constitute 80 percent of the total consumption of A class items. A specific distribution will be found for these items. Rest of the A items are first classified according to number of observation, i.e. number of delivery and continued to be grouped based on their mean tardiness at the third level, also B and C type items are classified with the same procedure. It is important to note that three levels classification is used to fit distribution for tardiness, since there are 20000 items which have lateness in their delivery, there is enough data left to fit a distribution. Remember that it was not possible to classify the items in three levels for reject rate distribution. Classification is presented in Table 9.

Price	Number of Orders	Mean Lateness
A class	**<5**	**All**
	>5	**0<ML=<1**
		1<ML=<3
		ML<3
B&C class	**<5**	**All**
	>5	**0<ML=<1**
		1<ML=<3
		ML<3

Table 9 Classification of the items for the tardiness

To fit distributions to the tardiness, all the orders from the period of 04.01.2010 to 17.04.2011 are analyzed. Tardiness is calculated by the difference between goods received date and required date of the order of the item. However this data is too much contaminated because of the call in and call out of the order. So when the difference is bigger than 10, then the tardiness is calculated by the difference between goods received date and supplier confirmed due date. If this difference is also bigger than 10 for that order, this observation is considered as outlier and neglected during the analysis. Then tardiness's of the all scheduled receipts for each classification are combined and this data is tried to fit into a distribution.

Firstly, again continuous type distributions such as exponential and normal are tried to be fit since if the data is fit into the exponential distribution, it is easy to update the distribution parameters since only the first moment (mean) determines the parameters of the exponential distribution; Thus it is easy to update the safety time of the item. Moreover it could be the case that different distributions can propose different safety time, so it is important to compare these proposed safety times in the simulation model and choose the appropriate ones. Note that this comparison will be made later.

As it can be seen from the Table 10, exponential distribution is fitting for the most of the cases. Moreover analysis shows that also for the items that are found by the Pareto analysis, exponential distribution can be used for the tardiness. As it is already discussed, exponential distribution is useful due to easiness of implementation.

Price	Number of Orders	Mean Lateness	Distribution
A class	<5	All	**Expo(0,50527)**
	>5	0<ML=<1	**Expo(1,8487)**
		1<ML=<3	**Expo(0,595)**
		ML<3	**Norm(3,44;3,38)**
B&C class	<5	All	**Expo(1,0823)**
	>5	0<ML=<1	**Expo(2,0904)**
		1<ML=<3	**Expo(0,6336)**
		ML<3	**Norm(3,69;3,42)**

Table 10 Distribution results for lead time tardiness

To be able to apply the methodology of Tijms (1994), the data must be reorganized to have a good fit. As one can easily understand, the tardiness data consists of mostly zeros and the other positive numbers ranged between 1 and 10. So we can represent the data like that

$$Tardiness\ in\ period\ t\colon\ X_t = 0\ with\ a\ propability\ \theta;$$

$$X_t \neq 0\ with\ a\ probability\ 1-\theta$$

To have a good fit of mixed Erlangian distribution, only positive values must be fitted to the mixed Erlangian. I.e.:

$$Tardiness\ in\ period\ t\colon\ X_t = 0\ with\ a\ propability\ \theta;$$

$$X_t \sim Mixed\ Erlangian\ or\ Hyperexponential\ with\ a\ probability\ 1-\theta$$

If the coefficient of the variation of the data is less than 1, mixed Erlangian distribution is selected, otherwise Hyperexponetial distribution is chosen. In the light of this discussion, the results are shown in Table 11.

Price	Number of Orders	Mean Lateness	Distribution
A class	<5	All	**Erlang**
	>5	0<ML=<1	**Erlang**
		1<ML=<3	**Erlang**
		ML<3	**Erlang**
B&C class	<5	All	**Erlang**
	>5	0<ML=<1	**Erlang**
		1<ML=<3	**Erlang**
		ML<3	**Erlang**

Table 11 Two moments mixed Erlangian distribution results for tardiness

Since two different distributions are derived for the lateness of the distribution, they may propose different safety time values for the same classification. These safety values will be calculated and tested in the simulation model at the subsequent chapter.

5.3 Distribution Fitting to the Consumption Amounts

Although the formulas for safety stock and time are developed for the deterministic demand and it is already said that artificial values for the variance of demand uncertainty during the lead time of an item (σ_d) will be used, still a specific distribution for the demand must be found to mimic the consumption process in the simulation model.

Distribution of the demand is found by fitting a distribution to the consumption rates for each classification (see Table 6). Remember that consumption rates for each classification for 67 weeks are already found (see section 5.1). Note that normal or exponential distribution is considered for the demand due to easiness of the use. Other types of distributions are not analyzed because of the fact that project focuses only the supply uncertainty and demand uncertainty is not in the scope.

6. Simulation Model

As already discussed in Chapter 5, a simulation model is developed to mimic the ASML environment. First, the aim of the simulation model and its scope is discussed. Afterwards simulation model is explained with its input, output parameters, notations, schedule of events and its design. Lastly, verification and validation of the simulation model is explained.

6.1 Aim of the Simulation and Supply Chain in Scope

It is important to make a simulation model which enables to compare different methodologies of safety buffer calculation in terms of service level and cost in different scenarios. Moreover the simulation model can help to understand the nature of the problem and give insights to the decision maker for future improvements.

Since the aim of this project is to define the safety buffer requirements for all buy parts and buy under buy parts, only these items will be considered and remaining stages which are required for modular and end item level will not be taken into account. So the downstream stage of the supply chain which is basically supplier side will be the scope of this simulation model. From the ASML point of view, which is shown in the Figure 7 below, all the production stages such as ASSY and FASY will be ignored.

