MASTER

Implementation of postponement in a complex assemble-to-order environment
case study in the high-tech supply chain of VDL ETG

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Implementation of postponement in a complex assemble-to-order environment

Case study in the high-tech supply chain of VDL ETG

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Abstract

In this thesis, theoretical inventory levels have been determined to benchmark the current performance with the theoretical inventory levels. The largest delta was found for *project WIP* and this delta was caused by finished wafer handlers on stock waiting to be shipped. Finished wafer handlers have a massive impact on the inventory level due to their high prices. Therefore, the focus of this thesis was to reduce the delta between the theoretical values and the current values for *project WIP*. One of the causes of this stock was the rescheduling of ASML in the final weeks, which was caused by the current order lead time of eighteen weeks. ASML does not know their demand eighteen weeks in advance; this becomes clear approximately six weeks before the start of their production. Consequently, the focus was on reducing the order lead time to a maximum of six weeks. This is achieved by implementing *postponement* and moving the location of the Customer Order Decoupling Point downstream towards ASML. To realize this, a theoretical framework has been applied for the implementation and evaluation of *postponement*. The result was that placing the CODP before Final Assembly proved to be the best option.

Management summary

This report presents the findings of the master thesis project executed at the Atmospheric Wafer Handler chain of VDL ETG.

Problem statement

VDL ETG is active in the manufacturing and assembly of complex, innovative mechatronic systems and modules for businesses. The environment in which these companies operate is very complex in terms of high demand and supply uncertainty; low volumes; complex bill of material structures and dependencies; expensive materials; rapid technological developments; capacity restrictions; and customer lead times that are shorter than integral throughput times.

Currently, the amount of inventory and WIP is high. The amount of WIP and inventory to planned sales is very high compared to other industries, e.g., automotive. VDL ETG extensively tracks their inventory levels via several inventory metrics and turnover ratios. However, these inventory levels currently have no benchmark to which they can be measured. The general, 'the lower, the better' principle is applied. Having quantitative targets increases potential problem detection, trend detection, and results in improved timely and effective decision making (Rachad, Larabi, Nsiri, & Bensassi, 2017). Based on these inventory levels, a solution direction is chosen to reduce the inventory level of VDL ETG. Therefore, the main research question is as follows:

"*How can VDL ETG reduce inventory while maintaining a high service level?"*

Supply chain analysis

In order to gain an understanding of the complex situation, a general analysis is performed. The AWH chain is currently operated as an Assemble-to-Order chain. This means that certain processes are based on an actual order whereas other operations are done on speculation. The production of VDL ETG knows two departments: *Parts* and *Systems. Systems* is further subcategorized as Pre-Assembly and Final Assembly. PRE-ASSY is operated as a job-shop and FASSY is designed as a one-piece flow shop. The capital investment in inventory is divided into two main drivers: *Inventory* and *Work-in-Progress*. *Purchasing* is also monitored but it is not included in stock control since these items have not yet arrived at VDL ETG. *Inventory* and *WIP* are further subcategorized in *anonymous inventory and WIP,* and *project inventory and WIP*. *Anonymous* means operations that are done on speculation are not linked to an actual order. *Project* means that these operations are only done based on a specific order.

VDL ETG applies six logistical models with their suppliers: 1) Make-to-Order, 2) Two-Bin, 3) Fixed Pricing, 4) Logistical Forecast Agreement, 5) Vendor Managed Inventory, 6) Vendor Managed and Owned Inventory. The difference between these models are the owner of the inventory, the frequency and responsibility of the replenishment decision, and the commitment. What model is applied with a supplier is mostly dependent on two things: the trust of VDL ETG towards the supplier and capability of a supplier to follow a forecast.

The commonality analysis shows that the products have extremely high commonality percentages, especially if the XT and NXT product families are analyzed individually. Moreover, it appears that for all left and right configurations, the difference is made during FASSY, in the final three weeks.

Theoretical inventory levels

VDL ETG keeps track of their inventory investment. However, these categories show absolute numbers, no targets are defined to benchmark the current investment in inventory. KPIs do not carry

much value without targets and managers are better able to understand trends, identify potential problems and assist in making quick and effective decisions via the measurement of KPIs.

For the calculation of the average inventory levels based on the current parameters, single-item single-echelon inventory models are used. With these models, all inputs are measured on a local level, and other echelons and entities are not considered. Single-item single-echelon models may appear simplistic, but they are widely used due to the ease of implementation and the limited computational effort that is required (Silver Pyke and Peterson, 1998). All the different logistical models applied with suppliers have different parameters of the (R, s, Q) model. Only VMI and VMOI are not calculated using this model since the replenishment decision is not VDL ETG's responsibility. The WIP levels are determined using Little's Law which calculates the average amount of items in the system.

Once the inventory levels have been determined, a delta analysis can be made comparing the theoretical levels to the actual levels. For confidentiality reasons, the numbers cannot be shown. Therefore, percentages are used. *Project WIP* shows a very large delta of current inventory compared to the theoretical inventory level. Moreover, this group is responsible for 56% of the current inventory investment. This means that the largest inventory delta is caused by this group. Therefore, the focus shifted to *project WIP.* When focusing on this group, it is analyzed that over 98% of inventory is caused by finished wafer handlers that are stocked before shipping.

Table: Difference current inventory investment vs theoretical values

	Anonymous inventory	*Project inventory*	*Anonymous WIP*	*Project WIP*	*Total*
Inventory WH systems	118%	684%	135%	325%	**206%**
Theoretical Inventory	100%	100%	100%	100%	**100%**

Table: Percentage of inventory compared to total

	Anonymous inventory	*Project inventory*	*Anonymous WIP*	*Project WIP*	*Total*
Inventory WH systems	30%	7%	7%	56%	**100%**
Theoretical Inventory	52%	2%	10%	36%	**100%**

Uncertainty analysis

Since the largest inventory delta was for *project WIP*, the uncertainty analysis focused on the customer side. First of all, the demand distribution fitting methodology indicated that the demand follows a Poisson distribution. Because the delivery date is not always in line with the requested date of ASML, both the first requested date as well as the final delivery date were used for this analysis. Both moments followed a Poisson distribution. Because the supply chain of VDL ETG relies heavily on forecasts, the forecast error has been determined per end-item as well.

An analysis of the rescheduling of ASML showed that ASML reschedules very frequently, and often ineffective. The figure below shows on average, how often ASML reschedules an order line. The result was that in 34% of the weeks ASML sends a rescheduling message towards VDL ETG and there were no orders that have not been rescheduled. Finally, it was analyzed that most of these rescheduling messages occurred in the final weeks. The impact of rescheduling on stock level is huge considering that finished wafer handlers are, on average, 30 to 35 days on stock. In a normal ATO chain this is supposed to be zero. Considering the high prices of finished wafer handlers, the impact on the inventory level is massive.

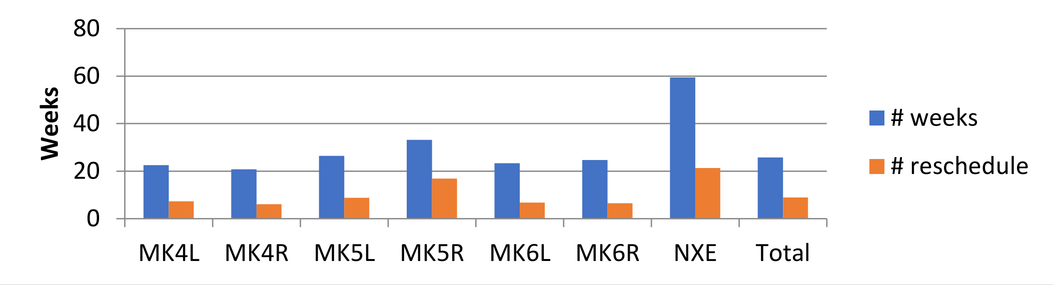

Figure: Rescheduling of ASML per end-item

Diagnosis

Based on the current analysis and the academic literature, a solution direction is chosen. The solution was chosen based on the high inventory delta for *project WIP*, the large amount of rescheduling and the fact that the order lead time is currently eighteen weeks, while ASML only knows their demand six weeks in advance. Therefore, the solution is to reduce the order lead to a maximum of six weeks such that the demand for ASML is clear at their moment of ordering, thus reducing the need to reschedule previously ordered wafer handlers. To realize this, *postponement* is implemented moving the location of the CODP downstream towards the customer.

Solution design

For the solution design the theoretical framework of Ferreira, Tomas, & Alcântara (2015) is followed. This framework consists of three main parts: 1) drivers for *postponement*, 2) implementation of *postponement*, and 3) evaluation of *postponement*.

In the first section the drivers of *postponement* are compared to the situation of VDL ETG to determine the applicability of *postponement* and the potential gains. The main reasons that *postponement* is applicable are the high levels of commonality, both in product and process; the demand uncertainty and specifically, the negative demand correlation; and the increase of information availability during the delay period.

The second section explains the implementation steps that need to be taken to implement *postponement*. First of all, the possible decoupling points need to be chosen. Three potential points were identified: concept 1) after FASSY, concept 2) before FASSY, and concept 3) before PRE-ASSY. After that, the products in scope and the type of *postponement* strategy need to be determined. The focus is on the NXT product family (MK5L and MK5R) because of the high commonality percentage. Moreover, *form postponement* was chosen due to the standardization of upstream processes which is necessary for the implementation. The third step contains the required process changes. For concept 1, both PRE-ASSY as well as FASSY need to be changed to *anonymous*. The second concept requires PRE-ASSY to be operated *anonymously*. The third concept does not require process changes. The final step is the determination of the required safety stock at the CODP. The first concept required the largest buffer due to the stocking of finished wafer handlers, which results in a high buffer value due to their high prices.

The final section contains the performance evaluation of the three concepts compared to the current situation. The performance evaluation framework of Zhang & Tan (2001) is followed. However, since rescheduling was one of the root causes for this solution direction, this needs to be incorporated into the performance evaluation framework. Therefore, the rescheduling cost performance measure of Vieira, Herrmann, & Lin (2003) has been added to the framework of Zhang & Tan (2001). After removal of the irrelevant measures for VDL ETG, the framework shown in the table below was used. The implementation of the performance measurement framework provided the following results, these are also shown in the table. The rescheduling costs are not mentioned specifically since these are incorporated into the inventory level. Both concept 1 and 2 both score best on one category and second on the other. Moreover, concept 1 entails stocking finished wafer handlers. This analysis only focused on one product family. If this is implemented for the entire AWH chain, the result would be that all end-items needed to be buffered resulting in a massive buffer stock and commonality between end-items would not be optimally used. Therefore, the best option is concept 2.

Table: Results adapted performance evaluation framework for VDL ETG. Adapted from Zhang & Tan (2001), combined with Vieira et al. (2003)

Type	Performance measures	Option 1	Option 2	Option 3	Option 4
Asset management	Inventory level | Inventory holding cost | Inventory turns	Concept 2	Concept 1	Concept 3	Current
Customer service	Fill rate | Order lead time	Concept 1	Concept 2	Concept 3	Current

Conclusion and recommendations

The conclusion of the master thesis is that *postponement* can result in a shorter order lead time, reduced rescheduling and a reduced inventory investment. Finally, it is shown that this does not decrease the service level. The recommendations for VDL ETG are:

- Implement the *postponement* strategy of concept 2 to push the location of the CODP downstream towards the customer and to reduce the order lead time to four weeks.
- The current order process is very outdated. Even though it is possible to reduce the order lead time to one week with the current method. This can be reduced much further by automizing the procedure. This can result in a further reduction of the order lead time.
- Implementing *postponement* can be valuable for the XT product family as well. Therefore, the same analysis should be done for the XT product family as well. Moreover, if the new wafer handlers that are currently in development are added on a regular basis, these should be included as well.
- Use the setup of the rescheduling analysis to analyze the requested due date differences in the new situation to determine whether the number of rescheduling messages really goes down as expected.
- The single-item single-echelon inventory levels can be used to regularly check the differences between the theoretical inventory levels and the current inventory levels. It is important that parameter changes are also changed when calculating the theoretical inventory levels.

Preface

This report contains the final report of the master thesis performed at VDL ETG. This marks the end of my study period at TU/e and opens a new chapter in my life. I have learned a lot during this time, both about myself as well as about working life.

I want to thank all my colleagues for creating a pleasant working atmosphere and helping me whenever I had questions. Moreover, I want to thank John for giving me the opportunity to perform my thesis at VDL ETG. A special thanks to Jacobien and Derya for your guidance and involvement in the project. I learned a great deal on business life and the differences between academic work and a real operational environment and it was very pleasant and meaningful to work alongside you.

The completion of this master thesis project was a long and challenging road that could not have been completed without support of the people around me. First of all, I want to thank my family and friends for their support by always lending an ear and helping me put my mind off the thesis when it was necessary. A very special thanks to my girlfriend Maria who unconditionally supported me, put up with me, believed in me, listened to the problems I encountered, and gave useful advice. I could not have done it without you.

Finally, I want to thank my first advisor Dr. Boray Huang for providing me the freedom to conduct my own project. I also want to thank you for the guidance throughout this master thesis project and for the useful advice. Your comments really improved this master thesis. I want to thank Dr. Zümbül Atan for being my second assessor and providing me with useful feedback on my report.

Thanks again everybody, I would not have been able to do this on my own.

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Abbreviation	Meaning
AIC	Akaike Information Criteria
ATO	Assemble to Order
ATS	Assemble To Stock
AWH	Atmospheric Wafer Handler
BIC	Bayesian Information Criteria
BOM	Bill of Materials
CODP	Customer Order Decoupling Point
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
FASSY	Final Assembly
FP	Fixed Pricing
KPI	Key Performance Indicator
LFA	Logistical Forecast Agreement
LL	Loglikelihood
LSL	Lower Stock Level
MLE	Maximum Likelihood Estimation
MOQ	Minimum Order Quantity
MPS	Master Production Schedule
MR	Move Rate
MRP	Material Requirement Planning
MSE	Mean Squared Error
MTO	Make to Order
NB	Negative Binomial
OEM	Original Equipment Manufacturer
PO	Production Order
PRE-ASSY	Pre-Assembly
RS&S	Repair Spare Parts & Services
SS	Safety Stock
USL	Upper Stock Level
VDL ETG	VDL Enabling Technology Group
VMI	Vendor Managed Inventory
VMOI	Vendor Managed and Owned Inventory
WH	Wafer Handler
WIP	Work In Progress

Contents

Chapter 1. Introduction

This report describes the research project performed at VDL Enabling Technology Group (hereafter 'VDL ETG'). VDL ETG is part of the large international business VDL Group. The VDL Group currently consists of 104 companies, spread out over 20 countries with more than 17.000 employees. VDL ETG is an international company with nine locations in five countries and 1.800 employees. VDL ETG is a tier-one design & contract manufacturing partner with global operations. Their customers are 'Original Equipment Manufacturing' (OEM) companies, which have a leading role in high-tech manufacturing equipment and users of advanced production lines. VDL ETG is active in the following markets: semiconductor, solar, medical, science & technology, mechanization and analytical.

VDL ETG is active in the manufacturing and assembly of complex, innovative mechatronic systems and modules for businesses. VDL ETG originates from Phillips Machinefabrieken which was founded in 1900. During the 20th century, it developed into a company operating worldwide and supplied integrated systems to both Philips and other companies. In the year 2000, the name changed from Phillips Machinefabrieken to Phillips Enabling Technologies Group and in 2006, the company was taken over by the VDL group.

VDL ETG mainly produces modules for the lithography industry, but their customer base covers many industries. The substantial economic cycle within the lithography market has a significant impact on the demand for the modules VDL ETG produces. As their products are expensive, fluctuations in demand result in a high cost to the supply chain. A very common feature of this type of environment is the long internal throughput time. The customer order lead time is usually much shorter than the internal throughput time which requires specific modules and subassemblies to be produced based on speculation. Within the internal supply chain of VDL ETG, certain end-items are produced according to an Assemble-To-Order (ATO) structure, while others have a make-to-order (MTO) structure. The environment in which VDL ETG operates is very complicated in terms of high demand, supply, and manufacturing uncertainty. The mission statement of VDL ETG is as follows:

"To reach global leadership as tier-one contract manufacturing partner, by outperforming in delivering mechatronic solutions."

VDL ETG has several different divisions. General management is located in Eindhoven at the headquarters. There are three special divisions that are located in Eindhoven. These divisions are VDL ETG Projects, VDL ETG Precision, and VDL ETG T&D. Besides these three divisions, VDL ETG offers its serial production and assembling services in locations in Almelo, Switzerland, Singapore, Suzhou, and the USA. The scope of this thesis is VDL ETG Eindhoven. The special divisions and the other locations are not within the scope. Unless stated otherwise, VDL ETG Eindhoven is referred to as VDL ETG.

1.1. Problem Context

This section describes the problem context. First, the problem description is provided followed by the research questions that guide the project.

1.1.1. Problem description

The supply chain of VDL ETG is very complex and deals with many factors of uncertainty. Earlier research projects at VDL ETG identified nine sources of supply chain complexities (Arts, 2015; Kamps, 2015). Figure 1 shows the complex uncertainty factors that affect the supply chain of VDL ETG. These factors are:

- Complex Bill of Material (BOM) structures. A BOM can consist of thousands of items, components, and production steps.
- Low demand volume and short life cycles.
- Uncertainty in the due date of demand.
- The internal production of parts has capacity restrictions.
- High yield issues. In high-tech manufacturing, the possibility of yield problems is substantial.
- Variance in supplier lead times. Suppliers experience the same complexity and uncertainty as VDL ETG.
- Throughout time >> customer lead time. A large part of the supply chain is done on speculation.
- A high value of components.
- High, early customized products.

Figure 1: Supply chain complexity at VDL ETG. Derived from Kamps (2015) and Arts (2015)

A distinctive feature of the supply chain is the long internal throughput time compared to the lead times required by the customers. In the case of the wafer handlers ordered by ASML, the order lead time is 18 weeks while the integral lead time for VDL ETG is substantially longer. Therefore, in order to produce within the expected lead time, production has to start long before the order is placed.

Multiple factors cause this long integral lead time. First, component procurement lead times are very long (up to one year). Secondly, the current method to deal with supplier -, demand -, and production uncertainty within VDL ETG is to add safety time. For the wafer handler production, a safety time of three weeks is currently added for all purchase items. This means that all components required for assembly need to be ready three weeks before the internal start date. Safety time is necessary in order to buffer for uncertainties. However, safety time is a containment rather than a solution. Currently, safety time is added without much thought rather than dealing with the root causes. For example, to buffer against poor supplier performance, safety time is added rather than pushing for better supplier performance.

Currently, the amount of inventory and WIP is high. The amount of WIP and inventory to planned sales is very high compared to other industries e.g. automotive. VDL ETG extensively tracks their inventory levels via several inventory metrics and turnover ratios. However, these inventory levels currently have no benchmark to which they can be measured. The general, ‘the lower the better’ principle is applied. Having quantitative targets increases potential problem detection, trend detection, and results in increased timely and effective decision making (Rachad et al., 2017).

The demand date uncertainty is also a significant problem for VDL ETG. The demand uncertainty is mostly about the timing of the demand rather than the volume of the demand. In consensus with the customer, VDL ETG produces according to a certain Move Rate (MR). Once an order enters the system the customer is obligated to the purchase. However, the timing of the purchase is variable. After an order is placed in the system, the customer can re-in (advance) or re-out (delay) their orders. This results in a large amount of uncertainty, both towards suppliers and internal assembly/manufacturing which in term results in high inventory levels.

1.1.2. Research questions

The main research question is:

"*How can VDL ETG reduce inventory while maintaining a high service level?*"

Sub-questions:

- *What are the key characteristics of the supply chain of VDL ETG?*
- *What is the theoretical inventory level based on current parameters?*
- *What uncertainties propagate throughout the internal supply chain of VDL ETG?*
- *How can VDL ETG reduce its inventory investment while maintaining the service level?*
- *How can VDL ETG implement these improvements?*

1.2. Scope

The environment at VDL ETG is very complex. Therefore, defining the boundaries of the scope is essential. First of all, this thesis focuses on the VDL ETG location in Acht (Eindhoven). All other VDL ETG companies are considered out of scope. Secondly, the main focus is on the Atmospheric Wafer Handler (AWH) chain. This chain was chosen because of the pure ATO structure, and the high levels of WIP and Inventory compared to planned sales. The thesis only focuses on tier one suppliers for VDL ETG. This means that only direct suppliers will be incorporated into the analysis. The suppliers of our suppliers are not in the scope (Tier 2 and further).

Parts is a complex manufacturing process that is controlled as a job-shop. Due to the extreme complexity of *Parts* and the focus on the *Systems* department, *Parts* will be modelled as a supplier of *Systems* and will be seen as a black box. Because *Parts* is modeled as a supplier, the suppliers who deliver raw materials to *Parts* are integrated in the lead time of *Parts* production. VDL ETG can, therefore, be seen as a pure assembly manufacturer.

Finally, the AWH chain of VDL ETG also has a Repair Spare Parts & Services (RS&S) department. This department operates independently from the regular AWH chain. Therefore, it is not included in the scope.

Out of scope:

- Repair Spare Parts & Services (RS&S)
- VDL ETG locations besides Acht (Eindhoven)
- Expedition to customer
- Job-shop control at *Parts*
- Tier 2+ suppliers

1.3. Project methodology

This section contains the project methodology and the project approach.

1.3.1. Methodology

Several steps need to be completed to answer the research questions stated in the previous chapter. To structure this project, the problem-solving cycle by Van Aken & Berends (2018) is used. Figure 2 shows this cycle, which describes the structure of theory-informed and design-oriented research projects.

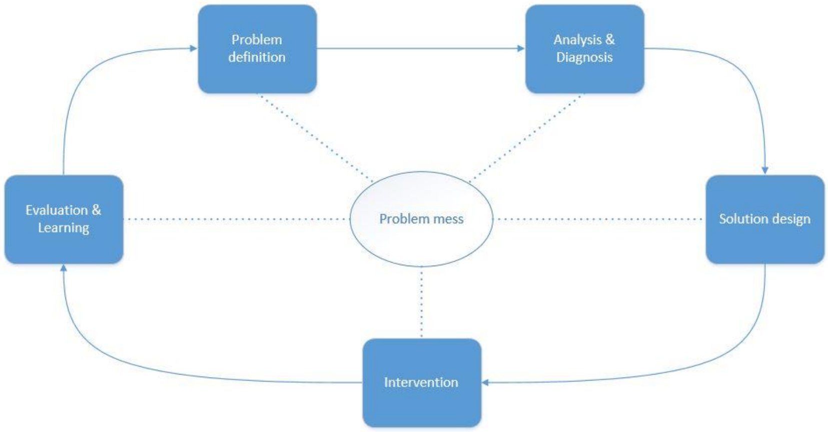


Figure 2: Problem-solving cycle by van Aken et al. (2018)

The first step of the problem-solving cycle concerns the problem definition. The problem definition is stated at the beginning of this chapter and is therefore not further explained. The second step is the analysis and diagnosis. In this step, the current situation of VDL ETG will be analyzed. From this analysis, a diagnosis will be made which serves as the basis for the solution design. The first step in the analysis will be the analysis of the supply chain of VDL ETG concerning the design, the capital investment in inventory, and the logistical model applied with suppliers. After the current analysis, the theoretical inventory levels will be determined to check where the largest gap is between the theoretical inventory level and the actual inventory levels. Subsequently, the uncertainties are analyzed. The diagnosis will be done based on the current analysis after which a solution direction is chosen. The last step entails the implementation of the solution design in the supply chain of VDL ETG.

As preparation for this master thesis, a literature review has been completed reviewing academic literature relevant to the inventory problem at VDL ETG. Throughout the thesis, additional literature will be required that fits better with the specific practical situation at VDL ETG. Besides academic literature, field data will be gathered to acquire contextual information at VDL ETG. This field data will consist of qualitative data regarding the operational processes and the supply chain design and quantitative data from the ERP system.

1.3.2. Project structure

The remainder of this report is structured following the problem-solving cycle of (Van Aken & Berends, 2018). The second chapter contains a general the analysis of the supply chain of VDL ETG focusing on the AWH chain. After that, the theoretical inventory levels and the delta analysis are discussed in the third chapter. The fourth chapter describes the uncertainty analysis. The diagnosis is stated in the fifth chapter combined with a brief literature review of the relevant academic concepts. The sixth chapter contains the solution design. Finally, the conclusion, limitations, and recommendations are provided in the final chapter.