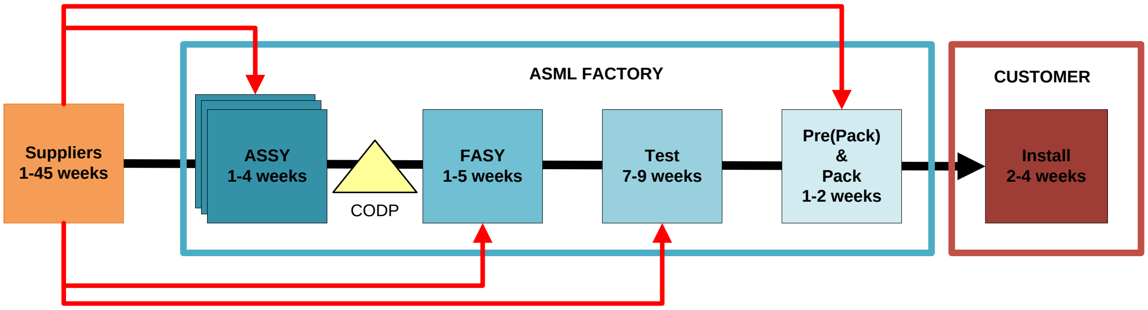


Figure 7 Supply Chain of ASML

6.2 Input & Output Parameters Description

During the analysis phase, by investigating the supply chain characteristics, four important aspects are identified which are essential during this master thesis project: Supply and Demand Uncertainty, Service level & Cost parameters and Inventory Management Methods (see, Figure 8). For inventory management; service level definition and cost parameters are necessary as an input for the inventory optimization and to compare and validate different safety buffer setting methods. Moreover, supply uncertainties which influence the inventory levels, should be incorporated in this simulation model. Scheduled receipt tardiness and random yield are identified as the main causes of supply uncertainty. Furthermore variability of the demand should not be ignored since it can affect the performance of safety stock methodology. Hence random yield, tardiness of the scheduled receipts and demand variability will form the different scenarios. Finally, the right inventory management method must be selected to represent the MRP environment of the ASML.

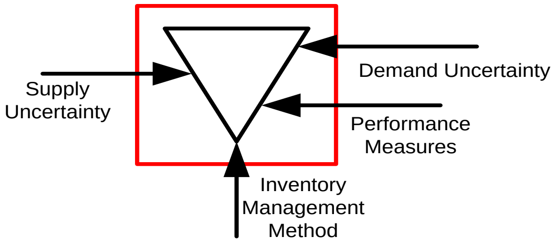


Figure 8 Four main elements of the simulation model

The inventory management method in this simulation is the single echelon base stock model which incorporates supply uncertainty factors. The ASML situation is inherently a multi-echelon multi-item situation. Ideally a simulation model should be developed accordingly. However; it is decided not to do so for the following reasons:

1. Multi-echelon multi-item systems with supply uncertainty are mathematically intractable. Even simple serial two-stage systems require limiting assumptions for a tractable analysis.
2. As the results of this study are implemented, we are of the opinion that tractable results from simple single stage single item models are an excellent starting point from which through careful monitoring simple corrections can be developed to improve on the initial “pragmatic” algorithms.
3. It is impossible to develop a simulation model that mimics the ASML situation. Given 1 and 2, it is proposed to develop a single echelon single item model that represents a single level in the BOM of ASML accurately. This model validates the “pragmatic” algorithms developed in this research.

Safety time will be given as an input to the simulation model and safety stock will be calculated and implemented by the model in each period during the simulation. Service Level is considered as fill rate which is defined as the long run fraction of demand satisfied directly from stock. However this is the long run service level, on the other hand service level in each period basically means the percentage of the jobs that are complemented on time. Lastly only inventory holding cost is taken into account to represent the total and average cost over the simulation period since backlog costs are hard to estimate.

Simulation will be done over H periods which must be bigger than the lead time of the item and also long enough to have reliable results. Hence, it is decided to run the simulation over 10000 periods for each case. Most importantly, random numbers must be generated for the variables which are demand, yield rate and tardiness of the order lead time. These numbers are generated based on the distributions discussed in Chapter 5.

6.3 Assumptions for the Simulation Model

This section presents the assumptions made in this simulation study. The assumptions indicate which aspects are taken into account and which aspects are beyond the scope of the simulation model.

- The model considers buy and buy under buy parts which have been rejected in the past or have some delivery problems.
- Shortages are backordered and will be delivered when inventory is available.
- Planning will be updated on a weekly basis (5 days).
- Resource capacity is not restricting.
- Safety stocks are integers and safety times are in weeks.
- In some cases, demand is known beforehand which means that forecasts are not subjected to the error. This setting will be used to analyze the performance of safety buffer settings in case of deterministic demand. However as already mentioned, there will be cases in which demand is stochastic to be able to analyze safety buffer methodologies.
- Yield uncertainty is modeled as stochastically proportional yield which is to specify the distribution of the fraction of good units (or yield rate). This method permits the

specification of both the mean and variance of the fraction of good items. On the other hand, it forces the distribution of the fraction good to be independent of the batch size.

- Amount of rejected material at the specific period will be calculated by multiplying yield rate with demand instead of scheduled receipts at that specific period. Reasoning of this situation is discussed in Chapter 4.
- Scheduled receipt either comes on time or next periods, it is not the case for the order to come earlier due to the re-out option of the Material Planner.
- Repaired items are not subject to tardiness, i.e. they always come after the specified repair lead time. However if there is no demand and backlog at that period, this order is called out until there is a demand.

6.4 Schedule of Events

Before the equations of the simulation model, it is important to define the schedule of events which must be designed in a way to reflect the environment of ASML correctly. Moreover this issue can influence the performance of the system dramatically. The schedule of the events follows as:

1. Demand arrives.
2. Scheduled receipt arrives (if any) and repaired items come.
3. Ordering decision is given (at the beginning of the period).
4. Yield occurs (at the end of period).
5. Inventory cost and performance is measured.

The update moments are shown in Figure 9. At the beginning of each period the demand occurs and safety stock is calculated based on the formula (2). Then base stock level is calculated. Next scheduled receipts arrive if there is no tardiness and repaired items are received. At this point it is possible to calculate the inventory position of the item for that period. Based on the difference between base stock and inventory position, an order decision is given. Note that all these procedures happen at the beginning of the period. Production is started, and then yield is realized at the end of the period. Here an assumption is made that yield is observed one period later however in reality it depends on the production time and when the product in that process is used. The rejected items are sent to the supplier to be taken back after a repair lead time plus 1 period since this situation happens at the end of the period. At this moment net inventory is calculated, backlog and inventory is found based on it, then service level is computed.

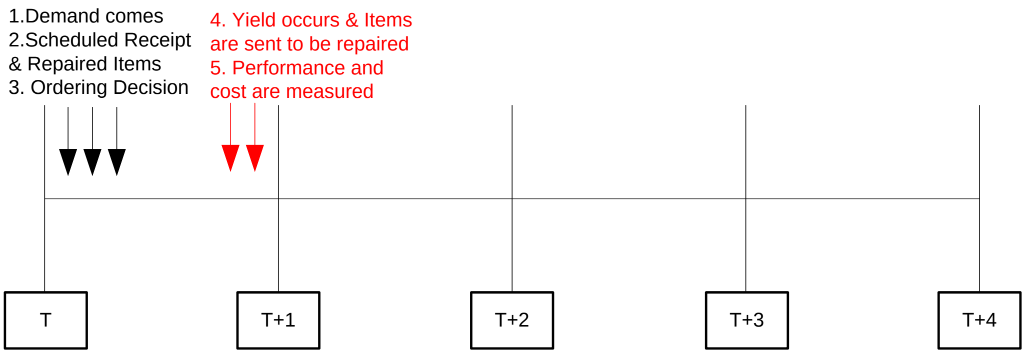


Figure 9: Update moments in time

Notations of the simulation model and design of it i.e. equations are shown in Appendix B and C respectively.

6.5 Verification and validation

Verification is concerned with determining whether the conceptual simulation model (mathematical model) has been correctly translated into a computer program (Excel Visual Basic), i.e. debugging the simulation computer program. Validation is the process of determining whether the simulation model is an accurate representation of the system, for the particular objectives of the study. The verification and validation are discussed consecutively in the next sections

6.5.1 Verification

When building the simulation model, parts of the model are verified separately. This makes easier to trace the problem, when problems were signaled during the verification phase. The model is debugged and afterwards it is checked whether the input data stayed unchanged after the simulation. Moreover correctness of the functions used in the simulation model are checked (i.e. does the function used resemble the mathematical formula in the mathematical model).

6.5.2 Validation

The model validity has been checked firstly by calculating some parameters such as inventory position and base stock level at a specific period by hand and comparing with the outputs of the simulation model. Also it is checked whether the orders arrive after a lead time.

Then the model validity has been assessed by checking whether the simulation model behaves as expected. Various scenarios are used to check the behavior of the simulation model which follows as:

Demand

In case of zero demand, the simulation model does not produce and the amount of backorders and inventory is equal to zero. In case of deterministic demand, the model has no backlog and inventory; moreover service level is equal to 1.

Physical Inventory

In case of zero physical inventory and no outstanding orders at the beginning of the simulation, all demand is backordered at the first weeks and an order is given every week. After a while, backorders are delivered and the system stabilizes. When physical inventory is much greater than the total demand at the beginning of the simulation, the system doesn't order any item until there is not sufficient inventory to fulfill demand.

Deterministic demand and random yield

When the demand is deterministic, in other words forecasts are not subjected to errors and demand is subjected to yield, the model doesn't have any inventory and only have backlog; when there is no safety stock.

Calculating fill rate with a formula

De Kok (2002) develops an exact formula for the fill rate of a single-stage inventory system that uses a general periodic-review base-stock policy. For normal demand, a fill-rate expression is formulated as:

$$P_2 = 1 - \frac{1}{R \times \mu}\left(\sigma \times \sqrt{L+R} \times G\left(\frac{S-(L+R)\times\mu}{\sigma \times \sqrt{L+R}}\right) - \sigma \times \sqrt{L} \times G\left(\frac{S - L \times \mu}{\sigma \times \sqrt{L}}\right)\right)$$

Note that the same notations in the safety buffer formulas and the simulation model are used. In our case R is chosen as one period and there is no safety factor for the demand uncertainty. The results are shown in Table 12. Note that for this case simulation model is run over 20000 periods. As it is already expected, the simulation model and formula give similar fill rates results.

(μ, σ, LT)	Fill rate Formula	Fill rate Simulation
(20,1,3)	96,01%	96,40%
(20,1,4)	95,54%	95,80%
(20,2,3)	92,02%	92,10%
(20,2,4)	91,08%	91,10%

Table 12 Fill rate results of the simulation and formula De Kok (2002)

The results of these scenarios are all in line with the expectations and therefore it is concluded that the simulation model is valid.

7. Results & Comparison of Methodologies

In this section, anticipated performances of the safety buffer methodologies in terms of service level and cost is presented. Firstly, safety time results of two different distributions are shown and compared in a simulation model. Afterwards, an algorithm is developed to calculate the safety stocks (based on formulas 2.1 and 2.2) and associated results are shown for each classification. Then an upgraded algorithm is presented which is also tested in the simulation model. These analyses are done for the deterministic case. Finally the performance of the safety stock methodology (based on formula 2.3) is tested for the stochastic demand case.

7.1 Results of the Safety Time

One can easily understand from the formula of safety time, the calculation basically depends on the distribution of tardiness. Remember that the formula to calculate the Safety Time is:

$$ST_i = \mu_i + \Phi^{-1}(\alpha) \times \sigma_i$$

Basically this method comes from these equations:

$$P(ST > X) = \alpha$$

$$F_X^{-1}(\alpha) = \mathrm{ST}\ (1.1)$$

Here F_X^{-1} is representing the inverse CDF of the tardiness distribution. This formula (1.1) can be used for the distributions except mixed Erlangian, since only positive values are fitted to the mixed Erlangian (see Chapter 5). Remember that distribution of the mixed Erlangian for the tardiness is:

$$Tardiness\ in\ period\ t\colon\ X_t = 0\ with\ a\ propability\ \theta;$$
$$X_t \sim Mixed\ Erlangian\ or\ Hyperexponential\ with\ a\ probability\ 1-\theta$$

Then safety time formula becomes for the mixed Erlangian as following:

$$F_X^{-1}\big(\alpha \times (1-\theta)\big) = \mathrm{ST}\ (1.2)$$

Remember that two types of distribution are found for the tardiness which are:

- Exponential and Normal (Distribution 1)
- Mixed Erlangian (Distribution 2)

It is natural to expect that different distributions will propose different safety time due to the different characteristics of the distributions. Safety times are calculated for a service level of 95% and the results are presented in Table 13.

Price	Number of Orders	Mean Lateness	Distribution (1) ST	Distribution (2) ST
A class	<5	All	6	4
	>5	0<ML=<1	2	2
		1<ML=<3	5	4
		ML<3	9	6
B&C class	<5	All	2	2
	>5	0<ML=<1	2	1
		1<ML=<3	5	3
		ML<3	9	6

Table 13 Safety time (ST) results for different distributions for each classification

As it can be seen from the Table 13, mixed Erlangian distribution always propose less or equal safety times than exponential and normal. That is logical since right tail of exponential is going to infinity and mixed Erlangian distribution has 3 parameters which allows it to fit more proper than Exponential.