Chapter 2. Supply chain analysis of VDL ETG

This chapter describes the internal supply chain of VDL ETG. First, the general structure is explained. After that, the capital investment in inventory is described with the respective KPIs. Subsequently, the supply side is analyzed, and the logistical models applied with the suppliers are explained. Finally, the commonality between the products is analyzed.

2.1. Supply Chain at VDL ETG

The activities of VDL ETG are producing parts, assembling and integration of modules and systems, and expedition. The core activity is the assembly and integration of modules, which are executed in the *Systems* department. The components used in this department are either produced internally at the *Parts* department or sourced from external suppliers. *Parts* mainly serves as a supplier to the *Systems* department, and occasionally fulfills external demand. *Parts* is designed as a job-shop with detailed production schedules, machine utilization control, and detailed set-up times. The workers are highly specialized and are only able to operate a few machines. Within *Parts*, the machines are considered the bottlenecks and the critical resources of the department, which substantially limits the flexibility of this department. The *Parts* department mostly functions independently. Planning *Parts* receives production orders from the integral planner and develop their production schedule. *Parts* suffers from manufacturing process uncertainty both in throughput time and yield, which results in unmet required lead times and low scores on performance measures.

The *Systems* department is responsible for the assembly and integration of modules. This can be split into Pre-Assembly (PRE-ASSY) and Final Assembly (FASSY). PRE-ASSY is operated as a job shop whereas FASSY is designed as a flow-shop with a one-piece flow. Both PRE-ASSY and FASSY occur in a cleanroom. The *Systems* department has a higher level of flexibility than the *Parts* department because of the generic characteristics of the activities. People are the critical resource within *Systems,* which implies that assembly capacity can be scaled up. This capacity increase can only be achieved long-term due to the required training of the employees. Thus, capacity is restricted in the short term. The suppliers for the *Systems* department are either the *Parts* department or operational procurement who procure materials with external suppliers. Figure 3 shows the structure of the supply chain at VDL ETG, derived from (Kamps, 2015). The one-piece flow shop of FASSY is shown in Appendix A.

The production office consists of *integral planning* and *order management*. *Order management* interacts with the customers about (future) orders and creates the demand plan. They are also responsible for matching demand with supply, and communication with *integral planning* and the customer in case of rescheduling. The final task of the *order manager* is the distribution to the customer. *Integral planning* is responsible for the goods flow control of VDL ETG. They develop a Master Production Schedule (MPS) based on customer demand. This customer demand is based on either a forecast or an actual order. Subsequently, the ERP system of VDL ETG (BaaN) suggests a Material Requirement Planning (MRP) production schedule based on the MPS to the integral planners. *Integral planning* can approve or, if needed, adapt this advice before sending the MRP to *operational procurement* and production. *Operational procurement* is responsible for the procurement of materials and components from external suppliers (both raw material for *Parts* as well as components for *Systems*).

As stated in the first chapter, the customer base of VDL ETG is small. Each customer has a separate supply chain within VDL ETG, and each chain has an *integral planner, order manager, supply chain Engineer,* and *operational procurer*. *Planning Parts* and *production assistants* are general functions and cover all chains.

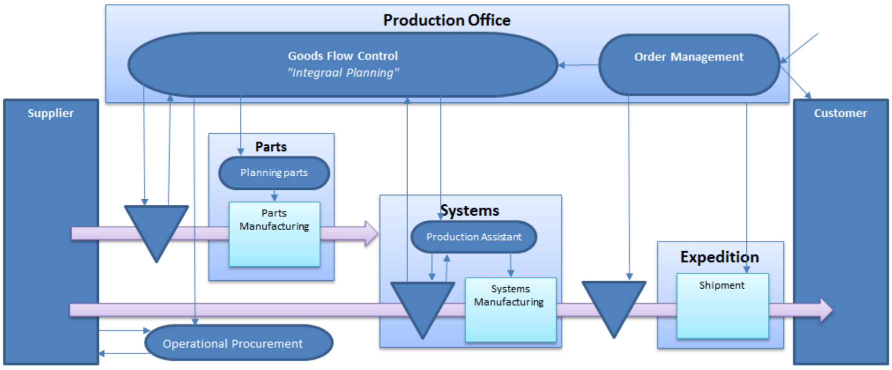


Figure 3: Supply chain structure at VDL ETG. Adapted from Kamps (2015).

2.2. Capital investment in Inventory

VDL ETG distinguishes three types of capital investments in stock:

Inventory. Inventory consists of all components, modules, raw material, and finished goods in the warehouse of VDL ETG.

Work-In-Progress. Work-In-Progress (WIP) of all materials and components which have started a production process but are not yet final.

Purchasing. This contains all the orders which have been purchased and released but not yet arrived at the warehouse of VDL ETG.

These capital investments can be split up into *anonymous* and *project*. The former is based on forecasts and speculation, whereas the latter is based on actual orders. The WIP is also divided into *anonymous* and *project WIP*. *Anonymous WIP* resembles WIP within *Parts* production and anonymous modules in PRE-ASSY. This is still not linked to an order and is therefore *anonymous*. *Project WIP* concerns operations that occur based on a specific order. Per customer chain, the difference between the percentage *anonymous vs. project* differs significantly because of the different supply chain structures.

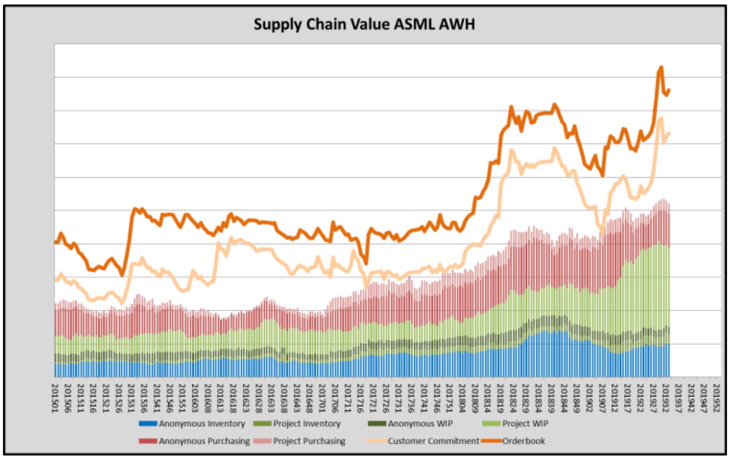


Figure 4: Supply chain value ASML AWH chain.

Currently, inventory levels are high. Figure 4 shows how inventory has built up over the years. The inventory levels have risen substantially since the beginning of 2019. However, when looking into details, it can be seen that only the *project OHW (WIP)* has increased substantially. The remaining inventory groups show relatively stable levels. When looking more closely at the *project WIP,* it can be seen that the increase is mostly caused by an increase in finished goods (further explained in Chapter 4). Because the chain is structured as an Assemble to Order (ATO) system, finished goods are usually shipped immediately to the customer. Therefore, the goal is to have zero finished goods on stock.

2.3. Suppliers of VDL ETG

This subchapter focuses on the supplier side of VDL ETG. VDL ETG purchases the majority of components at suppliers who often have long lead times combined with low delivery reliability. In total, over 500 different companies supply to VDL ETG. These suppliers are grouped into four categories based on the type of product family they supply. These groups are 1) materials, 2) mechanic, 3) OEM, and 4) surface and heat treatment. Within each group, there is a distinction between a strategic supplier, preferred supplier, approved supplier, and not approved supplier. The focus here is only on the suppliers relevant to the ASML AWH chain. Six logistical models are employed with the suppliers of VDL ETG. These models are 1) Make-to-Order (MTO), 2) Two-bin, 3) Fixed Pricing (FP), 4) Logistical Forecast Agreement (LFA), 5) Vendor Managed Inventory (VMI), and 6) Vendor Managed and Owned Inventory.

2.3.1. Logistical models

As stated before, VDL ETG applies six different logistical models with their suppliers. What model is applied depends on several factors. The two most important factors are the trust of VDL ETG towards the supplier and the suppliers' capability to follow a forecast. For example, it is challenging to implement a logistical model other than MTO with a supplier without an Enterprise Resource Planning (ERP) system. Another reason is the power of VDL ETG. VDL ETG might not have the influence to claim price reductions or other logistical agreements with large suppliers. Table 1 shows a summary of the most significant differences between the applied logistical models. The main differences between these models are the owner of the inventory, the responsibility and frequency of the replenishment decision, and the commitment.

Table 1: Characteristics of applied logistical models at VDL ETG

Logistical model	Owner of inventory	Replenishment decision	Commitment
MTO	VDL ETG	VDL ETG	Purchase order
Two-Bin	VDL ETG	Supplier/VDL ETG	No commitment
Fixed Pricing	VDL ETG	VDL ETG	Forecast Commitment
LFA	VDL ETG	VDL ETG	Forecast Commitment
VMI	VDL ETG	Supplier	Forecast Commitment
VMOI	Supplier	Supplier	Forecast Commitment

Make-to-Order

The Make-to-Order (MTO) logistical model is the most commonly employed model at VDL ETG. The question of whether to use MTO depends more on the trust and capabilities of the supplier than the value of the product. As stated before, certain suppliers cannot work based on a forecast. However, the supplier can still receive a forecast for information purposes. VDL ETG is committed once a purchase order is placed. Items that are ordered according to the MTO logistical model can either be ordered using MRP or manually. The order quantity of the MRP ordered items are based on an Economic Order Quantity (EOQ). However, the EOQ is a deterministic formula which ignores time variability and assumes a fixed demand (Silver, Pyke, & Peterson, 1998). For the manually ordered items, there is no standard order quantity. Therefore, the order quantity differs per order.

Two-Bin

With the Two-Bin logistical model, there are Two bins present at VDL ETG. One bin is in use, and the other bin is full. The bins are checked weekly. Once the first bin is empty, a new batch (equal to one bin size) is ordered. Within VDL ETG, two different two-bin systems are applied: 1) Two-Bin VMI, and 2) Two-Bin MTO. The difference is the entity responsible for checking the bins and the replenishment. For Two-Bin VMI, the supplier is responsible for this, whereas VDL ETG is responsible for Two-Bin MTO. Two-Bin only applies for items with a deficient value per piece (e.g. screws, bolts, and nuts). Finally, the size of the items should be sufficiently small that three to six months of demand fits in a bin.

Logistical Forecast Agreement

The next model is the Logistical Forecast Agreement (LFA). The focus of LFA is on products with high value and a regular demand/production. LFA is applied for companies with a similar structure and capabilities of VDL ETG. VDL ETG sends a forecast to these suppliers to which VDL ETG is committed. The commitment agreement under LFA consists of a full commitment zone and a limited commitment zone. The full commitment zone is always 100%. The lower commitment zone differs but is usually around 50%. The full commitment zone and lower commitment zone are longer than the call-off order period meaning that VDL ETG is already committed before an order is called off.

With LFA, an order call-off period of one or two weeks is used. These items usually have a supplier lead time that is larger than the call-off order period towards VDL ETG. Therefore, the supplier can choose to produce part of the product based on a forecast, i.e. the suppliers determine the customer order decoupling point. This means that the supplier can choose to produce finished goods based on a forecast, but the supplier can also produce semi-finished goods and make the final assembly after an order is called off. This is because the supplier also carries risks when producing on a forecast to enable the short lead time of the call-off period.

Fixed-Pricing

Fixed-Pricing (FP) can be seen as a lighter version of LFA. For FP, a fixed pricing agreement is made for three months. These prices are based on optimal production volumes at the supplier. It is important to note that the orders placed by VDL ETG do not necessarily have to be of this size. A commitment zone is specified under a FP contract. Within this zone, VDL ETG is obligated to purchase in agreement with the forecast. FP can best be implemented for products that are produced in batches (e.g. mechanical products). Moreover, the suppliers' willingness is an important factor here, since they might not want to offer price reductions. Fixed pricing is mostly applied to items with a low to medium value.

Vendor Managed Inventory

The last two models are the models with the highest level of supply chain integration. With these models, the relationship with the supplier is better described as a partnership. Vendor Managed Inventory (VMI) means that the supplier manages the inventory for VDL ETG. The ownership, however, still rests with VDL ETG. VDL ETG no longer places orders at the supplier; the supplier is responsible for this. A predetermined upper and lower stock level (USL and LSL) are set. The supplier is obligated to keep the stock levels between these two levels. Instead of working with orders, the supplier works solely according to the forecast of VDL ETG. The commitment under VMI works in a similar sense as for LFA with a full and lower commitment zone with their respective percentages. However, because no orders are placed, there is no call-off order period defined. Four criteria exist to determine the applicability of VMI for VDL ETG: insensitivity to changes, plan-driven production (flow production), continuous demand, and reliability of the supplier both in logistics as well as quality.

Vendor Managed and Owned Inventory

Vendor Managed and Owned Inventory (VMOI) is the last logistical model implemented at VDL ETG. VMOI is very similar to VMI. The only difference is the ownership of the inventory. With VMOI the ownership remains with the vendor, despite the stock being located at VDL ETG. The payment of the item is done when VDL ETG uses the product. Because the supplier is the owner, the financial holding costs are transferred to the supplier. Same as for VMI, an upper and lower stock level is determined. Due to the ownership of VM(O)I, it is expected that under VMI, the suppliers keep the stock level closer to the USL, whereas, under VMOI, it is probably held closer to the LSL.

2.4. Commonality

This section describes the analysis of the commonality between the end-items. Commonality is characterized as the number of parts/components that are used by more than one end-product (Ashayeri & Selen, 2005). There is exist many commonality measures. This thesis compared two measures: the degree of commonality index (Collier, 1981) and the percentage of component commonality (Wacker & Treleven, 1986). The degree of commonality index calculates the average number of products for which a component or part is used. The percentage of component commonality calculates the relative number of parts/components that is common. The percentage of component commonality is used for this thesis since it provides better insight into common components (Wacker & Treleven, 1986). The percentage of component commonality can be calculated as followed (adapted from Wacker & Treleven (1986)).

$$Commonality\ percentage_g = \frac{d_g}{d_t} \tag{1}$$

$$d_g = Number\ of\ components\ in\ group$$

$$d_t = Total\ number\ of\ components$$

Component group indicates a group of items specifically for one or multiple end-items. These groups are stated in Figure 6. This analysis includes all current end-items, excluding the NXE Wafer Handler (WH). This WH shows large differences compared to the other product families. Moreover, the NXE WH is not delivered directly to ASML, but internally to VDL ETG. The AWH chain considers two main product families: the NXT and the XT. Figure 5 shows what WHs are part of what product families. The MK5L and MK5R are part of the NXT product family. The MK4L, MK4R, MK6L, and MK6R are all part of the XT family. The MK6 is considered an extension of the MK4 and is, therefore, part of the same family.

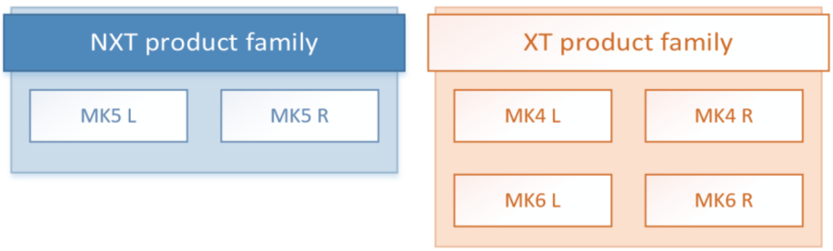


Figure 5: Product families wafer handlers

It is important to note that phantom items are excluded from this analysis as they are not 'real' items, and thus do not exist in inventory. Both the total commonality percentages as well as the commonality difference per internal process have been analyzed. This has been categorized as materials for Parts, Parts, materials for PRE-ASSY, PRE-ASSY, materials for FASSY, FASSY, and total.

	Material For Parts	PARTS	Material for PRE-ASSY	PRE-ASSY	Material for FASSY	FASSY	TOTAL
Commonality group	%	%	%	%	%	%	%
Common	53%	36%	36%	36%	71%	32%	50%
MK5	26%	33%	44%	33%	10%	20%	26%
MK4 - MK6	12%	20%	12%	23%	11%	19%	14%
MK4 - MK5	4%	6%	3%	5%	1%	3%	2%
MK6	5%	6%	4%	3%	3%	6%	4%
MK5 - MK6			0,3%				0,1%
MK4						1%	0,1%
MK4 L - MK6 L					0,2%		0,1%
MK4 R - MK6 R					0,2%		0,1%
uniek MK4 L					0,2%	3%	0,4%
uniek MK4 R					0,2%	3%	0,4%
uniek MK6 L					1%	4%	1%
uniek MK6 R					1%	4%	1%
uniek MK5 L					1,2%	3%	0,7%
uniek MK5 R					1,0%	3%	0,6%
Grand Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Figure 6: Commonality analysis of current MPS-items (excluding NXE WH)

The total commonality percentage for these items is 50%. Figure 6 shows the commonality for the wafer handlers and where the differences are made in the supply chain. As can be seen, the difference between MK4, MK5, and MK6 is made immediately in the materials required for Parts and PRE-ASSY. After that, the biggest commonality groups are the items that are specific to the MK5 and the items that are specific for the MK4 and MK6. As stated above, the MK6 is an extension of the MK4. Therefore, these items show much commonality. The group of items that is specific for both the MK4 and MK5 is tiny (2%). The difference between left and right configurations is only made in the final three weeks of the assembly process. Currently, the order lead time is eighteen weeks for all WHs which means that the wafer handler configuration of an order is determined long before this difference is made in production. Wacker & Treleven (1986) stated that commonality for all product families should be determined. Therefore, the product families are also analyzed separately.

First, the NXT product family is analyzed. This family consists of two end-products: MK5L and MK5R. This product family shows an extreme overall commonality percentage of 98.3%. The difference between these configurations is only made in FASSY, which happens in the final three weeks of the manufacturing process. An order lead time of eighteen weeks does not make much sense with respect to the results of the commonality analysis. In the fifteen weeks before FASSY, allocation decisions are already made where this is not necessary. Figure 7 shows the commonality of the NXT family.

	Material For Parts	PARTS	Material for PRE-ASSY	PRE-ASSY	Material for FASSY	FASSY	TOTAL
Commonality group	%	%	%	%	%	%	%
Common	**100%**	**100%**	**100%**	**100%**	**97%**	**90%**	**98%**
MK5 L					**1%**	5%	1%
MK5 R					**1%**	5%	1%
Grand Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Figure 7: Commonality analysis NXT family

The second family is the XT family consisting of the MK4 and MK6 configurations. As stated before, the MK6 is an extension of the MK4 and therefore shows high commonality. Figure 8 shows the commonality analysis of the MK4 and the MK6. The group of common components is 88%. However, the MK4 and the MK6 require different products that are made in *Parts* and PRE-ASSY, but this number is limited. The configuration differences are again made in FASSY.

	Material For Parts	PARTS	Material for PRE-ASSY	PRE-ASSY	Material for FASSY	FASSY	TOTAL
Commonality group	**%**	**%**	**%**	**%**	**%**	**%**	**%**
Common	89%	83%	87%	88%	93%	69%	88%
MK4	5%	8%	5%	7%	1%	5%	4%
MK6	6%	8%	8%	3%	3%	8%	6%
MK4 L - MK6 L					0,3%		0,1%
MK4 R - MK6 R					0,2%		0,1%
uniek MK4 L					0,2%	4%	0,4%
uniek MK4 R					0,2%	4%	0,4%
uniek MK6 L					1%	5%	1%
uniek MK6 R					1%	5%	1%
Grand Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Figure 8: Commonality analysis XT product family

To conclude, the commonality within the wafer handler department is significant, especially when the two product families are analyzed individually. The current order lead time of eighteen weeks results in modules being produced or assembled for a specific end-item where this is not yet needed. Therefore, the commonality is not optimally used in the current situation.

Chapter 3. Theoretical inventory levels

This chapter explains the theoretical inventory levels for the AWH chain of VDL ETG based on the current parameters. As stated before, VDL ETG keeps track of the investment in inventory via a stock control file. Here, the capital investment in inventory is divided into four categories: *anonymous inventory, anonymous WIP, project inventory,* and *project WIP*. Purchasing is not included in this document since these items have not yet arrived at VDL ETG. However, these categories show absolute numbers, no targets are defined to benchmark the current investment in inventory. KPIs do not carry much value without targets and managers are better able to understand trends, identify potential problems and assist in making quick and effective decisions via the measurement of KPIs (Rachad et al., 2017). This chapter first describes how the theoretical average inventory levels are determined starting with *anonymous inventory* followed by *project inventory*. Subsequently, the *WIP* inventory levels are explained. Finally, the current inventory levels are compared to the theoretical values to determine how VDL ETG performs and where the biggest improvement possibilities lie.

3.1. Anonymous Inventory

Anonymous inventory comes either from purchased materials or manufactured components. The section is divided into purchased items and manufactured items.

3.1.1. Purchased items

For the calculation of the average inventory levels based on the current parameters, single-item single-echelon inventory models are used. With these models, all inputs are measured on a local level, and other echelons and entities are not considered. Single-item single-echelon models may appear simplistic, but they are widely used due to the ease of implementation and the limited computational effort that is required Silver Pyke and Peterson (1998).

As stated above, a single-item single-echelon inventory model is used. These are called the classical inventory models. In general, the (R, s, Q) model best represents an MRP controlled system like VDL ETG since this implicitly implied in many MRP systems (Alatas, 2017). Each logistical model that is applied with the suppliers of VDL ETG is basically an (R, s, Q) policy with different parameters. For the determination of the average inventory on hand, formula 7.37 is used from the book of Silver et al. (1998).

$$E[OH]_i = Expected\ average\ on\ hand\ stock\ for\ item\ i$$

$$Q_i = Order\ quantity\ for\ item\ i$$

$$ST_i = Safety\ Time\ in\ days\ for\ item\ i$$

$$SS_i = Safety\ Stock\ for\ item\ i$$

$$s_i = reorder\ point\ item\ i$$

$$R = Review\ Period$$

$$a_{ij} = required\ amount\ of\ item\ i\ in\ enditem\ j$$

$$D_i = daily\ demand\ for\ item\ i\ for\ one\ week$$

$$MR_j = move\ rate\ per\ week\ for\ end\ item\ j$$

$$U_i = Undershoot\ item\ i$$

$$\hat{x}_i^{R+L} = Demand\ for\ item\ i\ during\ lead\ time\ L\ (in\ days)\ and\ review\ period\ R (in\ days)$$

$$\hat{x}_i^{R+L} = D_i * (L_i + R_i) \quad (2)$$

$$s_i = \left(SS_i + \frac{ST_i}{5} * D_i\right) + \hat{x}_i^{R+L} \quad (3)$$

$$D_i = \sum_{j=1}^{m} a_{ij} * \frac{MR_j}{5} \quad (4)$$

$$E[OH]_i = \frac{Q_i}{2} + \left(s_i - \hat{x}_i^{R+L}\right) \quad (5)$$

Combining the formulas above results in the following formula for the determination of the average stock level.

$$E[OH]_i = \frac{Q_i}{2} + \left(\left(SS_i + \frac{ST_i}{5} * D_i\right) + \hat{x}_i^{R+L} - \hat{x}_i^{R+L}\right) \quad (6)$$

Formula (6) assumes a fixed deterministic demand. To relax this assumption, undershoot needs to be incorporated. This an important concept to include stochastic demand. Undershoot is the difference between the reorder level and the inventory position at the moment of ordering. Figure 9 shows an example of undershoot (De Kok, 2002).