However, it is important to make a simulation which can test this different safety time proposals. Note that historical data is used for the lateness and each observation is counted as one unit demand in this simulation. This simulation is run as the number of observations for each classification. There are more than 20000 observations for each classification which makes the simulation results robust and the results are presented in Table 14.

Price	Number of Orders	Mean Lateness	Dist. (1) ST	Dist. (1) SL	Dist. (2) ST	Dist. (2) SL
A class	<5	All	6	96,90%	4	93,80%
	>5	0<ML=<1	2	96,09%	2	96,09%
		1<ML=<3	5	98,59%	4	95,57%
		ML<3	9	100,00%	6	95,15%
B&C class	<5	All	2	91,20%	2	91,20%
	>5	0<ML=<1	2	99,80%	1	91,60%
		1<ML=<3	5	96,09%	3	94,59%
		ML<3	9	98,56%	6	96,00%

Table 14 Anticipated Service Levels of the different Safety Times for each classification

These results show that anticipated service levels of the exponential or normal distribution safety times are always much more than 95 percent service level (except one case) and result in more inventory than needed. However, proposed safety times of mixed Erlangian are performing really close to the 95 service level in most of the cases which results in less inventory. However, the mixed Erlangian distribution needs two moments of the distribution which makes it difficult to update and it is already said that exponential distribution is easier in terms of applicability. But it is strongly suggested to use safety times of the Erlangian distribution for the items that are found by the Pareto analysis (see Chapter 5) due to huge potential saving in terms of inventory cost.

7.2 Algorithm to Calculate Safety Stock and Comparison with the Current Way (MACP)

Remember that the safety stock is calculated with the following formulas for the deterministic demand case:

$$SS_t = \mu_z \times \sum_{i=1}^{LT} D_{t+i} + \Phi^{-1}(\alpha) \times \sqrt{\sigma_z^2 \times \sum_{i=1}^{LT} D_{t+i}^2} \quad (2.1)$$

$$SS_t = \mu_z \times \sum_{i=LT-RLT+1}^{LT} D_{t+i} + \Phi^{-1}(\alpha) \times \sqrt{\sigma_z^2 \times \sum_{i=LT-RLT+1}^{LT} D_{t+i}^2} \quad (2.2)$$

Where as $\Phi^{-1}(\alpha)$ represents the inverse of standard normal cdf; however it is not possible to calculate such a standard normal cdf for the mixed Erlangian distribution. That brings to the point that this formula has to be upgraded so that it can be based on the generic distribution. Inderfurth (2011) calculates the safety stock from

$$Prob\ (\mathcal{E}_{t+L} \leq Safety\ stock) = \alpha$$

Here $\mathcal{E}_{t+L}$ is a random variable that covers the net deviations of outflows and inflows to stock from their means over the complete risk period. In this case, it has an expectation and standard deviation of:

$$\mathrm{E}[\mathcal{E}_{t+L}] = \mu_z \times \sum_{i=1}^{LT} D_{t+i}$$

$$\mathrm{Stdev}[\mathcal{E}_{t+L}] = \sqrt{\sigma_z^2 \times \sum_{i=1}^{LT} D_{t+i}^2}$$

Then the safety stock formula becomes:

$$F_{\mathcal{E}_{t+L}}^{-1}(\alpha) = Safety\ stock$$

An algorithm is developed to find the safety stock based on this formula. This algorithm increases the safety stock by one unit and checks the inverse F (cumulative distribution function) value. As soon as this value is above the target service level, it stops the increasing the safety stock.

This method is compared with the current methodology of ASML which is called as MACP (see chapter 2) for some classifications (see Table 6). The comparison is done for the deterministic demand case with different lead time settings for the target service level of 95%. Note that all the calculations for the safety stock are done based on the predefined the target service level of 95% in this paper. The results are presented in Table 15.

	E class Medium Items		C class High Items		A class Items	
			LT=6			
	SL	**Avg Inv**	**SL**	**Avg Inv**	**SL**	**Avg Inv**
Macp	88,26%	0,7109	52,98%	0,5384	52,98%	0,2899
New	99,36%	1,5826	97,58%	2,2922	100,00%	1,4384
RLT=3	99,60%	1,3000	97,10%	1,7179		
			LT=12			
	SL	**Avg Inv**	**SL**	**Avg Inv**	**SL**	**Avg Inv**
Macp	86,88%	1,0589	48,79%	0,7706	48,48%	0,2623
New	99,35%	2,2497	96,80%	2,9670	99,88%	1,5354
RLT=6	99,27%	1,5812	97,46%	2,2841	100,00%	1,4386
SL= Service Level, Avg Inv= Average Inventory, LT= Lead Time, RLT= Repair Lead Time						

Table 15 Comparison between MACP and new SS method in terms of service level and average inventory

The results show that the new method always reaches the target service level for each classification and different lead time settings. Moreover MACP is performing poorly for the classifications which have a high variability in the reject rate and it is performance is getting worse when the lead time is increased. It can be easily said that current methodology is far away from the reaching the high target service levels like 95% or 90%.

However the biggest problem is that this new method is too safe; i.e. performs much higher than target service level, which is 95% for this case. This problem is obvious in the cases where the rejection and consumption rate is too low. This issue can be explained in such an example that having one unit safety stock may correspond to 60 percent anticipated service level, however increasing it one unit will make it 98 percent. Due to the low consumption, it is impossible to reach the service level of 95 percent in each period.

7.2.1 The Upgraded Algorithm to Calculate the Safety Stock

To be able to solve this problem, an updated algorithm is presented. This algorithm firstly calculates the safety stock until required service level is reached like the first one and notes the associated service level for that amount of safety stock, and then the algorithm decreases the safety stock by one unit and looks at the associated service level. Depending on the absolute differences between target service level and two different service levels, the algorithm chooses the safety stock. To show this algorithm in notation:

$\alpha = Target\ service\ level$

$F_{\varepsilon_{t+L}}^{-1}(\mathrm{SS_h}) = \alpha_h \ \& \alpha_h \geq \alpha$

$\mathrm{SS_l} = \mathrm{SS_h} - 1$

$F_{\varepsilon_{t+L}}^{-1}(\mathrm{SS_l}) = \alpha_l \ \& \alpha_l < \alpha$

$(\mathrm{f1,f2}) = factor\ 1,\ factor2$

if $\mathrm{f1} \times (\alpha_h - \alpha) < f2 \times (\alpha - \alpha_l)$ Then

$Safety\ stock = \mathrm{SS_h}$, otherwise

$Safety\ stock = \mathrm{SS_l}$

Basically this algorithm chooses the safety stock whose service level is closest to the target service level and moreover one can make this algorithm more flexible by playing with the factor levels. If the value of factor1 is assigned more than factor2, then the algorithm will give much more preference to the lower safety stock level.

During the analysis of this algorithm with the simulation model, it is observed that selecting factor levels as equal (1, 1) is not decreasing the service level that much especially for the items which have a low consumption rate. Then the value of the factor1 is increased and associated service levels for each classification are analyzed. If the factor levels are chosen as (5, 1), i.e. giving 5 times more importance to the lower safety stock than the higher one, service levels are becoming nearly as 95% for most of the classifications. The simulation results for the deterministic demand case for the target service level of 95% are shown in Table 16 for 3 classifications. Note that the results for the other classifications (see Table 6) are shown in Appendix D.

	E class Medium Items		C class High Items		A class Items	
LT=6						
	SL	Avg Inv	SL	Avg Inv	SL	Avg Inv
Macp	88,26%	0,7109	52,98%	0,5384	52,98%	0,2899
New	99,36%	1,5826	97,58%	2,2922	100,00%	1,4384
New with Factor	95,76%	0,8285	95,71%	2,0399	98,16%	0,4755
LT=12						
	SL	Avg Inv	SL	Avg Inv	SL	Avg Inv
Macp	86,88%	1,0589	48,79%	0,7706	48,48%	0,2623
New	99,35%	2,2497	96,80%	2,9670	99,88%	1,5354
New with Factor	96,07%	1,4265	97,46%	2,8703	98,28%	0,4532

Table 16 Results of the Updated Algorithm and Comparisons between the other 2 methodologies

Simulation results show that having average service level close to the 95% can bring huge savings in terms of inventory cost (see Table 16). Remember that a Pareto analysis is done to find the items which constitute 80 percent of the total safety stock value against defects (see Chapter 4). It is strongly suggested to use the updated algorithm to calculate the safety stock of these items. For the rest of the items, a first algorithm can be used since the inventory cost for these items will not be that high compared to other items. However, the updated algorithm will be used in the rest of the papers due to its applicability.

Effect of Repair Lead Time

It is an important research topic for the ASML to analyze the effect of repair lead times on the average inventory and select the type of items for which it is worthwhile to make an agreement about a repair lead time with their suppliers. Based on this discussion, an analysis is done to see the reduction of the average inventory when the repair lead time is the half of the actual lead time of the item. The results are shown in Table 17.

	(Lead Time, Repair Lead Time)	
Classification of the item	(12, 6)	(6, 3)
A class	6,95%	3,28%
C class High	23,86%	11,38%
E class Medium	38,33%	17,68%
E class High	34,17%	17,62%

Table 17 Effect of Repair Lead Time on Average Inventory

As one can see from Table 17, repair lead time is effective when the consumption rate is high. This is also logical since when there is no consumption in the upcoming lead time period, repaired items which come early cannot be used for any purpose. Another interesting observation is that reduction of the average inventory is much bigger when the actual lead time of the item is high. So the conclusion is that it will be wise for ASML to determine the repair lead time for the items which have a high consumption rate, longer lead time and expensive.

Sensitivity of the Service Level with respect to Increase in Mean Reject Rate

It can be the case that the distribution of the reject rate is miscalculated during this study or distribution parameters are not updated in the future and the mean reject rate changes. Then it is interesting to analyze the effect of increase in mean reject rate on the service level. During the simulation, reject rate values are generated from the distribution in which the mean reject rate is 10% and 20% more than the original value and safety stocks are calculated based on the original distribution values. The results of this analysis (see Table 18) show that safety stock methodology is still performing well even the mean reject rate increases 10% than the original value. However when this value is 20%, it could be the case that performance of the calculation methodology is far away from the target service level of 95% which implies the importance of maintenance of the distribution parameters.

	Mean Reject Rate Increase	
	10%	**20%**
A class	95,94%	94,71%
C class High	91,50%	82,61%
E class Medium	92,00%	88,53%

Table 18 Sensitivity of the Service Level with respect to Mean Reject Rate Increase

7.2.2 Performance of Safety Stock Methodologies in the case of Stochastic Demand

As it is already discussed in section 4.3.3, it is crucial to develop a safety stock formula for the rejected parts in which the demand is stochastic and remember that it follows as:

$$SS_t = \mu_z \times \sum_{i=1}^{LT} D_{t+i} + \Phi^{-1}(\alpha) \times \sqrt{\sigma_z^2 \times \sum_{i=1}^{LT} D_{t+i}^2 + \sigma_d^2 \times \mu_z^2 + \sigma_d^2 \times \sigma_z^2} \quad (2.3)$$

However, finding the real values of σ_d requires an extensive research and must be the scope of the project which takes into account mainly demand uncertainty. So it is decided to use artificial values of σ_d and test the formula (2.3) by different values of σ_d.

In the simulation, formula (2.1) and formula (2.3) is compared in the uncertain demand case. By this way, it is aimed to show the consequences of the using a formula which is developed with the assumption of deterministic demand in the stochastic demand environment. It is decided to take σ_d as 0.2, 0.5 and 1 and lead time of the item as 6 weeks.

	E class Medium Items		C class High Items		A class High Items	
			$\sigma_d = 0.2$			
	SL	**Inc Inv**	**SL**	**Inc Inv**	**SL**	**Inc Inv**
Formula (2.1)	93,75%	5,48%	92,37%	21,64%	87,17%	25,53%
Formula (2.3)	94,84%		96,18%		97,95%	
			$\sigma_d = 0.5$			
	SL	**Inc Inv**	**SL**	**Inc Inv**	**SL**	**Inc Inv**
Formula (2.1)	92,71%	22,46%	87,77%	24,32%	75,87%	36,00%
Formula (2.3)	95,05%		96,34%		95,04%	
			$\sigma_d = 1$			
	SL	**Inc Inv**	**SL**	**Inc Inv**	**SL**	**Inc Inv**
Formula (2.1)	91,68%	40,51%	80,28%	48,70%	64,73%	20,02%
Formula (2.3)	95,69%		95,05%		96,03%	

Table 19 Performance of the different Methodologies in the Stochastic Demand Case

One can see from Table 19 that low consumption items are affected much seriously from the demand uncertainty in terms of service level and when the demand uncertainty is increased, the performance of the deterministic case formula (2.1) is getting worse which is a logical result. Moreover, it can be easily said that if the σ_d values are calculated, target service level can be reached with the formula (2.3). However it is up to ASML to implement this formula since Table 19 shows the additional investment if safety stocks are calculated with the formula (2.3) instead of (2.1), which can be huge and may not be bearable in some cases.