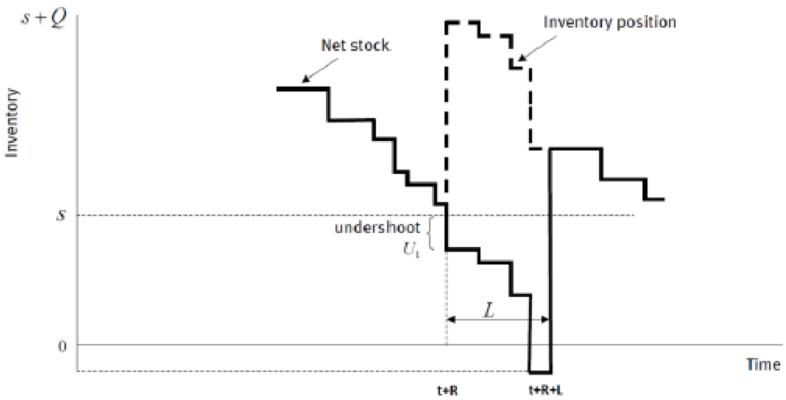


Figure 9: Example of undershoot (de Kok, 2010)

The undershoot can be calculated using the work of Thijms (1986). These are derived and adjusted from De Kok (2002).

$$E[U_i] = \frac{\alpha + 1}{2\lambda} \quad (7)$$

$$\alpha = \frac{E^2[D(0,R)]}{\sigma^2[D(0,R)]} \quad (8)$$

$$\lambda = \frac{\alpha}{E[D(0,R)]} \quad (9)$$

The problem of the formulas of De Kok (2002) is that they assume one end-item demand and no component commonality. This is not the case for VDL ETG. Therefore, the undershoot formulas have to be extended to include commonality and multiple end-item demand. This results in the following formulas for $E^2[D(0,R)]$ and $\sigma^2[D(0,R)]$. The mathematical proof of this extension is shown in appendix B. The effect of commonality on the expected undershoot is shown in appendix C. Here it is shown that this is an exponentially decreasing function as the percentage of commonality increases.

$$E[D(0,R)]^2 = \left(R\sum_{j=1}^{n}[a_{ij}\mu_j]\right)^2 \quad (10)$$

$$\sigma^2(D(0,R)) = R\left(\sum_{j=1}^{n} a_{ij}^2\sigma_j^2 + \sum_{j=2}^{n}\sum_{k=1}^{j-1} 2\rho_{jk}a_{ij}a_{ik}\sigma_j\sigma_k\right) \quad (11)$$

After the undershoot is determined, it can be included in the average inventory on stock calculation. This results in the following formula.

$$E[OH]_i = \frac{Q_i}{2} + SS_i + \frac{ST_i}{5} * D_i - E[U_i] \quad (12)$$

Another assumption is the fixed replenishment lead time, which is not the case at VDL ETG. Therefore, this assumption also needs to be relaxed to apply the formula at VDL ETG. This can be done by including variable lead time using the work of (De Kok, 2002). The formula for the expected inventory on hand becomes:

$$E[OH_i] = s_i + \frac{Q_i}{2} - E\left[D\left(\tau_1, \tau_1 + LT_{1,i}\right)\right] - E[U_i] \quad (13)$$

$$s_i = E[D(0,L)] + SS_i + \frac{ST_i}{5} * D_i \quad (14)$$

So, the inventory on hand formula which includes stochastic lead time and demand becomes:

$$E[OH_i] = E[D(0,L)] + SS_i + \frac{ST_i}{5} * D_i + \frac{Q_i}{2} - E\left[D\left(\tau_1, \tau_1 + LT_{1,i}\right)\right] - E[U_i] \quad (15)$$

In chapter 2, it was explained that the MRP purchased items use one of the logistical models applied at VDL ETG. A small portion of items uses manual purchasing without a fixed lot size. For the manually purchased items, there is no standard order quantity. Therefore, it is difficult to estimate an inventory value for these items. Moreover, these manually purchased items only account for 1.5% of the total inventory investment. Consequently, the decision was made to drop these items from the analysis. Items that are ‘grab stock’ are also removed, as no inventory value is assigned to these items by VDL ETG. Their stock levels are kept artificially high and are assumed to always be on stock. For all logistical models, the average expected on hand stock can be analyzed using the formulas above.

Make-to-Order

For items that are purchased using the MTO logic, the order quantity can either depend on the Economic Order Quantity (EOQ) or the Minimum Order Quantity (MOQ). No safety stock is used for MTO items, only safety time. The safety time buffer accounts for the safety time (in weeks) multiplied by the (weekly) move rate. The integral planner has approximately three order moments per week. This results in a review period of two days.

$$R = 2\ days$$

$$Q_i = EOQ\ or\ MOQ$$

Fixed pricing

With FP, orders are placed on a monthly basis. Therefore, the review period is 20 days. The order quantity is dependent on the expected move rate for a month.

$$R = 20\ days$$

$$Q_i = D_i * 20$$

Logistic Forecast Agreement

With LFA, items are ordered on a weekly basis. The order quantity, therefore, is only dependent on the weekly move rate. Because items are ordered on a weekly basis, the review period is five days.

$$R = 5\ days$$

$$Q_i = D_i * 5$$

Vendor Managed Inventory

VMI is an entirely different logistical system than the abovementioned ones, the (R, s, Q) model is not used in this case. Moreover, the ordering process is not the responsibility of VDL ETG anymore. Order quantities are therefore not important for the determination of the average inventory. A lower stock level (LSL) and an upper stock level (USL) are determined, and the average of these levels form the average inventory level. The LSL is equal to the Safety Stock (SS). Theoretically, these concepts are not interchangeable. Normally, inventory is not allowed to be lower than the LSL. SS usually serves as a buffer for high demand periods, implying the stock levels below the SS is allowed. Because VDL ETG uses these terms interchangeably, this thesis will do the same.

$$E[OH]_i = \frac{LSL_i + USL_i}{2} \tag{16}$$

Two-Bin and Vendor Managed and Owned Inventory

The final two logistical models are Two-Bin and VMOI. No inventory value is assigned to Two-Bin items and these are therefore not considered. Finally, VMOI is not included. Under VMOI, the supplier (vendor) is still considered the owner of the inventory, so the costs of inventory are not incurred by VDL ETG. VDL ETG only becomes the owner of the material when it is consumed.

3.1.2. Manufactured items

Anonymous inventory also comes from manufactured components. After the batch is produced at *Parts,* it goes into the *anonymous inventory*. Therefore, the average on-hand stock with a manufactured product is dependent on the batch size in which the items are manufactured combined with the safety parameters. The same formulas are used for the determination of the average stock on hand. The batch sizes are also calculated using the economic order quantity.

$$R = 2\ days$$

$$Q_i = optimal\ batch\ size$$

3.2. Project inventory

For the AWH chain, *project inventory* comes only from manufactured/assembled products that are stored, i.e. no *project inventory* comes from purchasing components. Because the items are produced specifically for a project, and the order quantity Q_i is often one. Therefore, the average theoretical inventory is mostly dependent on the safety time. The theoretical levels for *project inventory* can be determined using the same formulas as for *anonymous inventory.*

3.3. Work-in-Progress

An item is counted as Work-in-Progress (WIP) if its either being produced in *Parts* or assembled in *Systems*. Before or after, it either counts as *anonymous* or *project inventory*. The main driver is the number of batches that are in production. This is determined using Little's Law (Little & Graves, 2008) via which the average amount of items that are in WIP can be calculated.

$$T_i = MR_i * L_i \tag{17}$$

$$T_i = average\ amount\ of\ WIP\ items\ i\ in\ the\ system$$

$$L_i = Manufacturing\ Lead\ time\ in\ weeks\ of\ item\ i$$

Once the average amount of items in the system is determined, the average WIP costs can be calculated. From the moment a batch production starts, material costs for the entire batch is counted as capital investment in inventory. The processing and outsourcing costs are then gradually added as the batch progresses. The processing and outsourcing costs together are the added value. It is assumed that the added value is added at a constant rate. The average WIP costs per item are therefore

$$WIP\ costs_i = T_i * \left(Material\ costs_i + \frac{Added\ value_i}{2}\right) \tag{18}$$

The WIP is identical for both *anonymous* and *project WIP*.

3.4. Delta analysis expected inventory

After applying the formulas above, an analysis is made comparing the expected inventory on hand calculated using single-echelon single-item classic inventory models of Silver et al (1998) to the current capital investment in inventory by VDL ETG. This is useful to see where the biggest disturbances are in the internal supply chain.

First, there is a distinction between wafer handler systems and wafer handler spares (RS&S). RS&S is a different department that is responsible for repair and spare items towards ASML. The stock control of VDL ETG does not distinguish between the two. The scope of this thesis is solely on wafer handler systems. Therefore, it is checked what number of items are due to wafer handler systems and what is due to RS&S. This is done by comparing the BOMs of all current end-items with the measured stock investment. Due to confidentiality, the results are not shown. However, it is important to note that inventory items of RS&S are not included in the analysis. It is important to note that certain items appear both in RS&S as well as in regular systems. Since it is impossible to distinguish between the two for these items, it is assumed that RS&S does not account for these items.

When applying the abovementioned formulas, the theoretical inventory value can be determined. Due to confidentiality, the theoretical value cannot be displayed. Therefore, the theoretical number is stated as 100%, and the current values are shown as percentages compared to the theoretical number.

Table 2 shows the result of the expected inventory on-hand delta analysis. As can be seen from the table, the current investment in inventory is 2.06 times the theoretical value. The largest difference is in *project inventory* with a difference ratio of 6.84. However, the value of *project inventory* is very small compared to the total value. To better comprehend the results without breaching confidentiality, Table 3 shows the value of a group compared to the total value. Table 3 shows that *project inventory* only entails 2% of the theoretical value and 7% of the current value. Therefore, the absolute delta for *project inventory* is relatively small compared to other groups. Table 2 shows that *Anonymous inventory* and *WIP* perform fairly well compared to their theoretical levels. *Project WIP* shows both a very high ratio in Table 2, and it is responsible for 56% of the current inventory investment. Hence, it is concluded that the largest delta is caused by *project WIP*. Therefore, the focus shifted to *project inventory*

Table 2: Difference current inventory investment vs theoretical values

	Anonymous inventory	*Project inventory*	*Anonymous WIP*	*Project WIP*	*Total*
Inventory WH systems	118%	684%	135%	325%	**206%**
Theoretical Inventory	100%	100%	100%	100%	**100%**

Table 3: Percentage of inventory compared to total

	Anonymous inventory	*Project inventory*	*Anonymous WIP*	*Project WIP*	*Total*
Inventory WH systems	30%	7%	7%	56%	**100%**
Theoretical Inventory	52%	2%	10%	36%	**100%**

VDL ETG normally does not hold finished goods end-items, wafer handlers are fully assembled and stocked before cleaning in the cleanroom to prevent stocked wafer handlers from encountering unexpected yield problems. This means that finished wafer handlers count as *project WIP.* Only 1.6% of *project WIP* is not caused by the end-items. This means that the end-items cause 98.4% of the *project WIP.* This is very high since in chapter 2 it was stated that the goal of an ATO supply chain is to have zero finished goods. Table 4 shows the differences between the theoretical values for the end-item WIP and the current levels. Due to confidentiality, the actual values have been removed. The ratio current WIP levels to theoretic inventory value is used to show the differences. The cumulative ratio current WIP compared to theoretic value is 3.4. This means that the current inventory level for end-items is 3.4 times as much as the theoretic level. When the entire current investment in inventory is compared to the theoretical value, this ratio is only 2.1.

Table 4: differences in inventory investment in Project WIP caused by end-items. Current WIP levels and theoretic value are removed due to confidentiality. These are shown in the company version.

End Items	Current WIP Levels	Theoretic value
MK4L	386%	100%
MK4R	471%	100%
MK5L	291%	100%
MK5R	342%	100%
MK6L	385%	100%
MK6R	884%	100%
NXE	-	100%
Total WIP end items	340%	100%
Total WH items	**206%**	**100%**

From this chapter it can be concluded that the largest delta between theoretical inventory value and the actual investment in inventory is due to excessive *project WIP*. Focusing on this category it appears that over 98.4% is caused by finished wafer handlers that are kept on stock as *project WIP*. Therefore, the focus of this project shifted to the *project WIP* because this is where the highest potential gains are possible concerning inventory investment.

Chapter 4. Uncertainty within VDL ETG

Uncertainty saturates throughout every supply chain. (Davies, 1993) stated that understanding the relative impact of different uncertainty sources can substantially help an organization. Uncertainty knows many different definitions. This thesis uses the definition provided by Ho (1989), which divided uncertainty into environmental uncertainty and system uncertainty. Environmental uncertainty consists of uncertainty outside of the manufacturing process, such as supplier uncertainty and demand uncertainty. System uncertainty contains uncertainties within the production process, such as operation yield uncertainty, quality uncertainty, and production lead time uncertainty (Ho, 1989). In the Operations Research field, uncertainty is usually analyzed in isolation. Meaning that supply -, demand -, and manufacturing process uncertainty needs to be evaluated individually and independently from one another (Kampen, Donk, & Zee, 2010).

This chapter shows the analysis of the uncertainties that disturb the complex supply chain of VDL ETG. In the previous chapter, it was stated that the biggest inventory delta is at *Project WIP*. Therefore, this chapter focuses on uncertainty on the customer side. The supplier uncertainty and the system uncertainty analysis are shown in Appendix D.

First, a general demand analysis is performed to determine the average demand with its standard deviation and the probability distribution fitting method. Subsequently, the delivery due date uncertainty is analyzed in detail with a particular focus on rescheduling by ASML and its effect on the inventory level.

4.1. Demand uncertainty

This section entails the analysis of the demand of the six MPS-items within the ASML AWH chain that are within scope. For the years 2017 till week 33 of 2019, the first requested due date is used for the determination of the demand analysis. Once an order enters the system of VDL ETG, ASML is committed to the purchase. This means that the quantity will not change after the order enters the system, only the timing. To determine the demand variability, the first requested due date is preferred over the delivery date because the delivery date can be influenced by VDL ETG, which can cloud the accuracy of the data. Because the timing of the demand can change substantially, the delivery date has also been analyzed as a secondary check. Therefore, for both demand moments, a demand distribution is determined.

A demand distribution fitting methodology has been applied to the end-items (using Rstudio and the Fitdistrplus package). To determine what distribution best fits the data, the Maximum Likelihood Estimation (MLE) method has been used (Myung, 2003). MLE can be defined as a method for estimating population parameters (mean and variance of distribution probabilities) from sample data such that the probability (likelihood) of obtaining the observed data is maximized. Grange (1998) states that the negative binomial and the Poisson distribution are the best fit for low volume manufacturing. Moment matching estimation consists of comparing theoretical and empirical moments. A closed-form formula computes estimated values of the distribution parameters for the following distributions: ‘normal’, ‘Poisson’, ‘negative binomial’, ‘geometric’. These distributions are chosen based on the article of Grange (1998), and some often-used distributions have been added for an additional test. The full demand distribution fitting process is stated in Appendix E.

The result of the demand distribution fitting methodology is that the Poisson distribution shows the best fit to the data. Both the negative binomial and the Poisson are good fits, but the Poisson distribution performs slightly better. Both the first requested due date and the delivery date show similar results. A distinctive characteristic of the Poisson distribution is that the mean and variance are the same. Therefore, the standard deviation is the squared root of the mean. Figure 10 shows the plot for the distribution fitting of the MK5L. As can be seen, it shows a good fit. For confidentiality reasons, the y-axes of Figure 10 have been removed.

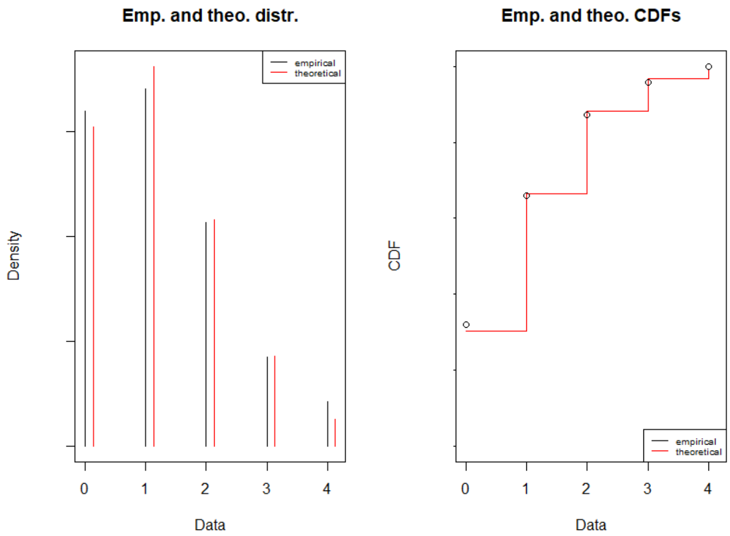


Figure 10: Poisson distribution Fitting plot MK5L

$\mu = Move\ Rate\ per\ week$

$\sigma = Standard\ deviation\ of\ the\ demand\ = \sqrt{\mu}$

For confidentiality reasons, the actual demands and standard deviations are not shown. These are provided in the company version of the thesis.

4.2. Forecast error

This section explains the forecast error. Silver et al. (1998) discuss that to anticipate forecast errors, the standard deviation of this error should be determined. This can be done using formulas 4.57 and 4.60 from the book of Silver et al. (1988). This contains the formulas for the determination of the Mean Squared Error (MSE). The standard deviation can be calculated by taking the square root of the MSE. The MSE can be calculated as follows:

$$MSE_j = \frac{1}{n} * \sum_{t=1}^{n} (x_t - \hat{x}_t)^2 \tag{19}$$

$$x_{t,j} = Actual\ deliveries\ period\ t\ for\ end-item\ j$$

$$\hat{x}_{t,j} = Forecasted\ deliveries\ period\ t$$

$$\sigma_j = \sqrt{MSE_j} \tag{20}$$

$$\sigma_j = standard\ deviation\ of\ the\ forecasted\ demand$$

This is determined for all the end-items within scope. For confidentiality reasons, the standard deviations are not shown. These are shown in the company version of the thesis.

4.3. Rescheduling

ASML often requests a change in the requested delivery date. This can mean an advancement or a delay of the order. This disturbs the manufacturing process of VDL ETG as orders either are delayed, which increases the investment in inventory, or advanced which results in capacity problems, escalations, and tardiness costs (Kamps, 2015).

4.3.1. Requested due date difference

Rescheduling poses a severe problem to VDL ETG. Both ASML reschedules towards VDL ETG, and VDL ETG reschedules towards their suppliers. This subchapter focuses on the rescheduling done by ASML towards VDL ETG. This analysis used data from 2018 to mid-2019, and only complete orders are included. An important note is that two weeks were missing from the database. It is assumed that no rescheduling occurred in those two weeks. On average, an order spends 24.8 weeks in the system of VDL ETG, and ASML sends a rescheduling message in 34% of the weeks for all orders in the system. This results in an average number of rescheduling messages per order line of nine. An important note is that the NXE is removed from the total number of weeks in the system because the order lead time of the NXE is substantially longer than for the remaining modules, see Figure 11. This is because the wafer handler is internally delivered to VDL ETG, the order remains in the system after the WH has been delivered. Figure 11 shows the average number of weeks that an order is in the system and how often it is rescheduled.

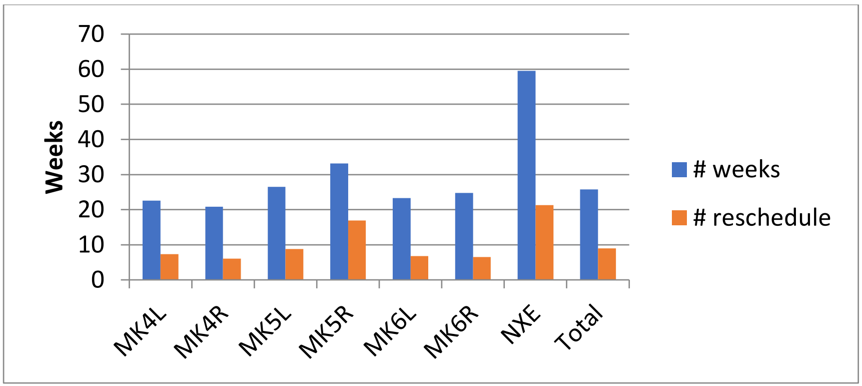


Figure 11: Average number of reschedules compared to the average number of weeks in the system per MPS-item

Figure 12 shows the difference between the first requested delivery date and the last requested delivery date. As can be seen, orders are delayed more often than they are advanced. The average delay of an order is six weeks. On only 9% of the orders, the first requested delivery date and the last requested delivery date was identical. It is interesting to note that the total number of orders without reschedules is <u>zero.</u> This means that even though the first and last requested delivery dates were the same, the order was still rescheduled while the order was in the system.

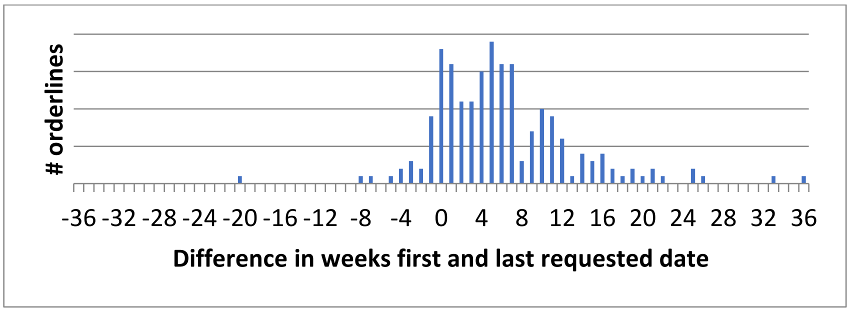


Figure 12: Difference between first and last requested delivery date by ASML of all end-items

Next, the rescheduling problem is analyzed from a weekly perspective which is shown in Figure 13. For readability reasons, weeks without rescheduling messages have been removed from the graph, as this is technically not a reschedule. Most delays or advancements are within ± ten weeks. However, there are some extreme cases. The most extreme being a delay of 40 weeks, and an advancement of 50 weeks. The average delay is 2.4 weeks, and the average advancement is 2.6 weeks. This section only provides the graphs for all items, for all graphs, consult Appendix F.

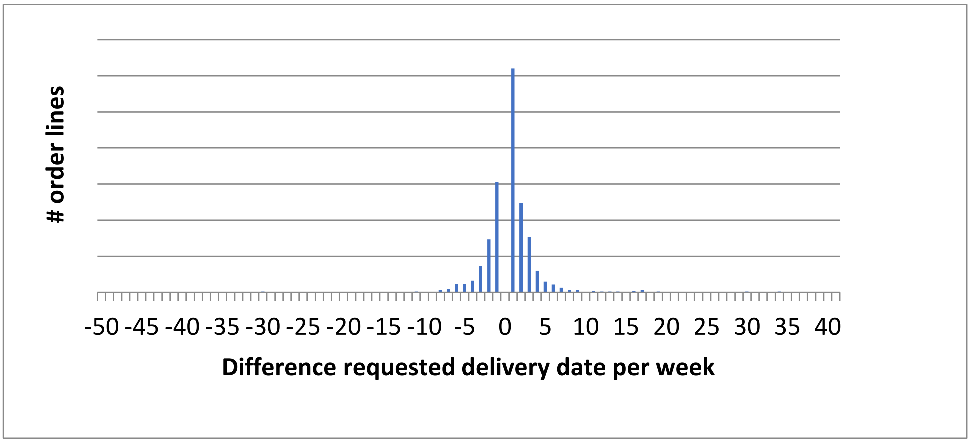


Figure 13: Requested due date difference per week for all wafer handlers

4.3.2. Effectiveness of rescheduling messages

Another interesting point is the number of contradicting rescheduling messages. It often happens that ASML requests a delay, and the subsequent week asks for an advancement. This shows that ASML requests delivery date changes that are ineffective. Figure 14 shows the effectiveness of scheduling. A distinction has been made between ineffective scheduling (contradicting rescheduling messages), effective advance, and effective delays. As can be seen, most of the rescheduling is ineffective. 52% of the requested delivery date changes are ineffective, meaning they are in the opposite direction of what has been asked already, 45% are effective delays, and only 3% are effective advancements.