8. Conclusions and Implementation

This final chapter presents the overall conclusions of this research project based on the results elaborated in the previous chapters, specifically in section 8.1. Hereafter section 8.2 is devoted to the implementation part to enable application of the results of this project to the ASML context. Finally, some further research areas based on this project topic are explored in section 8.3.

8.1 Conclusions

The project definition for this research was formulated as follows:

Develop a methodology to determine the buffer requirements of ASML for all buy and buy under buy parts to compensate for supply uncertainty, namely supplier lead time variability and defective items. Compare this methodology with the current way of working in terms of service level and cost, and develop a tool based on this methodology.

To be able to develop a methodology applicable to the ASML case, the current situation is carefully analyzed. Data analysis enables to quantify the size of the problem, several interviews have been held with the defined stakeholders in order to understand the process and underlying causes of the problem and finally a survey is handed out to the material planners to validate the findings and understand the problem in detailed.

Based on these analyses, current and to-be processes are made and problem definition is done. After understanding the characteristics of the problem and prospective solution, literature analysis is done to be able to gain some theoretical knowledge and find applicable methods from the literature. Unfortunately, we couldn’t find any applicable method directly from the literature, however the methods of Inderfurth (2011) and Hopp & Spearman (1993) are restructured in order to calculate the safety stock and time respectively. Afterwards under some assumptions, distribution of the random variables which are reject rate and order lead time tardiness are found so that proposed methods can be used and implemented.

A simulation model is designed to be able to compare the different methodologies of safety buffer calculation. The analysis shows that proposed methods always guarantee the predefined service level (chosen as 95%); moreover two different algorithms are created in order to calculate the safety stock in a more accurate way. The main conclusions from the simulation studies follow as:

- Proposed safety time of mixed Erlangian distribution is performing close to the target service level in most of the case; whereas safety times based on exponential distribution achieve higher target service level than needed which increases the average inventory. However it could be easily said that Erlangian distribution is harder to update than exponential since it requires two moments of the data and exponential distribution needs only the mean of the data to calculate the safety time.
- Current way of calculation (MACP) is not capable to reach high target service levels such as 90 or 95 percent. Moreover its performance is getting worse in the case of higher variability of reject rate and longer lead time.
- Proposed method of safety stock always reaches the target service level, however it is reaching higher service level than the target (95%) in the long run due to the low consumption rates. So an updated algorithm is developed which reaches the 95% target service level in the long run.
- Using repair lead time for the items which have a high consumption rate, longer lead time and expensive brings substantial cost savings.
- Demand uncertainty may affect negatively the achieved service level required for the rejected items, however additional investment to cover this uncertainty can be huge in some cases and may not be financially feasible.

8.2 Implementation and Recommendations

Implementation of the safety time doesn't require too much effort since it is not required to update safety time as frequent as safety stock; moreover safety time results depends on only one variable which is the distribution of the order lead time tardiness. Then only thing that ASML has to do is to implement the safety time values into MRP data for each item. Another difficulty arises during the updating the values of safety time since parameters of the distribution must be updated and this job is easier if the exponential distribution is decided to be used; but in any case it is not easy to obtain the order lead time tardiness data in ASML due to the corruption of this specific data with re-in and re-out of the orders. So it is recommended to the ASML to solve this data problem and make it automatic, if possible, to get the data of tardiness of order lead time for each item. Then it becomes really easier to update the parameters of the distribution. Note that it is strictly recommended to update the safety times in each quarter due to the possible change in the reliability of the suppliers.

Safety stocks must be updated in each review period because of the changes in the future consumption amount and reject rate of the item which determine the required amount of the safety stock. To be able to use the formula 2 and updated algorithm to determine safety stock requirements, one should find the classification of the item firstly, and then required safety stock amounts can be easily derived based on the future consumption amounts of that item. We believe that it is really easy to implement such a structure into SAP and make it automatic in the future. Likewise safety time, it is crucial to update the distribution parameters of the reject rate distribution and analysis shows that in 20 percent increase in the mean reject rate seriously affects the reached service level.

In this research, 95 percent target service level is used during all the analyses. However, different target service level may be used for each item in the implementation, since the interview and analysis show that price, criticality, where to use the item (before vs. after CODP) and development phase of the item (under development vs. no development anymore) may affect the safety stock of the item so basically these variables can be used to determine the target service level of the item.

As it is already discussed, there are many engineering changes (EC’s) over the life cycle of a product. For the implementation, if the item gets an EC because of its high rejection rate, this item must be considered as a new item and independent of its predecessor. However if the item is upgraded because of another reason, classification of this new item must be determined based on the data of its predecessor.

8.3 Future Research Topics

There are three important research areas defined which can be considered as prospective project topics:

- Multi item safety stock setting with respective to a budget constraint

In the ASML, it could be the case that proposed safety stock values are considered too high in terms of its monetary value especially in the downturn. Then the group leader of the Logistics department gives a budget for the safety stock to the Inventory Control Department. Future research can be done to define a multi item safety stock procedure which has a constraint of total investment to be able to allocate safety stock optimally.

- Multi echelon approach to determine the safety stocks

According to both to-be and current process, it is up to Material Handler to allocate safety stock from the warehouse level to the work centers. However, in the future this task can be the responsibility of the Inventory Control Department. Then a more scientific solution, i.e. multi echelon approach must be developed to determine the safety stock amounts both at warehouse and work center level.

- Safety buffer methodology for both demand and supply uncertainties

This paper mainly considers the uncertainties caused by the supply side of the company. However as it is already discussed, it is really difficult to separate the demand and supply uncertainties in reality since they interact each other. A more detailed study should be done to cover both demand and supply uncertainties simultaneously in the future.

References

Bollapragada, R. & Morton, T. "Myopic Heuristics for Random Yield Problem", *Operations Research Vol. 47, No. 5, September-October 1999, Pages 713-722*

Bollapragada,R. & Rao, U. "Replenishment planning in discrete-time, capacitated, non-stationary, stochastic inventory". *IIE Transactions, Volume 38, Number 7, July 2006 , Pages 605-617 (13)*

Cheng, O., "Safety Stock versus Safety Time in MRP controlled systems". *Management Science Vol. 40, No. 12, Dec., 1994*

De Kok A.G (2002), "Analysis of stock control models for one location with one product". *Working Paper*

De Kok, A.G. & Gudum, C.K. (2003) "A Safety Stock Adjustment Procedure to Enable Target Service Levels in Simulation of Generic Inventory Systems". *Working Paper*

Dolguia A. & Prodhon C., "Supply planning under uncertainties in MRP environments: A state of the art". *Annual Reviews in Control Volume 31, Issue 2, 2007, Pages 269-279*

Enns, S. T., "MRP performance effects due to forecast bias and demand uncertainty". *European Journal of Operational Research, Volume 138, Issue 1, 2002, Pages 87-102*

Hopp, W. C. & Hegedus,M.G. "Setting procurement safety lead times for assembly systems". *International Journal of Production Research Volume 39, Issue 15, 2001, Pages 3459 - 3478*

Hopp, W. C. & Spearman, M. L. "Setting safety lead times for purchased components in assembly systems". *IIE Transactions; Mar 1993; 25, 2; ABI/INFORM Global*

Inderfurth, K. (2011) "Concepts for Safety Stock Determination under Stochastic Demand and Different Types of Random Production Yield". *Working paper*

Mohebbi, E., "A replenishment model for the supply uncertainty problem". *International Journal of Production Economics, Volume 87, Issue 1, 2004, Pages 25-37*

Molinder, A., "Joint optimization of lot-sizes, safety stocks and safety lead times in an MRP system". *International Journal of Production Research, 1997*

Schmitt, A. J. & Snyder, L. (2010) "Infinite-horizon models for inventory control under yield uncertainty and disruptions". *Computers & Operations Research Article in Press, Corrected Proof*

Tijms H. C. (1994), "*Stochastic Models: An algorithmic approach*"

Whybark, D.C. & Williams, J.G. (1976) "Material requirements under uncertainty". *Decision Science 7, Pages 595–606*

Yano, C. A., Lee, H.L. "Lot sizing with random yields: a review". *Operations Research 1993; 43 (2): Pages 311–34.*

Yang, P.C., 2009. "Improve the design of the logistic infrastructure for ASML". PDeng. Eindhoven: Eindhoven University of Technology

List of Abbreviations

Abbreviation	Explanation
12NC	12 digits item referencing number
ASSY	Assembly at ASML
BOM	Bill of materials
CODP	Customer order decoupling point
CT	Cycle time
EC	Engineering change
FASY	Final assembly at ASML
Inv	Inventory
IP	Inventory position
KPI	Key performance Indicator
LT	Lead time
MN	Material notification
MP	Material planner
MPS	Master Production Schedule
MTO	Make to order
MTS	Make to stock
PU	Production unit
Re-in	Reschedule in the delivery date
Re-out	Reschedule out the delivery date
RLT	Repair Lead time
SL	Service level
SS	Safety Stock
ST	Safety Time
WC	Work Center

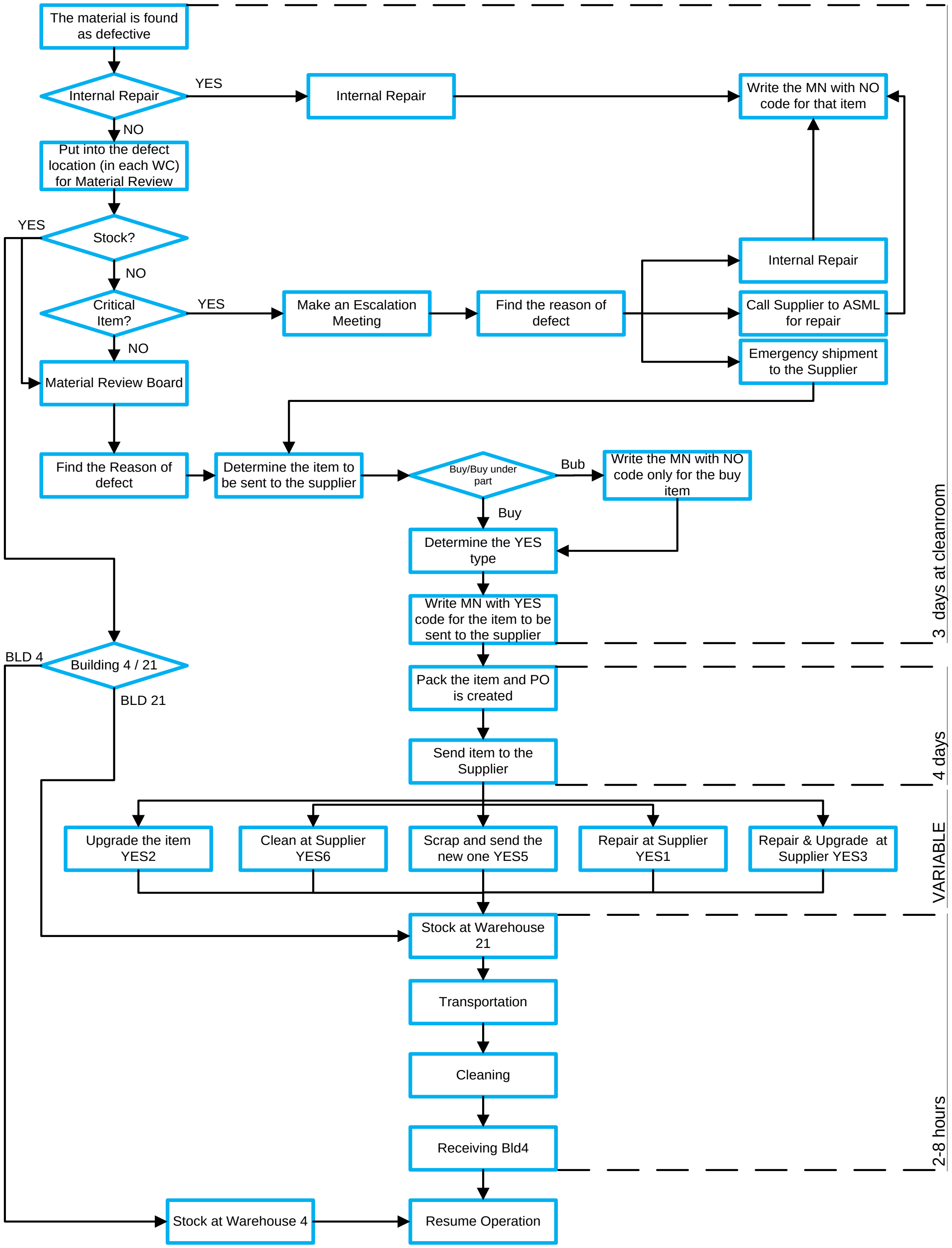
Note: Some additional abbreviations are defined in the tables itself.