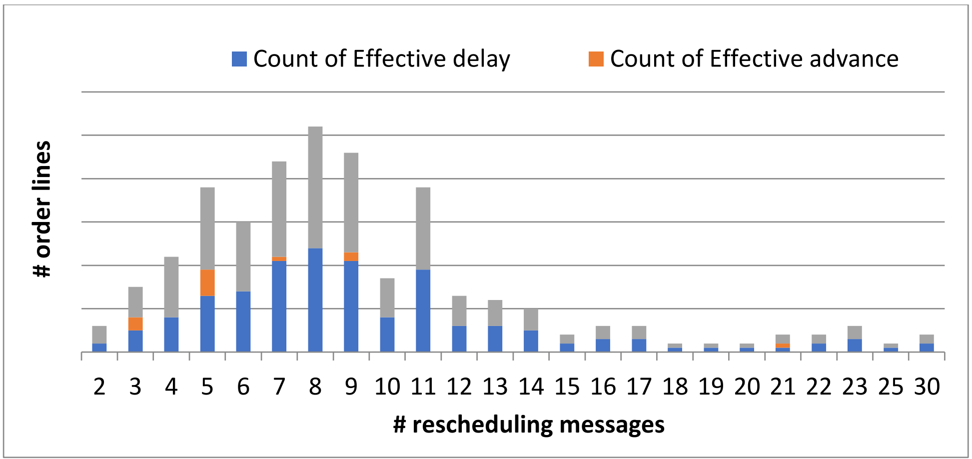


Figure 14: Effectiveness of rescheduling

4.3.3. Moment of rescheduling

The moment in which the rescheduling occurs is also vital. Figure 15 shows the moment of rescheduling (weeks remaining) per order line. This shows that the order is rescheduled substantially more in the final six weeks than before. This complies with the information provided by ASML that their demand becomes clear approximately six weeks before the start of their production.

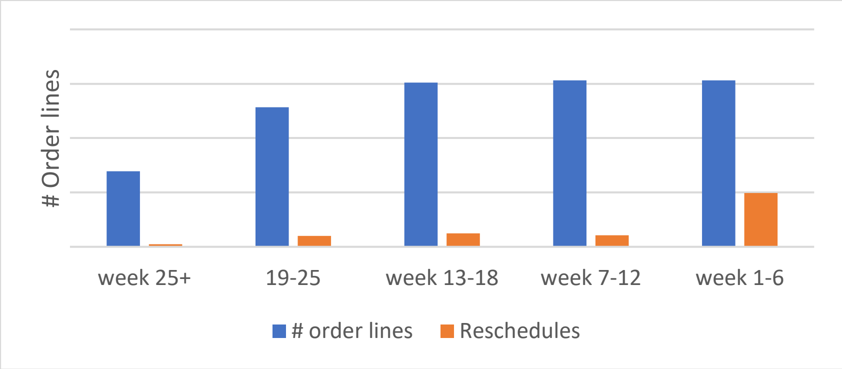


Figure 15: Moment of rescheduling

4.3.4. Impact of rescheduling on stock level

As stated before, the *Project WIP* levels have been very high the past year. From the previous chapter, it was concluded that this was due to end-items that are on stock. This is expected to be the result of rescheduling in the final weeks. Figure 16 shows that rescheduling increases significantly in the final weeks. FASSY is designed as a one-piece flow-shop with a very clear one-day cell structure (see Appendix A). VDL ETG does not change their schedule anymore if an order is rescheduled in the final weeks as this would result in lost capacity. Thus, once a WH starts FASSY, it is finished. Therefore, considering the fact that most rescheduling messages require a delay, finished wafer handlers are stocked until ready for delivery. Figure 6 shows the average time wafer handlers were on stock (red bars), the average wafer handlers on stock (yellow lines), the average production time of wafer handlers (blue bars), and the number of wafer handlers that were delivered to ASML. This figure shows that the production time of FASSY is fairly stable at 14 days, which complies with the lead time of FASSY. The average days on stock, however, are enormous with approximately 30-35 days on stock (excluding production). This resulted in a massive *project WIP* level. For confidentiality reasons, this number cannot be shown. To indicate the magnitude of the *project WIP,* it contained 80% of the total theoretical inventory values for all groups.

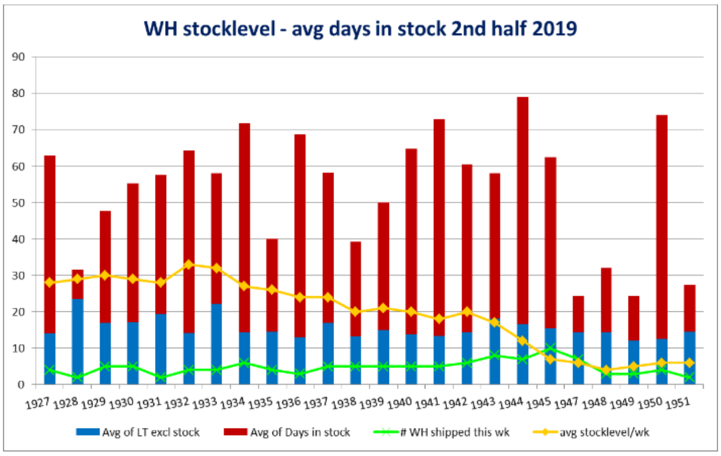


Figure 16: Effect of rescheduling on wafer handler stock

Chapter 5. Diagnosis & Literature

This chapter contains the diagnosis and a brief explanation of relevant theoretical concepts. Based on the information from the previous chapters, a solution direction is chosen. Subsequently, the relevant academic work from the literature is described.

5.1. Diagnosis

From the delta analysis of chapter 3, it can be concluded that the difference between the theoretical inventory values based on the current parameters and the actual inventory levels is the largest for *project WIP*. When this category was analyzed in more detail, it appeared that this vast delta was almost entirely caused by finished wafer handlers that are kept in the cleanroom ready to be shipped to ASML. This was, among other reasons, caused by the rescheduling of ASML, especially during FASSY. Rescheduling occurs mostly in the final weeks before the delivery, and therefore, has the biggest impact on inventory due to high module prices. FASSY is designed as a one-piece flow-shop. Therefore, once FASSY is started, VDL ETG does not comply with rescheduling messages of ASML anymore, since that would result in lost capacity in the cleanroom. Ergo, wafer handlers that start FASSY are finished. If the order is delayed during this time, the wafer handler will be kept on stock until it can be delivered resulting in a high investment in inventory.

The current customer order lead time for a wafer handler is 18 weeks. The order acceptance process has a maximum time of two weeks, resulting in a production time of at least 16 weeks. The commonality analysis showed that the end-items show high levels of commonality, especially if the NXT and the XT product family are separated. Moreover, the difference between the left and right configuration is only made at FASSY. Before FASSY, left and right wafer handlers are completely identical. For items currently produced or procured *anonymously*, this does not matter, since this is all done on speculation. However, for the modules that are built *on order* in PRE-ASSY, this results in unnecessary early allocation to an end-item, thus reducing the flexibility of the WIP (Lee & Tang, 1997).

ASML confirmed that approximately six weeks before their production, the demand becomes clear. This pattern can also be noticed by analyzing the moment of rescheduling, which substantially increases in the final six weeks. Therefore, reducing the order lead time to six weeks or less can result in significantly less rescheduling, since ASML does not have to order based on unclear demand. In order to reduce the rescheduling and its impact on *project WIP*, the customer order lead time will be reduced using the commonality between end-items and within the process of VDL ETG. A reduction of the lead time requires *postponement* to be applied to shift the Customer Order Decoupling Point (CODP) downstream towards ASML.

To conclude, the proposed solution is shifting the CODP downstream and reducing the order lead time. To realize this, *postponement* has to be implemented in order to delay the point of differentiation.

5.2. Literature review

This section provides a brief summary of the literature review done throughout the master thesis project. Two important concepts are introduced: The Customer Order Decoupling Point (CODP), and *postponement*. For a more extensive explanation, consult the full review (Bik, 2020).

5.2.1. Customer Order Decoupling Point

The ability of a company to deliver products with a very short lead time is considered critical for the success of a company (Can, 2008). Olhager (2003) defined the CODP as “the point in the value chain for a product, where the product is linked to a specific customer order.” The location of the CODP has a direct influence on the type of supply chain, see Figure 17.

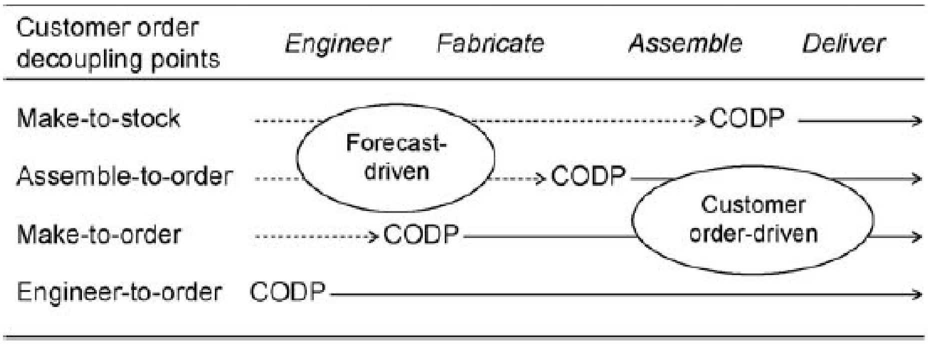


Figure 17: Effect of CODP location on the type of the supply chain. (Olhager, 2003)

There are many factors influencing the positioning of the CODP. Olhager (2003) developed a conceptual model summarizing what factors influence the location of the CODP. These factors are grouped in five categories: market characteristics, product characteristics, production characteristics, delivery lead time, and production lead time. Figure 18 shows the interaction between these different groups.

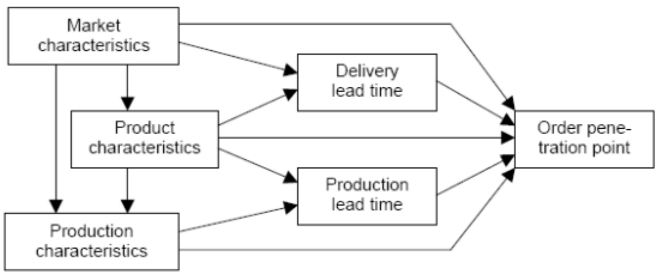


Figure 18: conceptual model CODP factors (Olhager, 2003)

A change in the CODP location should always be based on a strategic motivation (Olhager, 2003), e.g. shortening lead time to strengthen the competitive position. The two main reasons to move the CODP downstream closer to the customer are to increase the manufacturing efficiency and to reduce the order lead time. The reasons for shifting the CODP upstream are to increase the degree of product customization, reduce the reliance on forecasts, reduce or eliminate WIP buffers, and to reduce the risk of obsolescence inventory (Olhager, 2003).

5.2.2. Postponement

The high-tech market is very customer driven. Therefore, to be able to compete in that market, it is vital that companies are able to serve products and configurations that precisely fit the specific customer requirements. *Postponement* enables companies to improve the responsiveness of their supply chain by providing short and reliable lead times (Skipworth & Harrison, 2004).

In general, *postponement* is defined as: "delaying the activities in the supply chain until customer orders are received with the intention of customizing products, as opposed to performing those activities in anticipation of future orders" (Van Hoek, 2001). *Postponement* can be achieved through delaying distribution, assembling, production, packaging, and purchasing until customer orders are received (Van Hoek, 2001).

There are many different types, classifications, and strategies of *postponement*. Even though many academics use different terminology, they often have similar meanings and applications. Yang, Burns,

& Backhouse (2004) provided a classification of *postponement* strategies. The strategies of Zhang & Tan (2001) and Lee & Billington (1994) have been added to this classification, which resulted in the overview provided in Table 5. This thesis will use the classification framework of Zhang & Tan (2001) which distinguishes *form -, time -, and place postponement.*

Table 5: Classification of postponement strategies based on (Yang, Burns, & Backhouse, 2004), Zhang & Tan (2001) and Lee & Billington (1994).

Reference	Classification of postponement strategies
Zinn & Bowersox (1988)	Time postponement | Assembly postponement | Manufacturing postponement | packaging postponement | Labeling postponement | Purchasing postponement
Lee & Billington (1994)	Form postponement | Time postponement
Bowersox et al. (1996)	Logistics postponement (time and place postponement) | Manufacturing postponement
Lee (1998)	Pull postponement | Logistics postponement | Form postponement
Waller et al. (2000)	Production postponement | Upstream postponement | Downstream postponement
Zhang & Tan (2001)	Form postponement | Time postponement | Place postponement

Form postponement entails redesigning the function-added processes (procedures before the product finalization process) to postpone the point of differentiation (Zhang & Tan, 2001). They define two possible methods to implement *form postponement.* The first option is to standardize upstream processes such that the point of differentiation is postponed until a later stage. The other method is the modularization of components such that the assembly activity of these modules can be delayed until a later stage (Zhang & Tan, 2001).

Time (sequence) postponement is the redesign of the sequence of the processes to postpone the differentiating process. This strategy is also called operation reversal, which can lead to variance reduction and to quicker response time (Lee & Tang, 1997). The main deliberation is the sequence of process differentiation and the potential added costs of redesigning these processes (Zhang & Tan, 2001). As with the previous type, there are two possibilities to implement *time (sequence) postponement*: 1) redesign the process sequence such that the anticipation part of the supply chain can be delayed, 2) delay the implementation time of differentiating processes (Zhang & Tan, 2001).

Place postponement encompasses the reconfiguration of the geographical location of processes to postpone the differentiation of the product (Zhang & Tan, 2001). There are several different ways to implement *place postponement*. The first option is to delay the final manufacturing/assembly downstream. The second option is to delay the downstream movement of goods. The last option is to delay the forward deployment of inventory (Zhang & Tan, 2001).

Ferreira et al. (2015) developed a theoretical conceptual framework to identify the main steps companies have to take in order to implement postponement. Their work is based on several existing frameworks that focused on specific parts of postponement and distinguishes three parts: 1) drivers for *postponement*, 2) implementation of *postponement*, 3) evaluation of *postponement*. This framework provides a deeper understanding of the requirements and steps necessary for the implementation of postponement (Ferreira et al., 2015). Therefore, this framework will be followed and adapted to fit the specific situation of VDL ETG, as explained in the next chapter.

Chapter 6. Solution design

This chapter explains the solution design for the implementation of *postponement* in the supply chain of VDL ETG. The theoretical framework of (Ferreira et al., 2015) is used to support this process. The framework consists of three parts. First, the drivers for postponement are stated to assess whether shifting the CODP location downstream could be profitable for the AWH chain. Secondly, the implementation steps are explained that should be followed. Finally, the performance of the postponement strategy is evaluated.

6.1. Drivers for postponement

The drivers for *postponement* that apply to VDL ETG are categorized in three dimensions: 1) market, 2) product, and 3) process (Ferreira et al., 2015). For a full review on drivers for *postponement*, consult the literature review of Bik (2020).

6.1.1. Market dimension

Yang et al. (2004) consider 1) uncertain demand, and *2)* more information during delay as preconditions related to the market dimension. Uncertainty in demand is an important aspect of *postponement*; in an easily predictable environment, *postponement* would hold little benefits (Yang & Burns, 2003). The demand uncertainty driver is applicable at VDL ETG, as can be concluded from the demand analysis in chapter 4. Demand correlation is another factor that influences *postponement*. Garg & Tang (1997) and Swaminathan & Tayur (1998) both state the correlation between demand end-items has an influence on the potential gains of *postponement*. A negative demand correlation enables *postponement* whereas a positive demand correlation results in less potential gain (Garg & Tang, 1997; Swaminathan & Tayur, 1998). The demand shows a negative correlation, this is shown in appendix G. Therefore, the demand uncertainty precondition is met. The correlation between forecasted demand also shows a negative correlation, this is shown in appendix G as well.

In general, short-term forecasts are better than long-term forecasts. Moreover, making an aggregated forecast is easier than making a specific end-item forecast (Yang et al., 2004). Secondly, as stated in the current analysis, the demand for ASML becomes clear approximately six weeks before the start of their production. Reducing the order lead time below six weeks means that ASML supposedly has a clearer view of their demand which satisfies the second precondition: increased availability during delay (Yang et al., 2004)

6.1.2. Product dimension

Two important drivers of *postponement* in the product dimension are product price and product commonality (Ferreira et al., 2015; Van Hoek, Commandeur, & Vos, 1998; Zinn, 1990). Commonality has a diminishing effect on demand uncertainty via risk-pooling of end-items using the same components. This results in reduced total safety stock due to demand aggregation (Baker, 1985). From the percentage of component commonality analysis in chapter 2, it can be concluded that the level of component commonality is very high, especially if the product families are separated.

(Zinn (1990) stated that the higher the value of a product, the more potential benefits *postponement* has. This higher potential is due to increased possible inventory savings that can be generated via the implementation of *postponement*. In the current analysis, it appeared that products remained in WIP just before finalization because of demand uncertainty. In this state, products have a huge impact on inventory considering their high prices. Therefore, the potential benefits of *postponement* are substantial.

Product variation is another enabler for *postponement* (Ferreira et al., 2015; Van Hoek, 1999). Currently, the number of product variations is limited to seven (six within scope). However, there are nine wafer handlers in development at the moment. Eventually, these models will be introduced alongside the current product variations. These new products also show very high levels of commonality with the current end-items. This data is not shown for confidentiality reasons and these are wafer handlers that are not yet in production. Therefore, implementing *postponement* will have even more benefit once these new products are introduced.

6.1.3. Process dimension

Process commonality and modularity as well as lead time are process drivers for *postponement* (Ferreira et al., 2015; Van Hoek, 1999). Chapter 2 analyzed the commonality in the process of VDL ETG. The conclusion was that within product families, the process is identical until FASSY, which occurs in the final three weeks. This means that processes can be standardized resulting in risk-pooling and reduced inventory (Feitzinger & Lee, 1997; Swaminathan & Lee, 2003). From the component commonality analysis, it was concluded that the order differentiation point is made a long time before the differentiation point in the production of the WH. This means that the differentiation point can be moved downstream without making rigorous changes to the design of the supply chain and the product.

The lead time is another driver for applying *postponement* (Van Hoek et al., 1998). Currently, the lead time for the wafer handler is 18 weeks. As stated in chapter 4, this results in uncertain ordering of wafer handlers. Reducing the order lead time will result in an increased delivery performance (Van Hoek et al., 1998).

6.1.4. Conclusion drivers for *postponement*

This subchapter explained what drivers for *postponement* apply to VDL ETG and how these result in potential benefits for VDL ETG. The conclusion is that *postponement* is applicable to VDL ETG considering the high levels of commonality in both product and process, and uncertain demand (Ferreira et al., 2015), specifically, the negative demand correlation (Garg & Tang, 1997; Swaminathan & Lee, 2003). The high prices of modules and components also indicate that *postponement* can be beneficial due to the high potential inventory gains (Zinn, 1990). The last driver of *postponement* is the added information that becomes clear during the postponement time (Yang et al., 2004). From chapter 4, it appeared that ASML does not know what they are ordering eighteen weeks before the start of their production. Therefore, it is clear that more information would be known during the delay and *postponement* can be beneficial (Yang et al., 2004).

6.2. Postponement approach

This section entails the approach that is taken to implement *postponement* based on the framework of Ferreira et al. (2015). The framework is adapted to the specific situation of VDL ETG. Therefore, only the relevant steps for VDL ETG are followed. The first step is to identify the possible decoupling points combined with a feasibility analysis. After that, the selection of products that are included and the choice of *postponement* type is stated. Subsequently, the required changes in the process structure are given. The framework of Ferreira et al. (2015) does not incorporate the safety stock required at the CODP. Therefore, this step has been added to the framework and follows the work of (Baker, 1985).

6.2.1. Decoupling points

The first step in applying a *postponement* strategy is to determine the possible locations where the forecast driven part can be separated from the order driven part (Ferreira et al., 2015; Yang et al., 2004). All activities after the CODP are linked to an actual order whereas the activities before the CODP are based on speculation (forecast) (Wikner & Rudberg, 2005). In chapter 4, it was stated that the demand becomes clear for ASML approximately six weeks before their production starts. Therefore, this has been used as a constraint for the maximum lead time. When analyzing the final six weeks of the assembly process, three different decoupling points appear. The final weeks of the production process can be seen in Figure 19. In the final six weeks, both PRE-ASSY and FASSY occur. FASSY has a lead time of three weeks and PRE-ASSY a lead time of two weeks, resulting in a total production time of five weeks. As stated before, FASSY is designed as a one-piece flow shop and PRE-ASSY is designed as a job-shop. The stock points in this process are either before delivery, before FASSY, or before PRE-ASSY. These stock points indicate the postponable points. In Figure 19, these points are indicated with concept 1,2, and 3. The first concept concerns a CODP after FASSY. This would be an Assemble-to-Stock (ATS) supply chain instead of Assemble-to-Order (ATO). The second CODP location is before FASSY. The third CODP option is before pre-assembly (PRE-ASSY).

Figure 19: Assembly process of the final weeks of VDL ETG

These three points are chosen as a result of the commonality analysis and the analysis of the assembly process. The first point requires little explanation. This would involve building and stocking finished WHs. This would be ideal from an efficiency perspective, but from an inventory perspective this would result in a large investment considering the high prices of the WHs. Moreover, the differences between end-products are made in the final three weeks. Therefore, if the CODP would be located after FASSY, the commonality and negative correlation between end-item demand would not be used, which would result in a high expected safety stock of finished goods.

The second postponable point is before FASSY. This process has a lead time of three weeks. The differences between configurations are made during the final three weeks at FASSY. Using this concept would mean using the commonality between configurations optimally since everything before the CODP would be identical for both configurations of a product family and can thus be standardized.

The final postponable point is the stock point before PRE-ASSY. PRE-ASSY has a lead time of two weeks. Placing the CODP before PRE-ASSY would result in not fully using the commonality between end-items. In this scenario, PRE-ASSY is not standardized meaning the certain critical modules would be produced specifically for a configuration while it involves the exact same module. This implies that allocation to an order would be done before this is necessary as is the case for the current situation.

To conclude, if the final six weeks of the production process are analyzed three potential decoupling points appear. One after FASSY, one before FASSY, and one before PRE-ASSY.

6.2.2. Product selection and postponement type selection

The focus of the thesis is on the AWH chain of VDL ETG. Within this chain, seven end-items are currently sold. The NXE wafer handler was already dropped from the scope since this WH is delivered internally to VDL ETG, is not part of the two main product families and, therefore, shows low levels of commonality to other end-items. The current end-items are split among two product families: NXT and XT (see Figure 5). This research focuses on the implementation of *postponement* for the NXT product family (MK5L+MK5R), due to its higher level of commonality compared to the XT product family. However, the drivers for *postponement* also apply to the XT product family.

After the product selection, the type of *postponement* should be decided (Ferreira et al., 2015). As stated in the previous chapter, the *postponement* classification of Zhang & Tan (2001) is used which distinguishes 1) *form postponement, 2) time postponement,* and *3) place postponement. Place postponement* is not applicable since the production processes all take place at the VDL ETG location in Eindhoven. Geographical redesign is therefore not an option. *Time postponement* is also not an option for VDL ETG. Currently, the differentiating process is FASSY, after which only the testing of the module remains. Testing of the module is only possible for finished products. Therefore, resequencing FASSY, and the rest of the supply chain does not make sense. *Form postponement* is the best strategy for the AWH supply chain of VDL ETG. As stated before, *form postponement* can be done via standardizing an upstream process so that the differentiating point can be delayed. This is the only appropriate *postponement* strategy for VDL ETG, since processes before FASSY can be standardized as a result of the commonality between the end-items.

6.2.3. Process changes required for postponement

This section explains the changes necessary to implement *postponement*. *Form postponement* requires the standardization of upstream processes. By standardizing the process, this becomes common for all products. Therefore, risk is divided among the different products which results in reduced required inventory (Feitzinger & Lee, 1997; Swaminathan & Lee, 2003). Other benefits are that WIP levels are used more flexibly and that the system's overall service level is improved (Lee & Tang, 1997). Figure 20 shows the structure of the supply chain per *postponement* concept.