List of Figures and Tables

Figures

Tables

Appendix A Operational Flow of Defective Items



Appendix B Notations of the Simulation Model

First of all, it is worthwhile to mention all the notations which are used in the simulation model:

Parameters

$C = \text{ } Cost\ of\ the\ item$

$LT = \text{ } Lead\ time\ of\ the\ item$

$RLT = \text{ } Repair\ lead\ time\ of\ the\ item$

$ST = \text{ } Safety\ time\ of\ the\ item$

$H = \text{ } Simulation\ period\ (without\ taking\ into\ account\ warm - up\ period)$

System Outcomes

$Q_t = \text{ } Order\ quantity\ that\ is\ requested\ from\ the\ supplier\ at\ the\ period\ t$

$AQ_t = \text{ } Actual\ quantity\ that\ is\ received\ from\ the\ supplier\ at\ the\ period\ t$

$B_t = \text{ } Backlog\ in\ units\ of\ item\ at\ the\ end\ of\ period\ t$

$IP_t = \text{ } Inventory\ position\ of\ the\ item\ in\ period\ t$

$NI_t = \text{ } Net\ inventory\ of\ the\ item\ at\ the\ end\ of\ period\ t$

$PI_t = \text{ } Physical\ Inventory\ of\ item\ at\ the\ end\ of\ period\ t$

$BS_t = Base\ stock\ level\ at\ the\ period\ t$

$R_t = Amount\ of\ repaired\ items\ that\ come\ at\ period\ t$

$RA_t = Amount\ of\ rejected\ items\ \ at\ period\ t$

$SS_t = \text{ } Safety\ stock\ of\ the\ item\ at\ period\ t$

Random Numbers Generated

$D_t = \text{ } Demand\ for\ the\ item\ that\ comes\ at\ the\ period\ t$

$X_t = \text{ } Tardiness\ of\ the\ order\ quantity\ at\ period\ t\ (Q_t)(weeks\ late)$

$Y_t = \text{ } Yield\ factor\ of\ the\ demand\ at\ period\ t$

Performance Measure

$SL_t = \text{ } Service\ level\ of\ the\ item\ at\ period\ t$

Appendix C Simulation Model Design

In this simulation model three main types of inventory are distinguished, namely the Inventory Position (IP), Physical Inventory (PI) and Net Inventory (NI). The Physical Inventory is the inventory on stock which is actually free and available, the Net Inventory is physical stock minus Backlog which means it can be negative; and the Inventory Position is the Net Inventory plus the Scheduled Receipts.

At the beginning of the simulation model, safety time is calculated based on the formula (1).

$$ST_i = \mu_i + \Phi^{-1}(\alpha) \times \sigma_i \quad (1)$$

First demand comes, and base stock level can be calculated however before this calculation, safety stock must be calculated with the formula (2).

$$SS_t = \mu_z \times \sum_{i=1}^{LT} D_{t+i} + \Phi^{-1}(\alpha) \times \sqrt{\sigma_z^2 \times \sum_{i=1}^{LT} D_{t+i}^2} \quad (2)$$

$$BS_t = \sum_{i=0}^{LT+ST} D_{t+i} + SS_t \quad (3)$$

After demand occurs, scheduled receipt and repaired items receive, and actual quantity that is received at the beginning of the period is found by:

$$AQ_t = SR_t + R_t \quad (4)$$

Then inventory position is calculated as summation of all the outstanding orders, net inventory of the last period and actual quantity that is received at this period.

$$IP_t = AQ_t + NI_{t-1} + \sum_{i=1}^{LT-1} Q_{t-i} + \sum_{i=1}^{RLT} R_{t+i} \quad (5)$$

Now it is determined how much order should be requested from the customer. But before that, the following formula is used to check whether order is necessary.

$$IP_t < BS_t \quad (6)$$

If this is true, then the amount of the order is decided.

$$Q_t = BS_t - IP_t \quad (7)$$

Then this order becomes scheduled receipt after the lead time plus tardiness period. So simulation model decides the amount of week that the order is late at this moment.

$$SR_{t+X_t} = Q_t \quad (8)$$

All these processes happen at the beginning of the period (week) and at the end of the period rejection occur on the demand and rejected amounts are sent to the supplier to be repaired and sent back the repair lead time plus 1 period later.

$RA_t = Y_t \times D_t \quad (9)$

$R_{t+RLT+1} = RA_t \quad (10)$

Then net inventory, backlog and physical inventory can be calculated with the following formulas. If the net inventory is bigger than zero, it becomes physical inventory (formula 12); otherwise it becomes a backlog formula (13).

$NI_t = NI_{t-1} + AQ_t - RA_t - D_t \quad (11)$

$PI_t = NI_t \quad (12)$

$B_t = -NI_t \quad (13)$

Lastly fill rate (service level) for this period is calculated as follows:

$SL_t = 1 - \frac{B_t}{D_t} \qquad (14)$

However it could be the case that backlog amount is bigger than demand at that period since backlog is cumulated. In this case, service level becomes negative according to this formula but it is assumed to take service level as zero. In another case, demand can be zero for that period, and then it is impossible to calculate service level with this formula. If there is backlog and no demand, service level is calculated as zero and if there is no backlog and demand, service level is not calculated and left as blank for that period.

At the end of the simulation, average fill rate and inventory are calculated by the following formulas subsequently.

$$\overline{PI} = \frac{\sum_{t=1}^{H} PI_t}{H} \quad (15)$$

$$\overline{SL} = \frac{\sum_{t=1}^{H} SL_t}{H} \quad (16)$$

Appendix D Simulation Results of the Items

Class of the Item	Service Level	Average Inventory
B class Low Items	**96,72%**	**1,65**
B class High Items	**97,32%**	**2,88**
C class Low Items	**98,00%**	**1,12**
D class Low Items	**97,46%**	**1,10**
D class High Items	**94,93%**	**2,60**
E class Low Items	**97,35%**	**1,65**
E class High Items	**94,66%**	**3,61**

Note: Lead time is taken 12 weeks and target service level is chosen as 95% for these simulations.