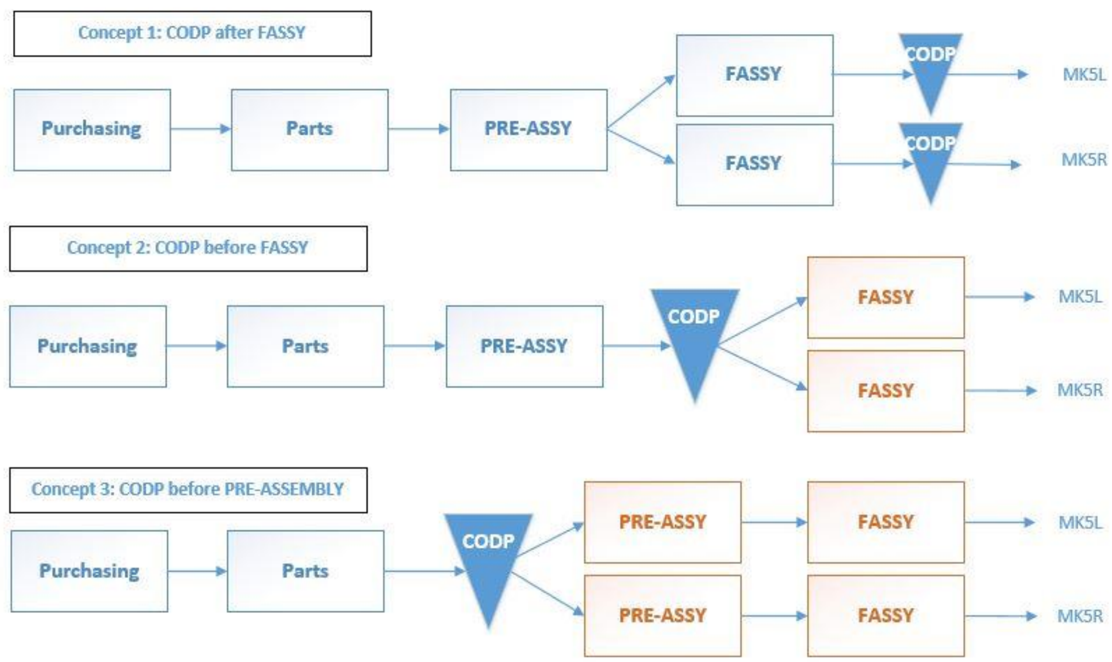


Figure 20: Process structure per postponement concept (according to COPD location). Blue boxes are anonymous processes, orange boxed indicate on order processes

All concepts will still be MRP-controlled. The current situation has both MRP-project controlled items and MRP-anonymous as stated in the current analysis.

In the case of concept 1, FASSY and PRE-ASSY would need to be produced *anonymously* since finished wafer handlers would be kept on stock. This means that the entire production process of VDL ETG would be done *anonymously*. *Project inventory* and *project WIP* would therefore cease to exist as this would all be moved to *anonymous inventory* and *anonymous WIP.*

For concept 2, FASSY would remain *on order* as no standardization would be necessary for this process. PRE-ASSY however would require several changes. Certain critical modules that are currently assembled *on order* would need to be changed to *anonymous*. For the production of PRE-ASSY, nothing would change, only settings in the ERP system of VDL ETG (BaaN) would need to be changed.

For concept 3, no changes would be necessary. The current supply chain is designed such that no standardization of processes is necessary. The only difference would be the moment at which the order arrives in the system.

Standardizing a process often goes hand in hand with standardizing of components (product redesign). Unique components are replaced by standardized common components to enable process standardization (Swaminathan & Lee, 2003). When analyzing the commonality with respect to the manufacturing operations, it appears that for the MK5L and MK5R, everything is common until FASSY. Therefore, a change in product design is not necessary to be able to standardize upstream processes. Currently, PRE-ASSY is done *on order* while the modules that they build are identical for both configurations. Therefore, standardizing PRE-ASSY can be done without redesigning the product. In the current situation, these modules are allocated to end-items before this is necessary. It is technically possible to reallocate these modules in case of shortage, but this is a tedious process.

To conclude, implementing *postponement* concept 1 would mean the process redesign as both PRE-ASSY as well as FASSY would have to be changed to *anonymous.* For concept 2, only PRE-ASSY would have to be produced *anonymously.* For the third concept, no process changes are required as this would be the same as the current situation.

6.2.4. Safety stock required at the CODP

To be able to move the CODP downstream, an additional buffer is required to catch variable demand. The current safety times in place buffer against lead time uncertainty of suppliers. No buffer against demand uncertainty is in place, which means that the buffer will complement the current buffers in place. A shift in the CODP downstream has an impact on the expected inventory level, since more expensive modules have to be kept on stock (de Kok & Fransoo, 2003).

As stated before, the current buffer method is to add three weeks of safety time to almost all items and components to buffer against supplier lead time uncertainty. In the operations research field, uncertainties in demand and supply are usually studied in isolation (Kampen et al., 2010). Since the solution direction focuses on the demand uncertainty, the supplier uncertainty safety times are kept in place.

For the determination of the required safety stock, the stochastic elements need to be defined first. As analyzed in chapter 4, the demand for finished goods follows a Poisson distribution with mean μ_i and standard deviation $\sqrt{\mu_i}$. However, since the supply chain at VDL ETG is MRP controlled and heavily relies on the forecast. The safety stock should be calculated based on the standard deviation of the forecasted error as calculated in chapter 4.2.

Since the focus is on uncertainty on the customer side, and the current buffers against lead time uncertainty are kept in place, lead times are assumed to be constant. The safety stock ensures that demand during lead time can be met according to a defined service level. After determination of the standard deviation of the end-items, one can calculate the required safety by multiplying this safety value with a corresponding safety factor k (Hax & Candea, 1984). This results in the following formula:

$$SS_i = k_\beta \sigma_j * \sqrt{LT_i} \tag{21}$$

$$k_\beta = safety\ factor$$

$$\sigma_j = standard\ deviation\ forecasted\ demand\ end\ item\ j$$

$$LT_i = Lead\ Time\ item\ i$$

The value of the safety factor is dependent on the required service level. This can be found using a standard normal table. For VDL ETG, a service level is 95% is generally required resulting in a safety factor of $k \approx 1.65$. From this formula, it appears that the higher the demand variability, the higher the risk of a potential stock out is. Therefore, the required safety stock increases if the standard deviation increases (Baker, 1985).

When components have commonality, the determination of the safety stock changes. Greater commonality allows more end-item demand to be aggregated while determining the requirements. This aggregation results in inventory efficiency because the standard deviation of an aggregated demand is always less than the sum of two individual and independent standard deviations, $\sigma_{12} \leq \sigma_1 + \sigma_2$ (Baker, 1985). The effect of commonality on the safety stock is further explained in appendix H. Here it is shown that as the percentage of commonality increases, the buffer decreases. An exponentially decreasing trend is shown.

When a component is not common, the safety stock is given by the following formula:

$$SS_i = k_\beta a_{ij} \sigma_j \tag{22}$$

$$a_{ij} = Number\ of\ component\ i\ required\ for\ end\ item\ j$$

Furthermore, in case of component commonality with independent demand, the formula becomes:

$$SS_i = k_\beta * \sum_{j=1}^{n} \left[a_{ij}^2 \sigma_j^2\right]^{\frac{1}{2}} \tag{23}$$

Nevertheless, as described in the current analysis, the demand is not independent. The demand is negatively correlated to one another. This makes inventory efficiency due to demand aggregation even larger (Baker, 1985; Garg & Tang, 1997; Swaminathan & Lee, 2003). The safety stock formula for correlated demand with commonality is:

$$SS_i = k_\beta * \left[\sum_{j=1}^{n} a_{ij}^2 \sigma_j^2 + \sum_{j=2}^{n} \sum_{k=1}^{j-1} 2\rho_{jk} a_{ij} a_{ik} \sigma_j \sigma_k\right]^{\frac{1}{2}} \tag{24}$$

However, the formulas for the determination of the safety stock of Baker (1985) do not include the lead time. His model assumes a one-period off-set as lead time. This is not the case for VDL ETG. The safety stock is required to buffer against a variable demand over the lead time (Hax & Candea, 1984). Therefore, to apply the formulas of Baker (1985) to the situation of VDL ETG, the formulas have to be improved to incorporate the lead time. This can be done using the formula (16) of Hax & Candea (1984) results in the following formulas:

$$SS_i = k_\beta a_{ij} \sigma_j \sqrt{LT_i} \tag{25}$$

$$SS_i = k_\beta * \sum_{j=1}^{n} [a_{ij}^2 \sigma_j^2]^{\frac{1}{2}} * \sqrt{LT_i} \tag{26}$$

$$SS_i = k_\beta * \left[\sum_{j=1}^{n} a_{ij}^2 \sigma_j^2 + \sum_{j=2}^{n} \sum_{k=1}^{j-1} 2\rho_{jk} a_{ij} a_{ik} \sigma_j \sigma_k \right]^{\frac{1}{2}} * \sqrt{LT_i} \tag{27}$$

Formula (25) is the safety stock for uncommon components. Formula (26) contains the safety stock for common components in case of independent demand. Finally, formula (27) entails the safety stock derivation for common components including dependent demand.

These formulas can be further extended to include lead time uncertainty. However, this is not included in the calculation for now since uncertainties are usually studied in isolation (Kampen et al., 2010). Not including the lead time uncertainties allows a fair comparison between the current situation and the new concepts. The extended safety stock formulas are shown in the discussion and proved in appendix I.

Concept 1: CODP after FASSY

In this concept, safety stock at the CODP are finished wafer handlers. Therefore, the impact on inventory level is substantial due to the high prices of the product (de Kok & Fransoo, 2003), 2003). In this concept, the commonality between the end-items is not used. The required safety stock for concept 1 is €1,987,695, see Table 6. If this concept is chosen for both product families, six end-items will have to be stocked which causes a substantial burden on the inventory level due to the high prices of finished WHs.

Concept 2: CODP before FASSY

In this concept, the CODP contains materials needed to start FASSY. All BOM items that are required at FASSY are incorporated in the safety stock analysis. In order to be able to produce the wafer handler in the required four weeks, all these items require additional safety stock. In total, a safety stock value of €1,349,946 is required for concept 2, as can be seen in Table 6.

Concept 3: CODP before PRE-ASSY

In this concept, all materials before PRE-ASSY need to be buffered in order to assure a lead time of six weeks. However, items at the stock point before FASSY that have a lead time longer than two weeks also need to be buffered. This results in a total buffer value of €1,631,866, see Table 6.

Conclusion

Table 6 shows the summary of the required safety stock for each concept in the CODP. To conclude, concept 2 contains the least buffer value. The main reason for this is that the commonality between the two end-items allows the safety stock to be aggregated resulting in more inventory efficiency (Baker, 1985). For concept 3, items required at FASSY with an order lead time longer than two weeks also need to be buffered. Concept 1 requires the largest investment in safety stock due to the very high prices of finished wafer handlers.

Table 6: Safety stock required for each concept

	Concept 1	Concept 2	Concept 3
Value	€1,987,965	€1,349,946	€1,631,866

6.3. Performance evaluation of postponement

Several authors proposed measures to evaluate *postponement* in a company. Zinn & Bowersox (1988) developed normative cost systems for each *postponement* type which measured the direct cost and benefits for a given customer service level. Lee & Billington (1994) proposed several cost measures to evaluate the implementation of *postponement*. Inventory management, material management, transportation management, and other costs are included in their analysis. Each of these costs are categorized as measurable or immeasurable (Lee & Billington, 1994). Lee & Tang (1997) developed a similar model that calculated the cost and benefits of *postponement* under a given service level. Their model included project cost, processing cost, inventory cost, and lead time. Van Hoek (1999) focused on measures for the production and distribution stages in which *postponement* is possible. These measures evaluated two dimensions: efficiency and customer service. Zhang & Tan (2001) developed the only performance measurement framework that grouped performance measures to enable a complete view of the implementation of a *postponement* strategy. Moreover, it is the only framework that includes all aspects and only includes measurable performance measures (Ferreira et al., 2015). Therefore, the study by Zhang & Tan (2001) is used as a performance measurement framework in this study.

However, the framework of Zhang & Tan (2001) is still not complete for VDL ETG. The cause for the implementation of *postponement* was the high inventory investment in end-item WIP caused by rescheduling. Therefore, the impact of rescheduling on inventory level should be incorporated in the performance evaluation. To measure this, the performance measure concerning rescheduling cost developed by Vieira, Herrmann, & Lin (2003) is used. They define rescheduling costs as the costs associated with the implementation of a new schedule. This can be either the costs of developing a new schedule and the associated effect on inventory level (Vieira et al., 2003).

6.3.1. Performance measurement framework

Table 7 shows the performance measurement framework of (Zhang & Tan, 2001), combined with the rescheduling cost performance measure of Vieira et al. (2003). The implementation of these performance measures for VDL ETG will be described in the next section. Many performance measures are irrelevant for VDL ETG, as they are not affected by the *postponement* strategy.

Table 7: Postponement performance measures. Adapted from Zhang & Tan (2001), combined with Vieira et al. (2003)

Dimension	Type	Performance measure
Internal	Cost	Transportation cost | Warehousing cost | Labelling cost | Packaging cost | Manufacturing cost | Order processing | Reverse cost | Material cost | Direct labor cost
	Asset management	Inventory turns | Inventory holding costs | Inventory level | One-time asset investment
	Total cost	Total cost | Total cost per unit | Total cost as a percentage of sales
	Customer service	Fill rate | Stock-out rate | On time delivery rate | Backorder cycle time | Order lead time
	Rescheduling	Rescheduling cost
External	Environment	Taxes to local government | Localizing degree of the product | Localizing degree of the labor

6.3.2. Adapted performance measurement framework to VDL ETG.

As stated above, many of the abovementioned KPIs do not differ for VDL ETG if *postponement* is implemented. Therefore, these measures are dropped from the framework since the different concepts would score identical on these measures. The costs for assembling and building a wafer handler do not change, since no product redesign occur, and process redesign only includes standardization of upstream processes. Consequently, since the individual costs stated in Table 7 do not change, the total costs also do not change and are not included. Finally, the environmental performance measures are dropped since no *place postponement* occurs. Therefore, all environmental measures do not change. The reasoning behind the removal of unaffected KPIs is explained in more detail in Appendix J. The adapted performance measurement framework containing relevant measures for the implementation of *postponement* at VDL ETG is shown in Table 8.

Table 8: Adapted performance measurement framework for VDL ETG. Adapted from Zhang & Tan (2001), combined with Vieira et al. (2003)

Type	Performance measures
Rescheduling	Rescheduling cost
Asset management	Inventory level | Inventory holding cost | Inventory turns
Customer service	Fill rate | Order lead time

6.4. Postponement evaluation at VDL ETG.

This section entails the performance evaluation of all three *postponement* concepts compared to the current situation based on the performance measures stated in Table 8. First, the effect of rescheduling on wafer handler WIP is stated followed by the asset management KPIs. Finally, the customer service performance measures are calculated after which a conclusion is made regarding the implementation of *postponement*.

6.4.1. Rescheduling performance measure

The first category contains the rescheduling cost performance measure of Vieira et al. (2003). As stated in chapter 5, the focus was on rescheduling during FASSY since this resulted in the vast amount of *project WIP*. Grubbström & Tang (2000) developed a rescheduling decision-making framework considering two options, to reschedule or not. This framework is shown in Figure 21. FASSY is designed as a one-piece flow shop. Once an order starts FASSY, it is completed since rescheduling an order would result in lost capacity. Therefore, in the rescheduling-framework, the option not to reschedule is always chosen and the end-item WIP is increased (Grubbström & Tang, 2000).

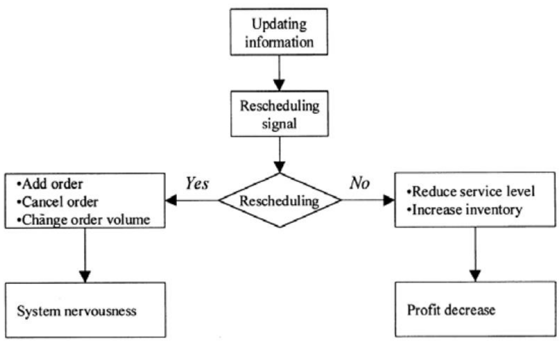


Figure 21: The rescheduling decision-making and the trade-off between different options (Grubbström & Tang, 2000).

To simulate the effect of rescheduling on end-item WIP, the simple simulation model by Kamps (2015) has been used. This model assumes a stochastic delivery due date change f_{dd}, and a deterministic assembly lead time. This model assumed that a possible due date difference is noticed at the delivery moment, while in reality it can occur earlier as well (Kamps, 2015). This assumption is justified since in the rescheduling framework of Grubbström & Tang (2000), the option not to reschedule is always chosen if a delivery shift change request arrives at FASSY. The first moment after FASSY is the delivery moment, where the due date shift will be clear. If a delivery date shift has occurred, a new delivery date is set. Again, at the new delivery date, it is checked whether rescheduling signals have been sent by ASML. This loop repeats itself until the wafer handler is delivered to ASML. A scheme of this loop is shown in Figure 22.

Since orders are not rescheduled by VDL ETG during final weeks, the assembly schedule does not change. Consequently, there are no costs associated with creating a new schedule, only the effect of wafer handlers that are kept on stock as a result of rescheduling.

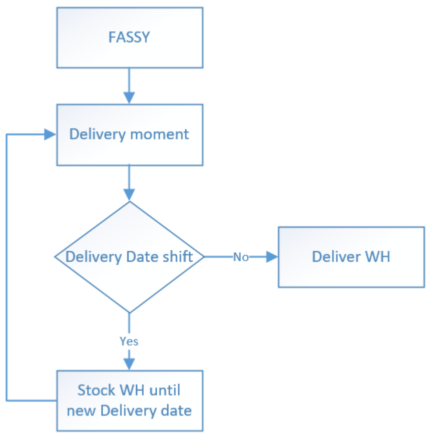


Figure 22: Simulation of FASSY rescheduling, based on simulation model of Kamps (2015)

For the current situation, the f_{dd} can be determined from the rescheduling data of ASML. However, for the new concepts, this is not possible as this data does not yet exist. Therefore, estimations are made for the stochastic probability delivery date change function if *postponement* is implemented. In chapter 4, it became clear that amount of rescheduling is dependent on the moment, as during the final weeks before delivery the number of rescheduling messages increased substantially. As stated before, since the lead time is decreased drastically in the new concepts, the amount of rescheduling is expected to decrease due to the increase in information availability (Yang et al., 2004). In order to estimate the delivery date change probability density function for the new concepts, the rescheduling messages in the first weeks are used instead of the final weeks.

Rescheduling costs current situation

Chapter 4 analyzed the effect of rescheduling during FASSY on wafer handler inventory level. On average, a WH was on stock for approximately 30-35 days. The stochastic delivery due date difference probability density function is determined by using the rescheduling of ASML in the final weeks. As stated in chapter 4, ASML reschedules substantially more during the final weeks, due to unclear demand while ordering. The due date differences are measured in weeks. This results in the following due date difference function f_{dd}.

$$Pr(X = x) = \begin{cases} 0.013 & x = -2 \\ 0.013 & x = -1 \\ 0.433 & x = 0 \\ 0.420 & x = 1 \\ 0.093 & x = 2 \\ 0.013 & x = 3 \\ 0.013 & x = 4 \end{cases}$$

The results of the simulation are shown in Figure 23. On average, an order line is kept on stock for an additional 6.47 weeks. This coincides with the results from the current analysis. Therefore, the simulation is assumed valid.

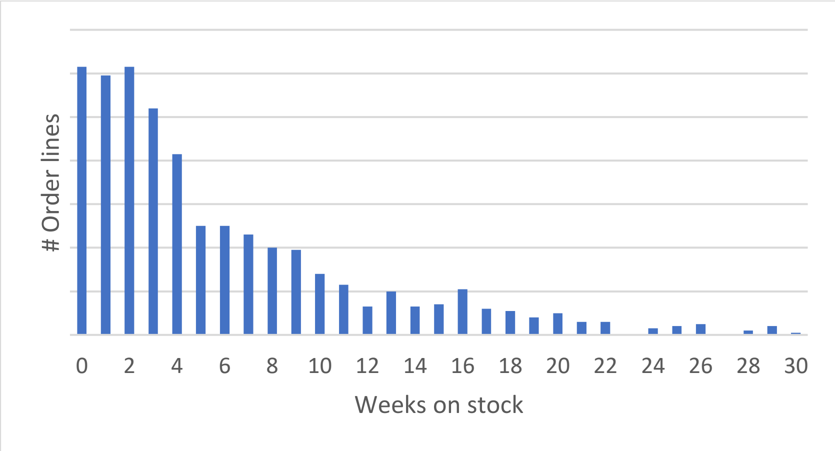


Figure 23: Simulation results for the current situation.

In the simulation of the current situation, a wafer handler is kept on stock for an additional 6.47 weeks after FASSY production. To calculate the effect on the inventory level, the move rate of the MK5 L and MK5 R must be multiplied by the average weeks on stock. This results in an added WIP due to rescheduling of €2,380,797.

Rescheduling costs concept 1

In this concept, all potential rescheduling messages fall between the moment the order arrives and the moment it is shipped one week later. For the estimation of the delivery date change probability density function, the delivery date changes from the first to the second week an order was in the system have been analyzed. This resulted in the following probability density function f_{dd}.

$$Pr(X = x) = \begin{cases} 0.02 & x = -2 \\ 0.04 & x = -1 \\ 0.86 & x = 0 \\ 0.02 & x = 1 \\ 0.04 & x = 2 \\ 0.02 & x = 3 \end{cases}$$

The result of the simulation is an average week on stock of 0.25 resulting in a rescheduling WIP of €93,821. Figure 24 shows the results of the rescheduling simulation for concept 1.

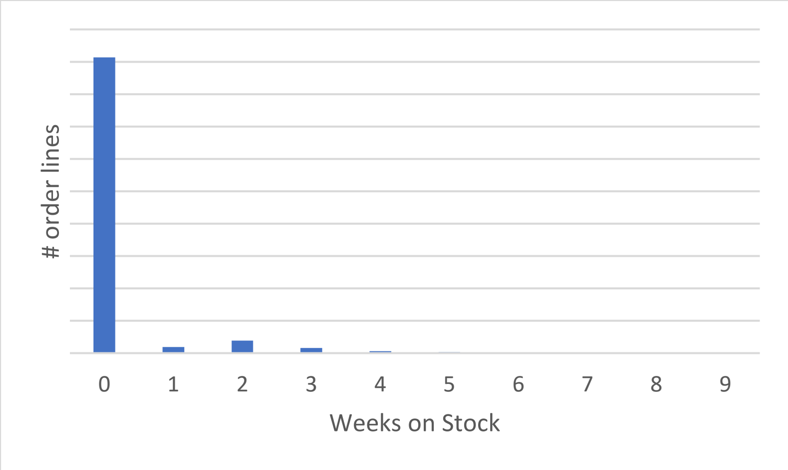


Figure 24: Simulation results concept 1

Rescheduling costs concept 2

To determine a probability density function for this concept, the rescheduling messages for weeks 17-15 have been taken. This resulted in the following delivery date probability function f_{dd}.

$$Pr(X = x) = \begin{cases} 0.007 & x = -3 \\ 0.020 & x = -2 \\ 0.047 & x = -1 \\ 0.860 & x = 0 \\ 0.020 & x = 1 \\ 0.027 & x = 2 \\ 0.020 & x = 3 \end{cases}$$

In this concept, the average time on stock is 0.51 weeks. This is a substantial difference compared to the current situation. This results in an added WIP due to rescheduling of €191,359. Figure 25 shows the results of the simulation for concept 2.

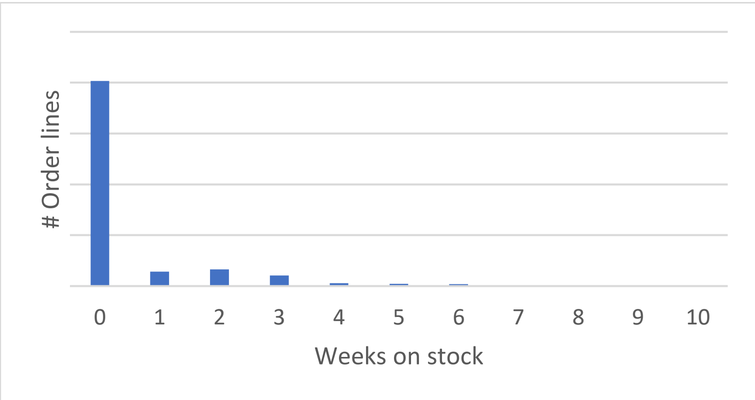


Figure 25: Simulation results concept 2

Rescheduling costs concept 3

Following the same logic of the current situation, rescheduling during FASSY is determined for this concept. Rescheduling before that period does not result in finished wafer handlers on stock as FASSY can be postponed complying with the new due date of ASML. The rescheduling messages have been analyzed from week 12-14 to determine the delivery date change probability density function f_{dd}.

$$Pr(X = x) = \begin{cases} 0.02 & x = -3 \\ 0.02 & x = -2 \\ 0.05 & x = -1 \\ 0.65 & x = 0 \\ 0.15 & x = 1 \\ 0.08 & x = 2 \\ 0.03 & x = 3 \\ 0.01 & x = 4 \end{cases}$$

The average weeks on stock in this concept is 1.65 resulting in an average WIP due to rescheduling of €616,737. The results of the simulation for concept 3 are shown in Figure 26.

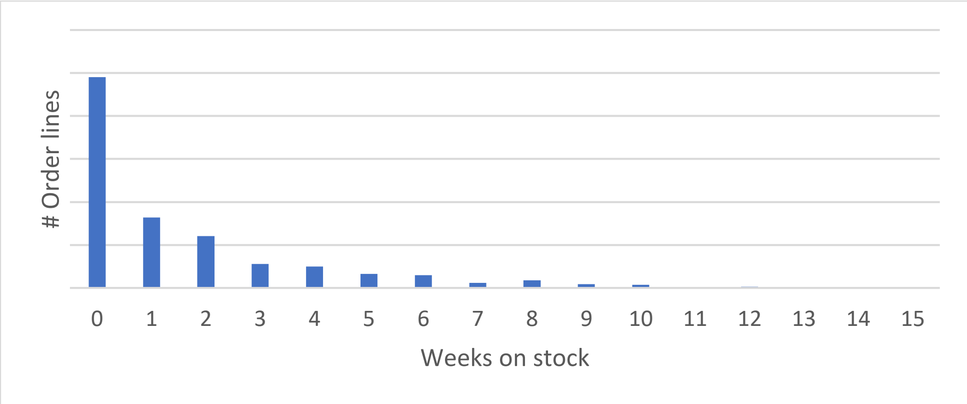


Figure 26: Simulation results concept 3

Conclusion rescheduling performance measure

From the rescheduling cost measure of Vieira et al. (2003) it appears that the first concept is best regarding rescheduling cost, followed by concept 2 and 3. This is logical considering in the first concept there is only one week in which ASML can send a rescheduling signal. Table 9 shows a summary of the rescheduling cost of the current situation with the new concepts. As can be seen, all concepts show a substantial improvement over the current situation.

Table 9: Rescheduling cost simulation results

	Rescheduling costs
Current	€2,380,797
Concept 1	€93,821
Concept 2	€191,359
Concept 3	€616,737

6.4.2. Asset management performance measures

This section contains the performance measures regarding asset management. The inventory level, inventory holding cost, and inventory turnover rate are determined using the theoretical inventory values calculated in chapter 3 combined with the rescheduling costs of the previous section.

Inventory level

The average inventory level in the supply chain is affected by the implementation of *postponement*. First of all, the safety stock levels differ per concept, see Table 6. Moreover, the average inventory level can be measured using the theoretical inventory values of chapter 3. The theoretical inventory levels determined in that chapter included all seven end-items. However, the *postponement* analysis focused on the MK5L and the MK5R. Therefore, all items that are not used in these two items are removed. For confidentiality reasons, the value of the removed items is not shown.

In the current situation, there is no safety stock to meet fluctuating demand. As stated in the current analysis, VDL ETG almost exclusively buffers in safety time. According to Kampen et al. (2010), safety time is more appropriate under supplier uncertainty whereas safety stock is better for buffering against any type of demand variability. Kampen et al. (2010) also state that demand uncertainty and supply uncertainty should be analyzed individually. This thesis focuses on the demand uncertainty. Because the safety time implemented buffers against supplier lead time uncertainty, they are unaffected in the new concepts.

Inventory level for concept 1

In the first concept, the entire wafer handler is produced *anonymously*. Therefore, *project inventory* and *project WIP* have an inventory value of zero. In this concept, finished wafer handler are stocked for a value of €1,546,195. This should be added to *anonymous inventory.* Moreover, the *project WIP,* is moved to *anonymous WIP* as a result of standardization of PRE-ASSY and FASSY. Table 10 provides the inventory values for concept 1.

Inventory level for concept 2

In the second concept, items at the stock point before FASSY are buffered. Because PRE-ASSY is standardized in this scenario, *project inventory* no longer exists. *Project WIP* remains although its value decreases since PRE-ASSY is standardized. Items assembled at PRE-ASSY will now belong to *anonymous WIP* instead of *project WIP.* The items assembled at FASSY still remain in *project WIP*. The required additional safety stock for concept 2 has been calculated in this chapter. A buffer value of €1,234,766 is required at the CODP. The inventory level of this concept is shown in Table 10.

Inventory level for concept 3

For the implementation of this concept, no process standardization is required. All operations before PRE-ASSY are already done *anonymously* whereas PRE-ASSY and FASSY are *on order* in the current configuration. Table 10 shows the inventory values based on this concept. The only added value is the required safety stock at the CODP before PRE-ASSY.

Conclusion inventory level

With the implementation of *postponement*, the inventory levels are expected to decrease. This is mainly due to the expected rescheduling costs. As analyzed in the current analysis, more than 50% of current inventory is caused by finished wafer handlers that are waiting for shipment. Due to the reduced order lead time, ASML no longer orders without a clear picture of what is required improving the match between supply and demand. Therefore, less rescheduling during FASSY will occur reducing the number of days a wafer handler is on stock before it is delivered. Table 10 shows the inventory level results comparing the current situation with the three possible concepts. For confidentiality reasons, the numbers are not shown. Instead, the current situation is considered 100%, and the new scenarios are shown compared to the current situation. Concept 2 is the concept with the least expected inventory levels and results in an expected inventory reduction of 12.4%. Concept 1 also scores well but implementing this concept for all end-items will result in enormous required finished WHs as safety stock. Therefore, this concept performs well for the scope of the MK5L and MK5R, but overall this concept is expected to perform worse if all WHs are included.

Table 10: Inventory level performance measure results

	Anonymous Inventory	Anonymous WIP	Project Inventory	Project WIP	Rescheduling WIP	Total
Current	100%	100%	100%	100%	100%	**100%**
Concept 1	176%	318%	-	-	4%	**96%**
Concept 2	152%	125%	-	88%	8%	**88%**
Concept 3	159%	100%	100%	100%	26%	**98%**

Inventory holding costs

The inventory holding costs also change with the implementation of *postponement*. A standard rate of 7% holding cost is used. VDL ETG currently uses a holding cost percentage of 7% which coincides with the average WACC determined by KPMG in their yearly Cost of Capital study. The inventory holding costs are calculated using the average inventory level multiplied by the holding cost percentage (Zhang & Tan, 2001). The holding costs are directly dependent on the inventory level shown in Table 10. Since there is a direct relation between inventory level and inventory holding costs, the results are the same as for the previous KPI. Table 11 shows the inventory holding costs per concept. As can be seen, concept 2 performs the best whereas the current situation results in the highest holding costs. As expected, concept 2 also results in a reduction in inventory holding costs of 12.4%. For confidentiality reasons, percentages are used instead of actual numbers again.

Table 11: Inventory holding costs performance measure results

	Inventory holding costs
Current	100%
Concept 1	96%
Concept 2	88%
Concept 3	98%

Inventory turns

Inventory turns is determined by dividing the cost of goods sold with the average inventory investment (Zhang & Tan, 2001). This measures the number of times inventory is turned over during the year. This measure is again directly dependent on the inventory levels shown in Table 10. As expected, the results are the same as for inventory level and inventory holding costs. The cost of goods sold for one year is dependent on the weekly move rate and the cost per wafer handler. Table 12 shows the results of the inventory turns KPI. Concept 2 performs best followed closely by concept 1, the current situation has the lowest inventory turns.

Table 12: Inventory turns performance measure results

	Inventory turns
Current	2.82
Concept 1	2.95
Concept 2	3.21
Concept 3	2.88

Conclusion asset management performance measures

Concept 2 performs the best in this dimension for all three KPIs. First of all, the theoretical inventory value is the lowest due to the rescheduling costs, and the least buffer required at the CODP. The remaining KPIs are directly dependent on the inventory level. Therefore, it is logical that concept 2 also performs the best on these KPIs. Concept 2 is closely followed by concept 1. However, concept 1 does not use the commonality in the process as finished wafer handlers are stocked. Within the limited scope of this thesis, concept 1 could be a viable option. However, applying concept 1 to the XT product family as well would result in an enormous safety stock since all end-items would have to be stocked.

6.4.3. Customer service performance measures

This section describes the fill rate and order lead time customer service KPIs. First, the fill rate is analyzed followed by the order lead time.

Fill rate

For the determination of the customer service performance measures ChainScope has been used. ChainScope is a multi-echelon tool for supply chain evaluation and optimization. For a full explanation on ChainScope, consult Appendix K. ChainScope is designed to analyze a complete supply chain from a multi-echelon perspective. This tool allows the evaluation of the current performance, and the evaluation of three *postponement* concepts. It is important to note that ChainScope is based on mathematical models and thus, it is not a discrete-event simulation. ChainScope also has an optimization function to determine the optimal stock levels. However, since the goal in this section is to evaluate the performance of the different concepts according to the design described in this chapter, the optimization function is not used.

The entire BOMs for the two end-items are not modelled for the ChainScope analysis, since this would not be possible within the time frame of this project. Instead, several critical modules are included entirely up until suppliers of *Parts*. The expectation is that the fill rates will be approximately the same because safety stock is added at the CODP to catch variable demand and that the safety times are unchanged.

Table 13 shows the result of the ChainScope performance evaluation. As expected, the fill rate for the different concepts are similar as the fill rate of the current situation. The current situation scores approximately 91%. Considering that the target is 95% this model can be assumed valid since human interference is not included in the model as well as other non-modellable flexibility measures.

Table 13: Fill rate performance measure results

	Fill rate
Current	90.6%
Concept 1	91.2%
Concept 2	89%
Concept 3	89.1%

Order lead time

This KPI concerns the total lead time of a product. It is defined as average time from when a backorder is generated to the time the shipment is received at the customer (Zhang & Tan, 2001). The equation for this is the manufacturing lead time + transportation time + order processing time. The manufacturing lead time is defined as the moment an order is processed to when the order is shipped to the customer. This is unrelated to the total lead time of VDL ETG to produce a WH, which is substantially longer. The order lead time changes significantly with the implementation of *postponement*. The transportation time is zero days, as it is delivered the same day as it is sent by VDL ETG.

Current situation

Currently, the order lead time is 18 weeks. The current order processing time is maximum two weeks. This is long considering to the amount of work required to accept an order. The manufacturing time is currently 16 weeks. However, this is dependent on how quickly the order is accepted. The transportation time is zero weeks.

Order lead time concept 1

In the first concept, the wafer handlers are assembled to stock (ATS) and the order penetrates the system after FASSY. The manufacturing time is reduced to zero since *Parts*, PRE-ASSY, and FASSY are done anonymously and finished wafer handlers are kept on stock. The order acceptance process is done by the *order manager* and *integral planner.* They indicated that this can easily be done within a week as the current order acceptance time is unnecessarily long. Therefore, if *postponement* is implemented, an order processing time of one week is used. Figure 27 shows the order lead time of concept 1.

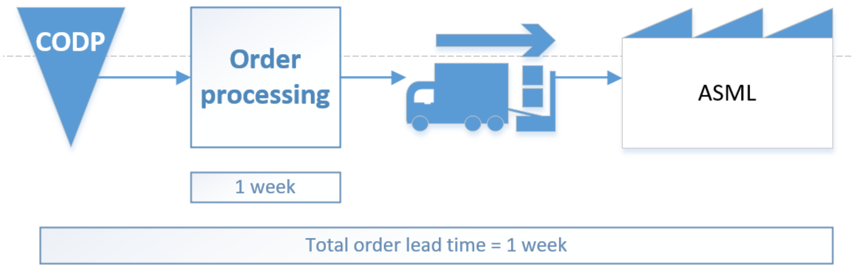


Figure 27: Order lead time concept 1

Order lead time concept 2

In the second concept, the order penetrates the system before FASSY. All operations before FASSY are done *anonymously*. Therefore, the manufacturing time consists only of FASSY. The order process is equal to concept 1 which takes one week. Therefore, the order lead time is four weeks. Figure 28 shows the order lead time of concept 2.

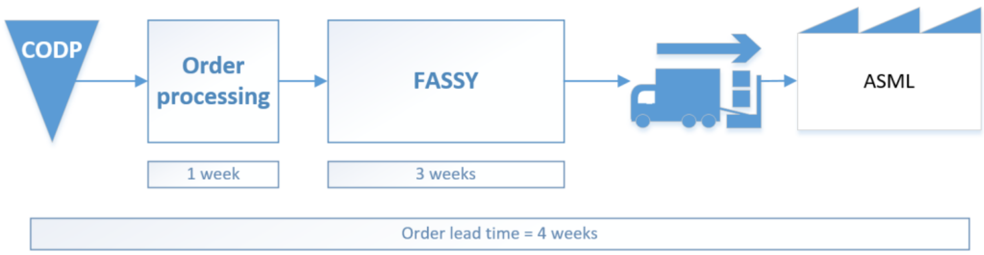


Figure 28: Order lead time concept 2

Order lead time concept 3

In this scenario, the order penetrates the system before PRE-ASSY. Therefore, the manufacturing time consists of PRE-ASSY plus FASSY. This results in a manufacturing time of five weeks. Order processing again takes one week, which results in a total order lead time of six weeks. Figure 29 shows the order lead time for concept 3.

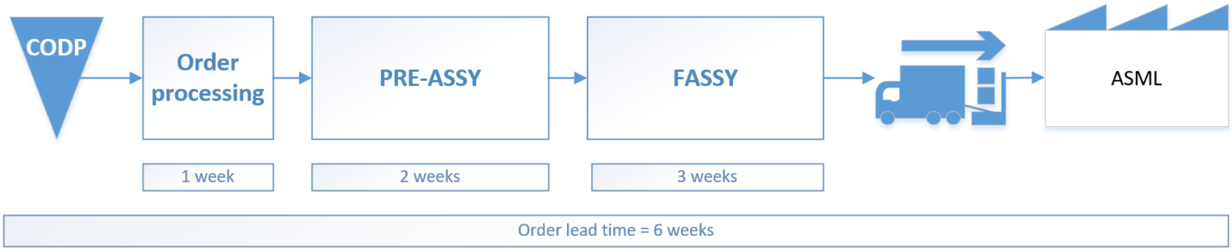


Figure 29: Order lead time concept 3

Conclusion order lead time

From a customer's perspective, a shorter lead time will always be preferable. Therefore, the first concept is the best option from the customer's perspective. For VDL ETG, a shorter lead time also provides benefits since the ability to deliver with a short lead time is considered critical for the success of a company (Can, 2008). Moreover, the responsiveness of VDL ETG also increases by providing short and reliable lead times (Skipworth & Harrison, 2004). The full results are shown in Table 14. All the potential concepts are a major improvement compared to the current situation with respect to the order lead time. First of all, because the absolute lead time will cut by at least 67%. Moreover, ASML stated that their customer demand becomes clear six weeks in advance. Therefore, from an information point of view, the new concepts would also provide significant benefits.

Table 14: Order lead time performance measure results

	Manufacturing time	Order processing time	Transportation time	Order lead time
Current	16 weeks	2 weeks	0 weeks	18 weeks
Concept 1	0 weeks	1 week	0 weeks	1 week
Concept 2	3 weeks	1 week	0 weeks	4 weeks
Concept 3	5 weeks	1 week	0 weeks	6 weeks

6.4.4. Conclusions postponement performance evaluation

This section describes the results of the performance evaluation of the implementation of *postponement*. The framework of Zhang & Tan (2001) is combined with the rescheduling cost performance metric of Vieira et al. (2003). Table 15 shows a summary of the performance evaluation. Option 1 means the best choice and option 4 means the worst choice on that specific category. As analyzed, concept 1 performs the best on rescheduling costs of end-items. However, the rescheduling costs are included in the asset management category since they are included in the inventory level. Therefore, Table 15 only shows asset management and customer service. Concept 1 shows the best option for customer service due to the order lead time of one week. Concept 2 shows the best results for the asset management measures. As can be seen from the table, the current situation shows the worst performance on all performance measures. Concept 3 performs third on all performance measures showing significant improvements over the current situation, but not as good as the other two concepts.

Table 15: Summary performance evaluation framework

Categories	Performance measures	Option 1	Option 2	Option 3	Option 4
Asset management	Inventory level | Inventory holding cost | Inventory turns	Concept 2	Concept 1	Concept 3	Current
Customer service	Fill rate | Order lead time	Concept 1	Concept 2	Concept 3	Current

Both concept 1 and 2 perform best on one performance measurement category and second on the other. However, the performance evaluation only focused on one product family. Both product families show at least 50% commonality, which would not be used in concept 1. Implementing concept 1 for both product families would result in very high safety stock since all the different WHs would have to be stocked separately. Considering the minimal difference between the first and second concept, and the downsides of implementing the first concept, the conclusion is that the second concept should be implemented at VDL ETG.

6.5. Recommendation and implementation postponement strategy

From the drivers of *postponement* analysis, it became clear that implementing *postponement* is beneficial to the AWH chain of VDL ETG. The main reasons are the high commonality between end-items (Ferreira et al., 2015), the current location of the differentiating processes, the demand uncertainty (Yang et al., 2004) and the negative demand correlation (Garg & Tang, 1997; Swaminathan & Lee, 2003).

The conclusion of the performance evaluation was that the second concept is the best option. For the implementation of *postponement* according to concept 2, several changes must be made. First of all, the PRE-ASSY process needs to be changed. Currently, part of this process is done *anonymously,* and certain critical modules are produced *on order*. With this concept, all items that are assembled in PRE-ASSY need to be done *anonymously.* This does not require product changes, since the same modules will be assembled. The only change that is necessary is the configuration in the ERP system. For FASSY, nothing changes, as this remains fully *on order*. To be able to reduce the order lead time, safety stock needs to be added at the CODP to catch variable demand. The added safety stock levels need to be added in the ERP system as well.

The solution design only focused on the NXT product family. However, from the commonality analysis it became very clear that this can also be implemented for the XT product family. Considering the commonality in product and process, it is expected that concept 2 will also prove the most beneficial for this product family. However, the performance evaluation framework should also be applied to the XT product family to confirm this statement. After PRE-ASSY is changed to *on order* for the NXT, the XT can be switched easily since many modules are similar. Therefore, very few ERP changes are necessary. Finally, safety stock calculations need to be redone including the uncertain end-item demand of the XT product family and the negative correlations. Including both product families will further decrease the necessary safety stock since 50% of all components are shared by all end-items. The more end-items are included, the more the risk-pooling effect of aggregated demand results in a higher inventory efficiency (Baker, 1985).

In the future, more products are added to the current catalogue. Since they are mostly variations of the current produced wafer handlers, the commonalities are again very high. This means that once these items are produced regularly, they can be added to the *postponement* strategy. Figure 30 shows how the product families will be in the near future. When these items are added, the safety stock calculations need to be redone including the new end items. The profitability of *postponement* is expected to increase even further in this scenario since the inventory efficiency will improve.

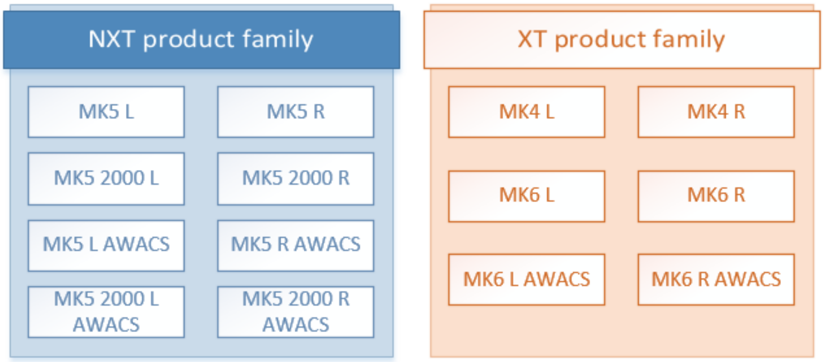


Figure 30: Future wafer handler product families

Chapter 7. Conclusion and recommendations

This chapter revisits the research questions stated in the first chapter and summarizes the conclusions that are drawn from this thesis. After that, the discussion and limitations of the thesis are provided. The recommendations for VDL ETG are discussed afterwards. Finally, the limitations are indicated and the recommendations for the future are provided.

7.1. Research questions

This section provides answers on the research questions of chapter 1.

RQ1: What are the key characteristics of the internal supply chain of VDL ETG?

The internal supply chain of VDL ETG, and specifically the AWH chain, is characterized by high levels of commonality between end-items. Overall, the end-items in scope show a total commonality percentage of 50%. If the two product families are separated, the NXT product family shows a commonality percentage of 98% and the XT product family shows a commonality percentage of 88%. This commonality can potentially result in inventory efficiency. However, in the current situation the commonality is not used since items are allocated to an order long before the differentiation point occurs.

VDL ETG uses six different logistical models with their suppliers: 1) MTO, 2) Two-bin, 3) Fixed Pricing (FP), 4) Logistical Forecast Agreement (LFA), 5) Vendor Managed Inventory (VMI), and 6) Vendor Managed and Owned Inventory. The differences between these models are based on the owner of inventory, responsibility and frequency of the replenishment decision and the commitment. These models have a direct effect on the expected inventory on hand as is explained in chapter 3.

RQ2: What is the theoretical inventory level based on current parameters?

The inventory performance on the metrics that are used by VDL ETG appeared high. However, there were no theoretical targets in place to measure this. The general, 'the lower the better' applied. KPIs do not carry much value without targets and managers are better able to understand trends, identify potential problems and assist in making quick and effective decisions via the measurement of KPIs (Rachad et al., 2017). To develop inventory targets, single-item single-echelon inventory models were used (Silver et al., 1998). After the inventory targets were determined, a delta analysis is done to detect where the biggest differences lie.

From chapter 3 it can be concluded that the largest delta between theoretical inventory value and the actual investment in inventory is due to excessive project WIP. Focusing on this category it appears that over 98% is caused by end-items that are kept in the cleanroom waiting to be delivered. Therefore, the focus of this project is shifted to the project WIP because this is where the biggest potential gains are possible concerning inventory investment.

RQ3: What uncertainties propagate throughout the internal supply chain of VDL ETG?

Due to the delta analysis done in chapter 3, the focus was shifted to *project WIP* and the uncertainties related to this. According to Ho (1989) uncertainty should be divided into system uncertainty and environmental uncertainty and these uncertainties need to be analyzed independent from one another (Kampen et al., 2010). The demand of the end-items follows a Poisson distribution. Both the first delivery date as well as the actual delivery date have been used for this determination. Chapter 4 also states that the rescheduling by ASML forms a serious problem. On average, finished wafer handlers were on stock as WIP before shipment for 30-35 days. This resulted in extra investment in *project WIP* of approximately 80% of the total theoretical inventory value of the supply chain. The moment of rescheduling is also important. From chapter 4 it appeared that the rescheduling increases substantially in the final weeks. This complies with the information provided by ASML that their demand becomes clear approximately six weeks before their production.

Chapter 3 shifted the focus towards *project WIP* because the biggest inventory reduction could be achieved there. Chapter four analyzed that this large project WIP was caused by rescheduling by ASML in the final weeks. The diagnosis indicated that the rescheduling effect on inventory will probably reduce if the order lead time is reduced by shifting the CODP downstream. To realize this, *postponement* can be implemented.

RQ4: How can VDL ETG reduce its inventory investment while maintaining the service level?

To reduce the investment in inventory three different type of *postponement* concepts were analyzed for the NXT product family (MK5L and MK5R). The concept which showed the best results meant placing the CODP before FASSY which reduced the order lead time to four weeks. This coincided with the commonality analysis that showed that the differences between configurations is made at FASSY. The entire process before FASSY is identical for both configurations. To determine the best concept for the implementation of *postponement*, the performance measurement framework of Zhang & Tan (2001) has been used. However, since rescheduling was the cause for choosing this solution direction, a rescheduling cost performance metric of Vieira et al. (2003) has been added to the framework of Zhang & Tan (2001). The results from the performance evaluation indicated that both the CODP after FASY as well as before FASSY showed the best results. However, applying *postponement* for all end-items would mean stocking six types of finished wafer handlers which would result in a very high safety stock investment due to the high prices of the wafer handlers. Therefore, concept 2 (CODP before FASSY) was chosen. To conclude, VDL ETG can reduce its inventory investment by implementing a *postponement* strategy and placing the CODP before FASSY reducing the order lead time to four weeks.

RQ5: How can VDL ETG implement these improvements?

Due to the current design of the supply chain, *postponement* can be implemented without rigorously changing the design of the supply chain. The only design difference is required is at PRE-ASSY, which needs to be standardized. Currently, the modules assembled here are partly done *anonymous,* and partly *on order*. Placing the CODP before FASSY means that all modules at PRE-ASSY need to be produced *anonymously.* However, no product changes are necessary to standardize PRE-ASSY because the modules assembled there are identical for both end-items. The only change that is necessary is that in the ERP system of VDL ETG, these items need to be changed from *on order* to *anonymous.*

VDL ETG also needs to buffer extra items to catch variable demand at the CODP. The current safety time buffers against lead time uncertainty. Consequently, the required demand uncertainty buffer needs to be added to existing buffer values. The buffer values determined in chapter 6 need to be adapted in the ERP system.

7.2. Discussion and limitations of the study

The safety stock determination in chapter 6.2.4. only includes demand uncertainty. Kampen et al. (2010) stated that demand and supply uncertainties are normally studied in isolation from one another. Therefore, the supplier uncertainties are not included in the determination of the required safety stock. This is done to focus on the changes caused by the implementation of *postponement*. If supplier uncertainty would be included, the safety level would drop compared the current situation since the current buffer levels are excessive (three weeks of demand for almost all items independent of uncertainty). Therefore, it would be difficult to indicate what part of the reduced inventory was caused by the implementation of *postponement* and what part was caused by the reduction of buffer due the implementation of the safety stock formula. To be able to make a fair comparison, supplier uncertainty has not been included in the safety stock formula.

However, if one wishes to include supplier uncertainty as well, a different formula is required. This can be derived from the safety stock formula of Jacobs, Berry, Whybark, & Vollmann (2011):

$$SS_i = k_\beta \sqrt{LT_i * \sigma_D{}^2 + \mu_D^2 * \sigma_{LT}^2} \tag{28}$$

$$\sigma_{LT}^2 = Lead\ time\ variance$$

$$\mu_D = Mean\ demand$$

These formulas are rewritten to include component commonality and multiple end-items. This results in the following formulas. Formula (29) is for uncommon components. Formula (30) is for common components with independent demand. Formula (31) is for common components with dependent demand. The proof for formulas (29), (30), and (31) is provided in appendix I.1. I.2, and I.3. respectively.

$$SS_i = k_\beta \sqrt{LT_i * a_{ij}^2 \sigma_j^2 + [a_{ij}\mu_j]^2 * \sigma_{LT}^2} \tag{29}$$

$$SS_i = k_\beta * \sqrt{\sum_{j=1}^{n} a_{ij}^2 \sigma_j^2 * LT_i + \left[\sum_{j=1}^{n} [a_{ij}\mu_j]\right]^2 * \sigma_{LT}^2} \tag{30}$$

$$SS_i = k_\beta * \sqrt{\left(\sum_{j=1}^{n} a_{ij}^2 \sigma_j^2 + \sum_{j=2}^{n}\sum_{k=1}^{j-1} 2\rho_{jk} a_{ij} a_{ik} \sigma_j \sigma_k\right) * LT_i + \sum_{j=1}^{n} [a_{ij}\mu_j]^2 * \sigma_{LT}^2} \tag{31}$$

To conclude, the supply uncertainty has not been incorporated into the evaluation of the solution design to enable a fair comparison of the changes caused by the implementation of *postponement*. To further reduce the required buffer, formula (29), (30), and (31) can be used to determine the new joint buffer size for demand and lead time uncertainty.

The rescheduling simulation of chapter 6 only includes rescheduling during FASSY. All rescheduling before FASSY, has not been incorporated. According to De Kok & Inderfurth (1997) it is almost impossible to express the effect of rescheduling on costs in most practical situations. However, since rescheduling messages during FASSY does not result in schedule changes for VDL ETG, it is technically not a rescheduling problem anymore. This allowed the determination of the effect on inventory level. However, for rescheduling before FASSY, this assumption does not hold anymore which means that the effect of rescheduling is almost impossible to determine for this period (De Kok & Inderfurth, 1997). Another limitation concerning the rescheduling simulation is that all rescheduling is assumed to be caused by ASML. However, it is also possible that a wafer handler was longer on stock due to yield, capacity, or different escalation problems of VDL ETG. This has not been included in the analysis.

The inventory levels have been determined using single-item single-echelon inventory models of Silver et al. (1998). These are often used because of their simplicity and limited computational effort required. However, they do not represent fully the complex multi-echelon situation at VDL ETG. Moreover, the inventory levels only included demand uncertainty and supplier lead time uncertainty. Other uncertainties like yield have not been included.

Implementing a change in a large company like VDL ETG can be difficult. Change management theory has not been applied to support the implementation of the solution design. This can be considered by management to ensure that the solution design is implemented as intended.

Finally, the ChainScope evaluation of the different *postponement* concepts did not include the full BOMs of the MK5L and the MK5R. Due to the size and complexity of this BOM, this was not deemed realistic within the time frame of the thesis.

7.3. Recommendations for VDL ETG

This section explains the recommendations for VDL ETG:

- Implement the *postponement* strategy of concept 2 to push the location of the CODP downstream towards the customer and to reduce the order lead time to four weeks.
- The current order process is very outdated. Even though it is possible to reduce the order lead time to one week with the current method. This can be reduced much further by automizing the procedure. This can result in a further reduction of the order lead time.
- Implementing *postponement* can be valuable for the XT product family as well. Therefore, the same analysis should be done for the XT product family as well. Moreover, if the new wafer handlers that are currently in development are added on a regular basis, these should be included as well.
- Use the setup of the rescheduling analysis to analyze the requested due date differences in the new situation to determine whether the number of rescheduling messages really goes down as expected.
- The single-item single-echelon inventory levels can be used to regularly check the differences between the theoretical inventory levels and the current inventory levels. It is important that parameter changes are also changed when calculating the theoretical inventory levels.

7.4. Scientific contribution

This research project has several scientific contributions. The first contribution is the addition of safety stock determination at the CODP to the framework of Ferreira et al. (2015). The theoretical framework did not include buffering at the CODP. This has been added to the existing framework and was based on the work of Baker (1985). The addition means the theoretical framework of Ferreira et al. (2015) is extended and improved. Moreover, the work of Baker (1985) assumed a fixed lead time and a lead time of one period. Both assumptions do not hold for VDL ETG as was proven in this thesis. Therefore, these assumptions needed to be relaxed to include stochastic lead time longer than one period. This resulted in safety stock formulas under stochastic lead time and demand with component commonality and multiple end-items. Furthermore, the effect of percentage of commonality on the required safety stock is also shown to be exponentially decreasing unless the demand correlation is fully positive. Furthermore, it has been mathematically proven that a mistake is made in safety stock formula (4) of Baker (1985). The performance evaluation framework of (Zhang & Tan, 2001) did not include the effect of rescheduling on the inventory level as a result of *postponement*. The effect of rescheduling is almost impossible to calculate according to De Kok & Inderfurth (1997). This thesis provides a simple method adapted from the thesis of Kamps (2015). The undershoot formulas of de Kok (2002) have also been extended to include multiple end-items and commonality. First, these formulas are mathematically derived. Subsequently, the effect of percentage of commonality on the expected cumulative undershoot is also proven to be exponentially decreasing. Finally, Ferreira et al. (2015) stated that their framework required implementation in a specific environment to test its applicability. Despite of the fact that not all steps of the framework were followed, it still formed the basis of the implementation process and therefore, the framework has been applied in the specific high-tech sector.

7.5. Future research directions

- This study included the effect of postponement on the rescheduling costs. However, technically it was not a rescheduling problem since VDL ETG did not comply to rescheduling messages during FASSY A future research direction can be to link the effect of postponement on rescheduling.
- True inventory optimization is still not possible for real life ATO-systems. Therefore, the need for analytical models that explain inventory performance in ATO-systems remains.
- This thesis focused on the AWH chain of VDL ETG. It would be interesting to check whether other chains within VDL ETG could benefit from the implementation of *postponement* as well. At least an evaluation of the current CODP can be useful as well as a commonality analysis.
- VDL ETG currently only uses VMI with their suppliers. However, it could also be interesting to investigate the possibilities of implementing VMI with customers.

Bibliography

Alatas, G. (2017). *Multi-echelon inventory analysis: A case study of setting inventory targets and assessing the impact of uncertainty factors*. Eindhoven University of Technology.

Arts, J. (2015). *Improving tactical buffer management and operational control under uncertainties in assemble-to-order systems*. Eindhoven University of Technology.

Ashayeri, J., & Selen, W. (2005). An application of a unified capacity planning system. *International Journal of Operations & Production Management*.

Baker, K. R. (1985). Safety stocks and component commonality. *Journal of Operations Management*, *6*(1), 13–22.

Caglar Can, K. (2008). *Postponement, Mass Customization, Modularization and Customer Order Decoupling Point: Models and Relationships*. *Building*. Linkoping University.

Collier, D. A. (1981). The measurement and operating benefits of component part commonality. *Decision Sciences*, *12*(1), 85–96.

Davies. (1993). Effective supply chain management. *Sloan Management Review*, *34*(4), 35–46.

De Kok, A. G. (2002). Analysis of one product/one location inventory control models. *Unpublished Course Notes at Technische Universiteit Eindhoven [circa 2002]*.

de Kok, T. G., & Fransoo, J. C. (2003). Planning supply chain operations: definition and comparison of planning concepts. *Handbooks in Operations Research and Management Science*, *11*, 597–675.

De Kok, T., & Inderfurth, K. (1997). Nervousness in inventory management: comparison of basic control rules. *European Journal of Operational Research*, *103*(1), 55–82.

Delignette-Muller, M. L., & Dutang, C. (2015). fitdistrplus: An R package for fitting distributions. *Journal of Statistical Software*, *64*(4), 1–34.

Feitzinger, E., & Lee, H. L. (1997). Mass customization at Hewlett-Packard: the power of postponement. *Harvard Business Review*, *75*, 116–123.

Ferreira, K. A., Tomas, R. N., & Alcântara, R. L. C. (2015). A theoretical framework for postponement concept in a supply chain. *International Journal of Logistics Research and Applications*, *18*(1), 46–61.

Garg, A., & Tang, C. S. (1997). On postponement strategies for product families with multiple points of differentiation. *IIE Transactions*, *29*(8), 641–650.

Grange, F. (1998). Challenges in modeling demand for inventory optimization of slow-moving items. In *1998 Winter Simulation Conference. Proceedings (Cat. No. 98CH36274)* (Vol. 2, pp. 1211–1217). IEEE.

Grubbström, R. W., & Tang, O. (2000). Modelling rescheduling activities in a multi–period production-inventory system. *International Journal of Production Economics*, *68*(2), 123–135.

Hax, A. C., & Candea, D. (1984). *Production and inventory management* (Vol. 1). Prentice-Hall Englewood Cliffs, NJ.

Ho, C. (1989). Evaluating the impact of operating environments on MRP system nervousness. *International Journal of Production Research*, *27*(7), 1115–1135. https://doi.org/10.1080/00207548908942611

Jacobs, F. R., Berry, W. L., Whybark, D. C., & Vollmann, T. (2011). *Manufacturing planning and control* *for supply chain management*. McGraw-Hill New York.

Kampen, T. J. Van, Donk, D. P. Van, & Zee, D. Van Der. (2010). Safety stock or safety lead time : coping with unreliability in demand and supply, *7543*. https://doi.org/10.1080/00207540903348346

Kamps, T. C. (2015). *Improvement of rescheduling policies in a dynamic multi-echelon MTO/ATO environment at VDL ETG*. Technische Universiteit Eindhoven.

Lee, H. L., & Billington, C. (1994). Designing products and processes for postponement. In *Management of Design* (pp. 105–122). Springer.

Lee, H. L., & Tang, C. S. (1997). Modelling the costs and benefits of delayed product differentiation. *Management Science*, *43*(1), 40–53.

Little, J. D. C., & Graves, S. C. (2008). Little's law. In *Building intuition* (pp. 81–100). Springer.

Myung, I. J. (2003). Tutorial on maximum likelihood estimation. *Journal of Mathematical Psychology*, *47*(1), 90–100.

Olhager, J. (2003). Strategic positioning of the order penetration point. *International Journal of Production Economics*, *85*(3), 319–329. https://doi.org/10.1016/S0925-5273(03)00119-1

Rachad, S., Larabi, Z. E. I., Nsiri, B., & Bensassi, B. (2017). Inventory management in closed loop structure using KPIs. *International Journal of Applied Engineering Research*, *12*(15), 4864–4869.

Silver, E. A., Pyke, D. F., & Peterson, R. (1998). *Inventory management and production planning and scheduling* (Vol. 3). Wiley New York.

Skipworth, H., & Harrison, A. (2004). Implications of form postponement to manufacturing: A case study. *International Journal of Production Research*, *42*(10), 2063–2081. https://doi.org/10.1080/00207540410001661373

Swaminathan, J. M., & Lee, H. L. (2003). Design for postponement. *Handbooks in Operations Research and Management Science*, *11*, 199–226.

Swaminathan, J. M., & Tayur, S. R. (1998). Managing broader product lines through delayed differentiation using vanilla boxes. *Management Science*, *44*(12-part-2), S161–S172.

Van Aken, J. E., & Berends, H. (2018). *Problem solving in organizations*. Cambridge university press.

Van Hoek. (1999). Postponement and the reconfiguration challenge for food supply chains. *Supply Chain Management: An International Journal*.

Van Hoek, Commandeur, H. R., & Vos, B. (1998). Reconfiguring logistics systems through postponement strategies. *Journal of Business Logistics*, *19*(1.1998), 33.

Van Hoek, R. I. (2001). Rediscovery of postponement a literature review and directions for research. *Journal of Operations Management*, *19*(2), 161–184. https://doi.org/10.1016/S0272-6963(00)00057-7

Vieira, G. E., Herrmann, J. W., & Lin, E. (2003). Rescheduling manufacturing systems: a framework of strategies, policies, and methods. *Journal of Scheduling*, *6*(1), 39–62.

Wacker, J. G., & Treleven, M. (1986). Component part standardization: an analysis of commonality sources and indices. *Journal of Operations Management*, *6*(2), 219–244.

Wikner, J., & Rudberg, M. (2005). Integrating production and engineering perspectives on the customer order decoupling point. *International Journal of Operations and Production Management*, *25*(7), 623–641. https://doi.org/10.1108/01443570510605072

Yang, B., & Burns, N. (2003). Implications of postponement for the supply chain. *International Journal of Production Research*, *41*(9), 2075–2090.

Yang, B., Burns, N. D., & Backhouse, C. J. (2004). Postponement: A review and an integrated framework. *International Journal of Operations and Production Management*, *24*(5–6), 468–487. https://doi.org/10.1108/01443570410532542

Zhang, & Tan, G.-W. (2001). Classification of Postponement Strategies and Performance Metrics Framework. *PACIS 2001 Proceedings. 4.*, 4. Retrieved from https://aisel.aisnet.org/pacis2001/4

Zinn, W. (1990). Should you assemble products before an order is received? *Business Horizons*, *33*(2), 70–74.

Zinn, W., & Bowersox, D. J. (1988). Planning physical distribution with the principle of postponement. *Journal of Business Logistics*, *9*(2).

Appendix

Appendix A. Final Assembly process

This appendix shows the one-piece flow shop of FASSY. Because it is a one-piece flow shop, once an order starts FASSY, it is not rescheduled anymore. This is done because if an order is rescheduled the result is lost capacity, because the next order has to start at the beginning again.

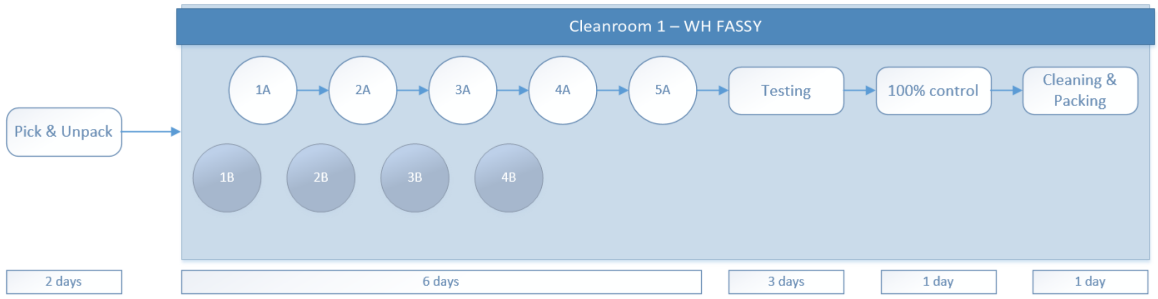


Figure 31: Final assembly process

Appendix B. Mathematical derivation extension undershoot formulas

This appendix provides the mathematical proof for the extension of the undershoot formulas of De Kok (2010) to include multiple end-item, commonality and demand correlation.

$$E[U_i] = \frac{\alpha + 1}{2\lambda} \tag{7}$$

$$\alpha = \frac{E^2[D(0,R)]}{\sigma^2[D(0,R)]} \tag{8}$$

$$\lambda = \frac{\alpha}{E[D(0,R)]} \tag{9}$$

Proof

Assume two end-item: X and Y (dependent demand). And one component m

Demand per period is mutually independent and identically distributed stochastic variable

Expectation

$$E[D(0,R)] = RE[D]$$

$$E[X] = Demand\ end\ item\ X$$

$$E[Y] = Demand\ end\ item\ Y$$

$$D = total\ demand = X + Y$$

$$E[D] = E[X + Y] = E[X] + E[Y]$$

Component m is required *a* times in end-item X, and *b* times in end-item Y.

$$Demand\ component\ m = E[aX + bY] = aE[X] + bE[Y]$$

$$RE[D] = R(aE[X] + bE[Y])$$

$$E[D(0,R)]^2 = (R(aE[X] + bE[Y]))^2$$

This can be generalized to multiple end items j and multiple required components a_{ij} and demand μ_j

$$E[D(0,R)]^2 = \left(R\sum_{j=1}^{n}[a_{ij}\mu_j]\right)^2 \tag{10}$$

Variance

$$\sigma^2(D(0,R]) = R\sigma^2(D)$$

$$\sigma^2(D) = V(D)$$

$$V(D) = V(aX + bY)$$

$$V(aX + bY) = a^2V(X) + b^2V(Y) + 2abCov(X,Y)$$

$$Cov(X,Y) = \rho_{XY}\sqrt{V(X)V(Y)}$$

$$V(aX + bY) = a^2V(X) + b^2V(Y) + 2ab\rho_{XY}\sqrt{V(X)V(Y)}$$

$$V(aX + bY) = a^2V(X) + b^2V(Y) + 2ab\rho_{XY}\sqrt{\sigma_X^2\sigma_Y^2}$$

$$V(aX + bY) = a^2\sigma_X^2 + b^2\sigma_Y^2 + 2ab\rho_{XY}\sigma_X\sigma_Y$$

$$\sigma^2(D(0, R]) = R(a^2\sigma_X^2 + b^2\sigma_Y^2 + 2ab\rho_{XY}\sigma_X\sigma_Y)$$

This can be generalized to multiple end items j and multiple required components a_{ij}

$$\sigma^2(D(0, R]) = R\left(\sum_{j=1}^{n} a_{ij}^2\sigma_j^2 + \sum_{j=2}^{n}\sum_{k=1}^{j-1} 2\rho_{jk}a_{ij}a_{ik}\sigma_j\sigma_k\right) \tag{11}$$

Appendix C. Effect of percentage of commonality on undershoot

The formulas for undershoot have been extended to include multiple end-items with commonality. Therefore, the effect of commonality on the undershoot will be determined in this appendix. Since the formulas use the same mathematical properties as in the safety stock formulas, the results are expected to be similar.

The same situation is used as in appendix H, a situation is assumed with two end items A and B and each item consists of 100 components. The demand follows a Poisson distribution with mean demand of $\mu_A = 1{,}4$ and $\mu_B = 0{,}6$. The standard deviation therefore is $\sigma_A = 1{,}18$ and $\sigma_B = 0{,}77$. To show the effect of commonality on safety stock, the lead time and lead time uncertainty are not included. The percentage of commonality is calculated using formulas (7), (8), (9), (10), (11). To show the effect, the cumulative undershoot of all items is used.

The first scenario is to check the relationship under independent demand. It is assumed that every component goes in an end-product only once. Figure 32 shows the relationship between the percentage of commonality and buffer stock under independent demand. This figure shows that increased commonality results in less buffer stock. Figure 32 can be described as exponentially decreasing. The equation for the graph and the R squared test is shown. The exponential decreasing function shows a very good fit. (R^2=0.98).

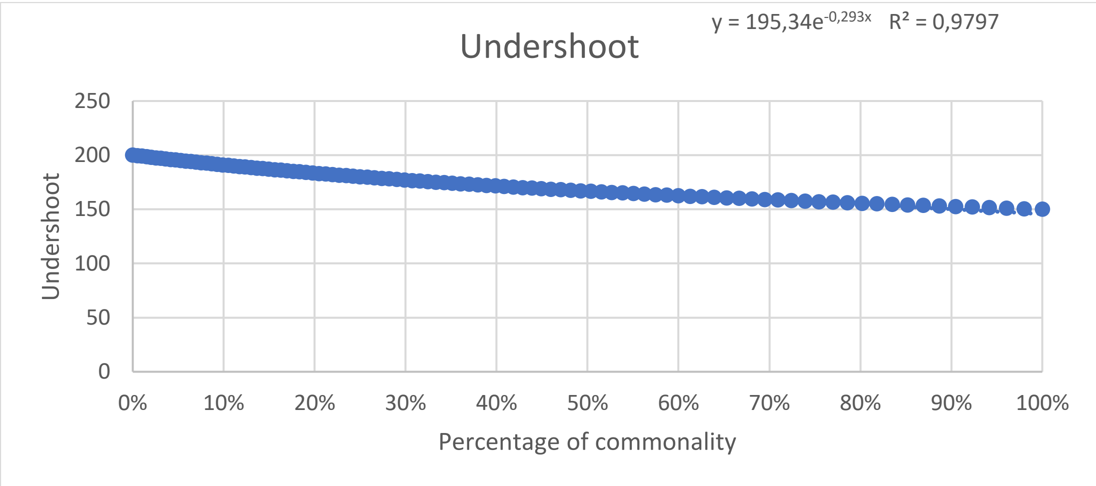


Figure 32: Effect of percentage of commonality on expected undershoot

Subsequently, this relationship is checked under dependent demand. To check the influence of demand correlation on the effect of the commonality percentage on buffer stock the two extreme values are used: full positive demand correlation and full negative demand correlation. First, a negative correlation of one is evaluated. As can be seen from figure 33 a negative correlation has an enormous impact on the relationship between commonality percentage and expected cumulative undershoot. Under a fully negative demand correlation, much higher inventory gains can be achieved. Figure 33 again is exponentially decreasing. The equation and R squared are shown at the top. This figure shows an even better goodness of fit ($R^2 > 0.99$)

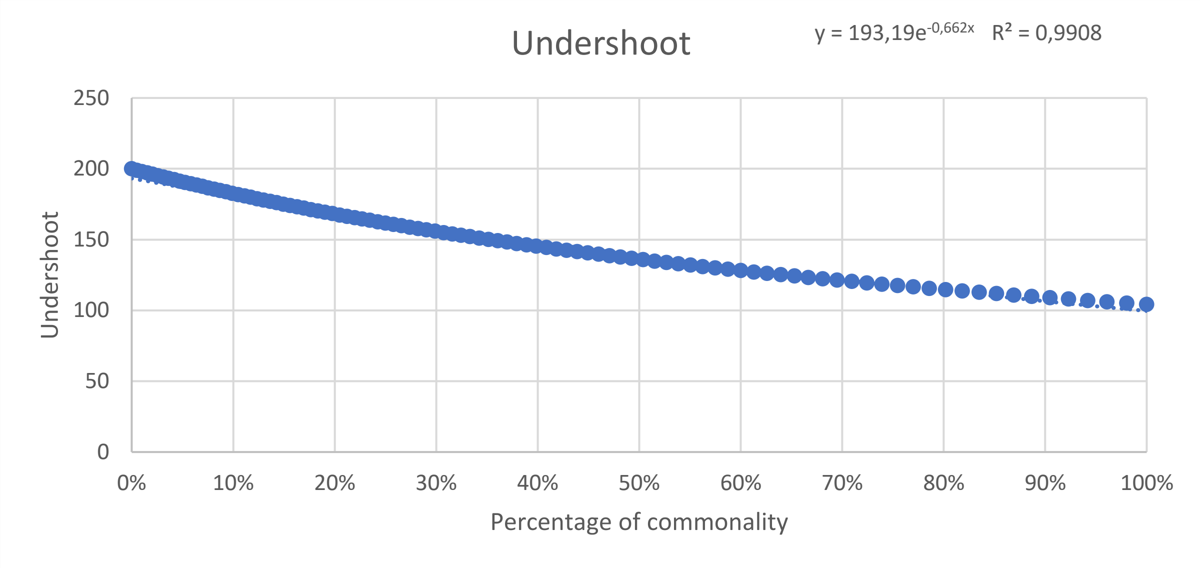


Figure 33: Relationship between commonality percentage and expected undershoot under full negative correlation

Since a negative demand correlation increases the inventory gains of commonality percentage, it is expected that less gains are possible with a fully positive demand correlation. This is shown in figure 34. This figure shows a very small exponential decreasing trend. An increase in commonality does result in less expected undershoot, but this effect is very small under a fully positive demand correlation. The R-squared test provided a goodness of fit of 0.97.

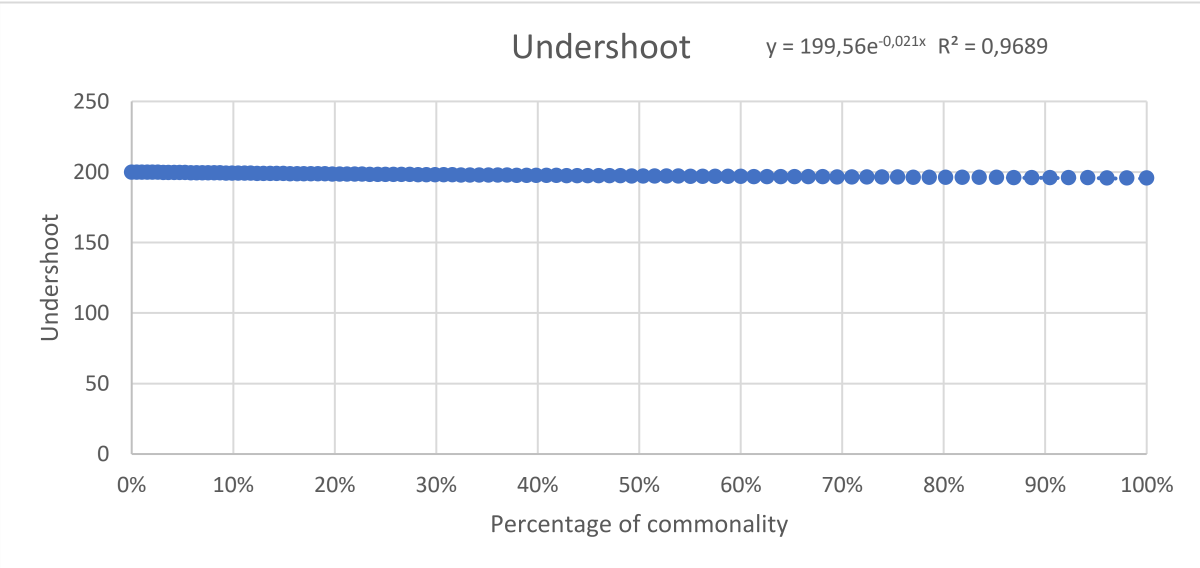


Figure 34: Relationship between commonality percentage and expected undershoot under full positive correlation

To conclude, increased commonality percentage results in substantial buffer reduction. Under a fully positive demand correlation, a minimal decrease in expected undershoot is shown. Under a fully negative correlation, a substantial decrease in expected undershoot is shown compared to independent demand. Both independent and negatively correlated demand show an exponential decrease in expected undershoot as the percentage of commonality increases.

Appendix D. Uncertainty analysis

Following the work of Ho (1989), the uncertainty is divided into environmental uncertainty and system uncertainty. The environmental uncertainty consists of supplier side and customer side whereas the system uncertainty entails the production uncertainty in *parts* and *systems.* The thesis focused on demand uncertainty due to the largest inventory delta for *project WIP.* However, the supplier uncertainty and system uncertainty have still been analyzed. These are shown in this appendix. First the supplier uncertainty is analyzed and after that, the system uncertainty. Following the work Kampen, Donk, & Zee (2010), the uncertainties will be considered independently and individually from one another.

D.1. Supplier uncertainty

The uncertainty of external suppliers is described in this section. This uncertainty is looked at from a quantity and a time perspective (Ho, 1989; Kampen et al., 2010). First, the lead time uncertainty is evaluated. After that, the delivery quantity is analyzed.

Supplier lead time uncertainty

This section analyzes the lead time of the suppliers towards VDL ETG. No distinction is made between deliveries to *Parts* or *Systems*. Data analyzed from the ERP system, and the planned and confirmed delivery date is compared to the actual delivery date. Twelve months of data is used (14-08-2018 until 13-08-2019), and only the ASML AWH chain is selected. This analysis focuses on absolute deviation in days. Relative delivery date deviance with respect to the lead time is not incorporated.

All order lines combined, the average difference in days is -0.07, with a standard deviation of 16.58 days. This means that, on average, orders are delivered slightly earlier than confirmed. Figure 35 shows the lead time uncertainty. To improve the readability of the graph, values < -80 and > 80 have been removed from the figure. Only 74 order lines fell outside this range. In general, more orders were advanced than delayed. However, the number of days delay was higher on average than the advancements. In total, 29% of the orders arrived too late, with an average delay of 12.7 days. 45% of the orders arrived too early, with an average of 8.6 days. Finally, 26% of the orders arrived precisely on the day they were supposed to arrive.

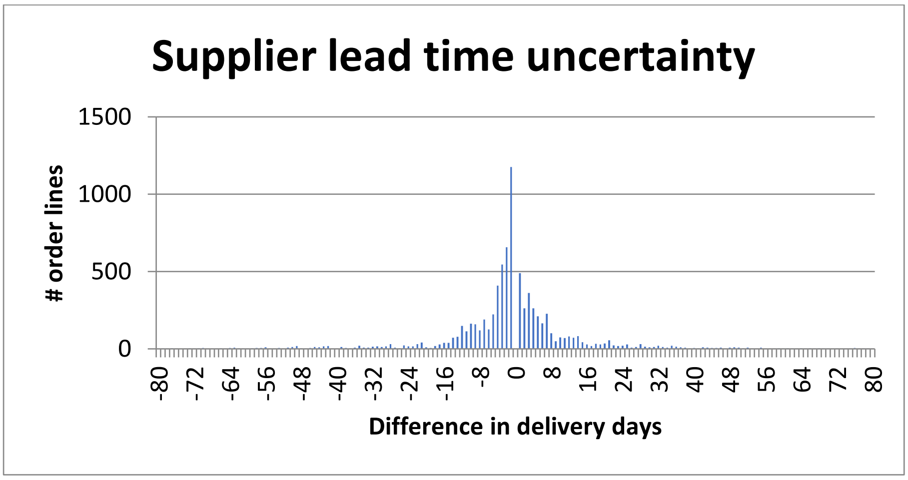


Figure 35: Supplier lead time uncertainty

Supplier delivery quantity uncertainty

When taking a quantity perspective, the suppliers of VDL ETG score significantly better. This analysis uses the same order lines as for the lead time analysis. In total, 97.2% of all order lines were delivered in the correct quantity. The average quantity difference is -0.91 units, with a standard deviation of

28.18 units. In the case of overage, the average surplus quantity is 27.8 units. In case of shortage, the average deficit amount is 44.9 units. Figure 36 shows the uncertainty in quantity for supplier deliveries. However, it is important to note that sometimes it occurs that an order is split into multiple orders because the supplier cannot deliver in full on the confirmed delivery date. In some instances, VDL ETG allows the supplier to deliver in multiple shipments. In that case, the order quantity is adapted to the amount of the split order. This results in orders counting as being delivered in full, whereas compared to the original order, it is not correct. Officially VDL ETG does not allow this, but in certain cases, to either prevent material shortage or to contain a good relationship with the supplier, exceptions are made. This does not occur often; the amount of split orders is 5.5%. To improve data accuracy, these split orders are removed from the analysis. Consequently, the number of order lines delivered in full is 91.7%. To improve the readability of the graph, two adjustments have been made. All orders that were delivered in full are removed from the graph, and order lines with a difference greater than ± 50 were removed as well. This resulted in the removal of 14 order lines. Figure 36 shows the supplier quantity deviations.

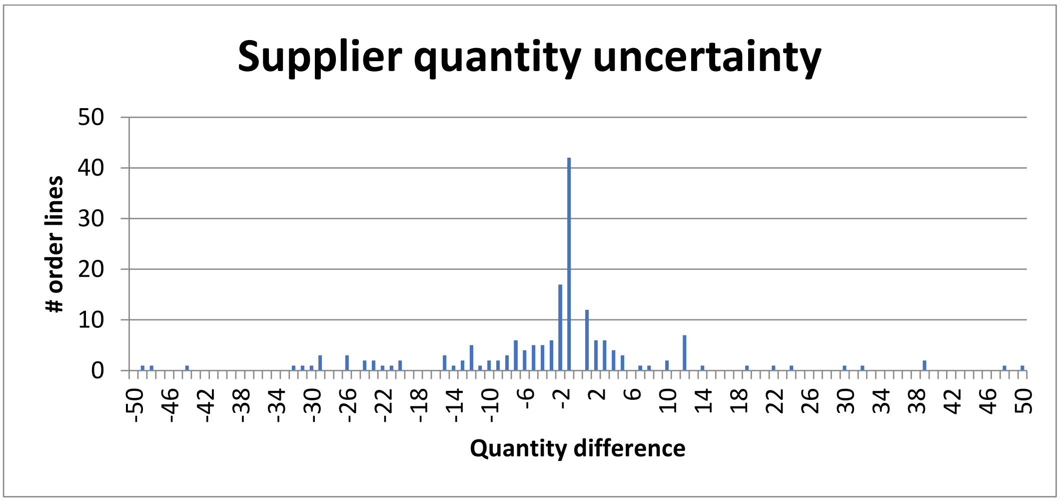


Figure 36: Supplier quantity uncertainty

The conclusion of this analysis that the delivered quantity with respect to the ordered quantity is good. Therefore, it is concluded that the lead time uncertainty poses a bigger problem for VDL ETG than the delivery quantity uncertainty.

D.2. System uncertainty

VDL ETG has two internal operations: *Systems* and *Parts*. As stated in the scope, *Parts* is seen as a black box and a supplier to *Systems*, it is vital to treat the production at *Parts* as a supplier as well. The lead time deviation can be analyzed with data from the ERP system. This is not analyzed structurally because of the many rescheduling activities that exist both in *Parts* and *Systems*.

Parts

The data for *Parts* is analyzed from 2018 until 2019. In the ERP system, a distinction is made between *Parts* 1 (sheet metal) and *Parts* 2 (mechanical workshop). They have been combined in this analysis. Sometimes items of *Parts* are outsourced due to insufficient capacity, or another company is cheaper. A total of 6.6% of the orders are outsourced. For the outsourced orders, a CLIP and ECLIP average score of 38.2% and 93.82% respectively. This means that almost all orders are delivered earlier than requested. For the remainder of this analysis, these orders are removed from the database since they come from suppliers.

Parts also has to deal with significant rescheduling problems. A lack of capacity, machine breakdown, material shortage, rejections, and wrong processing times in BaaN, are examples of internal reasons that an order is rescheduled. Another significant influence is the rescheduling done by ASML. This directly results in more rescheduling (the bullwhip effect) from VDL ETG towards *Parts* and their suppliers. First, *Parts* will be analyzed from a quantity perspective. The delivered quantity is compared to the ordered quantity. Figure 37 shows the difference between the number of items ordered and the number of items delivered. Orders which have been rejected are not included in the analysis, since yield is out of scope. The number of removed orders as a result of rejections is 7.8%. It is important to note that this is the absolute difference. Different items are produced with different batch sizes. This figure only shows the absolute difference. To improve the readability of the graph, the number of orders with the correct quantity has been removed. In total, 92% of the orders were delivered in full. It does not occur that more is produced than delivered. For certain items in *Parts,* a waste factor is used. However, this has no impact because the waste factor is not included in the ordered quantity. For example, if the waste is one item in a series of 10. The requested amount is 10, but the produced amount is 11, which after the fixed waste results in a delivery of 10 items. Figure 37 shows the quantity uncertainty of *Parts*. To improve readability, the order lines which were delivered in full are removed from the graph.

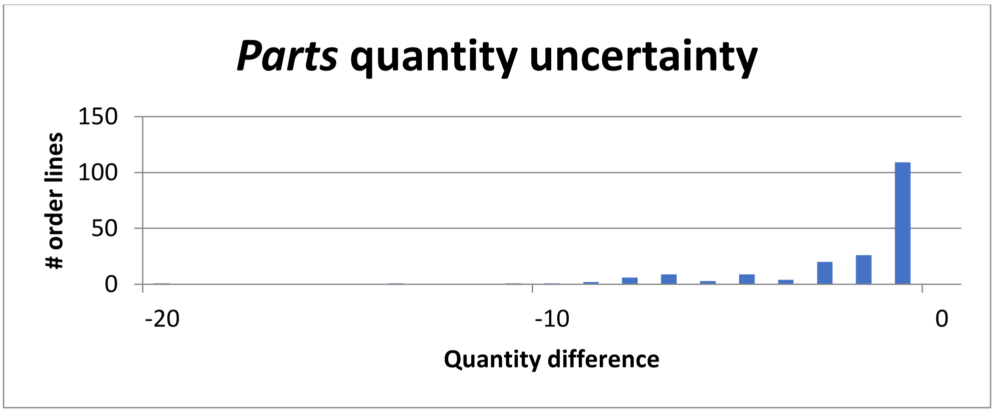


Figure 37: Parts quantity uncertainty

Parts is also exposed to lead time uncertainty. *Systems* is the biggest customer for *Parts*, this means that the primary customer is an internal customer. In general, a safety time of one week is applied between the internal and external delivery date of *Parts*. Moreover, the cleaning of *Parts* does not fall under *Parts* planning but is done by *Systems*. This added safety time can result in low delivery performance urgency for *Parts*. The uncertainty of *Parts* is substantially higher if the lead time is analyzed.

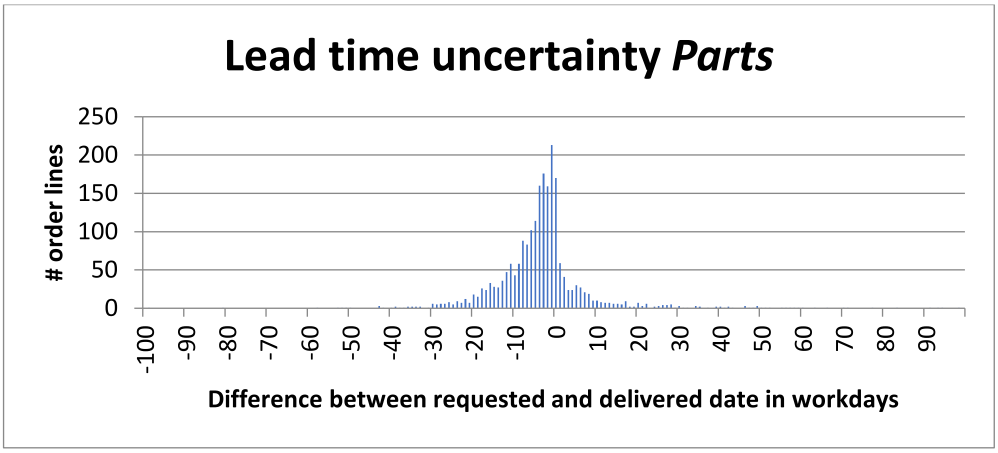


Figure 38: Lead time uncertainty Parts

Figure 38 shows the lead time uncertainty for *Parts*. To improve the readability of the graph, orders with a deviation of more than ± 100 workdays were removed. This resulted in a removal of 56 order lines.

Systems

For *Systems,* the same uncertainty analyses are done as for *Parts*. First, the uncertainty in delivered quantity is analyzed. Similar to the rest of the internal supply chain, uncertainty in quantity is minimal. 99% of the order lines for *Systems* were delivered in the correct quantity. Figure 39 shows the quantity uncertainty for systems. For readability reasons, orders delivered in full are removed from the graph.

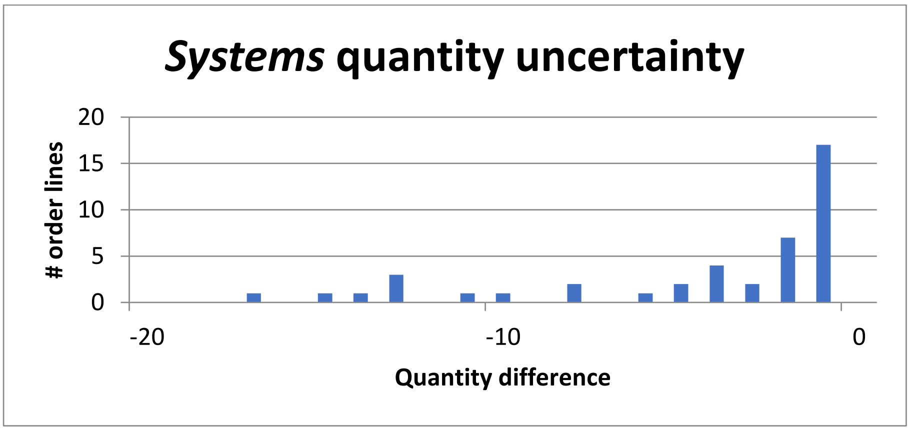


Figure 39: Systems quantity uncertainty

When looking at the lead time uncertainty of *Systems*, it appears that this poses a more significant problem to VDL ETG than the quantity uncertainty. However, it works slightly different for *Systems*. Because *Systems* ultimately delivers to the final customer, the internal delivery date uncertainty is less relevant than the final CLIP and OTIF scores. As can be seen before, ASML reschedules very often, and most of these are delays. Because the end-items are delayed, internal operations can also be produced later.

Figure 40 shows the delivery date deviation. As can be seen, more is delivered after the requested date than before. To improve the readability of the graph, orders which had a deviation of more than ± 100 workdays were removed from the figure. Therefore, 24 order lines were removed.

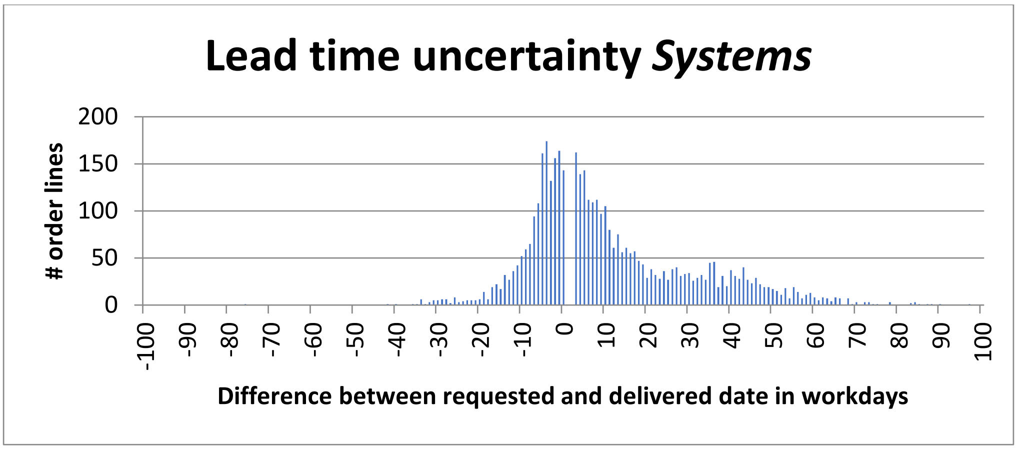


Figure 40: Lead time uncertainty Systems

D.3. Uncertainty placed in the supply chain of VDL ETG

The internal supply chain of VDL ETG is subjected to uncertainty in every step. This appendix analyzed the uncertainty throughout the entire chain separating environmental uncertainty from system uncertainty. For both uncertainties, variability in timing was a much more significant problem than variability in quantity. Figure 41 shows the uncertainties analyzed in this chapter and places them in the internal supply chain of VDL ETG.

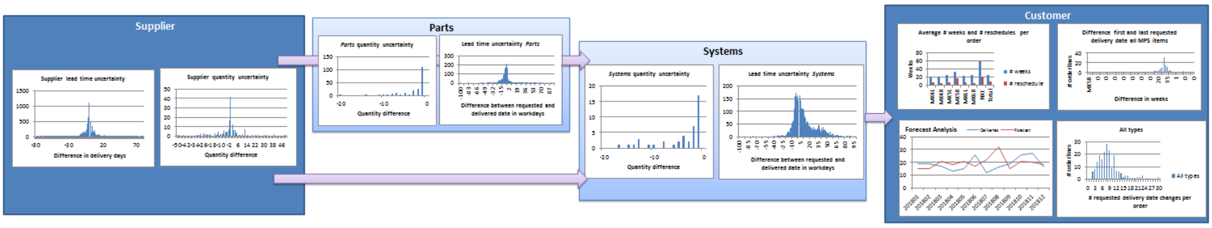


Figure 41: Uncertainties placed in the supply chain of VDL ETG.

Appendix E. Demand distribution fitting

This section explains the demand distribution fitting methodology that is used for chapter 4. For the determination of the demand distribution the Maximum Likelihood Estimation (MLE) is used. This can be used to evaluate the goodness of fit (GOF). GOF is assessed by the identification of parameter values of a certain model that best fits the data. This is called parameter estimation. MLE is a standard methodology for parameter estimation and inference in statistics (Myung, 2003). Moreover, many inference methods are based on the MLE properties. It is a prerequisite for the chi-squared test, the G-square test, Bayesian methods and inference with missing data. Therefore, the MLE methodology will be used to test several probability distributions to the demand data of VDL ETG. As stated before, both the initial requested date as well as the actual deliveries are used to determine the demand probabilities.

The MLE method has been executed using Rstudio and the Fitdistrplus package. This package allows the determination of the MLE for the GOF of various demand distribution to a demand stream. The Fitdist function provides the following numerical results: 1) the parameter estimates, 2) the estimated standard errors of the hessian matrix at the maximum likelihood solution, 3) the loglikelihood (LL), 4) Akaike and Bayesian information criteria (AIC and BIC), 5) correlation matrix between parameter estimates. Moreover, a probability density plot and a cumulative density plot can be used for visual GOF plot (Delignette-Muller & Dutang, 2015). For the demand distribution the LL, AIC, and BIC will be compared to one another to find the best distribution fit. The MLE should be maximized whereas the AIC and BIC should be minimized.

As stated in chapter X. the normal, geometric, negative binomial and the Poisson distribution are included in the analysis based on the work of Grange (1998). This section shows the demand distribution fitting for the MK5L and the MK5R. It is possible that the delivery date of the wafer handler does not completely coincide with the requested date of VDL ETG due to e.g. unforeseen yield errors. Therefore, the first requested date is initially used. To complement this, the delivery date is used as a secondary check. The first requested dataset is smaller than the delivery data set. The first requested data set was only available from mid-2018 till mid 2019 (50 weeks). The delivery dataset was from 2010 until 2019. Therefore, for the first requested data only 50 weeks have been used. For the delivery data, 1.5 years of data have been used (2018 till mid 2019).

First, the MLE, AIC, and BIC will be determined for the four mentioned distributions using the fitdist function. This resulted in the following results for the MK5L and MK5R for the first requested date of ASML, see Table 16. For both the MK5L and MK5R, the Poisson distribution shows the best results and the normal distribution shows the worst results. The Negative Binomial (NB) distribution and the Poisson show a lot of similarities. However, the Poisson outperforms NB, especially on the AIC and BIC criteria.

Table 16: Demand distribution fitting first requested delivery date MK5L and MK5R

WH	Criteria	Normal	Poisson	NB	Geometric
MK5L	LL	-71.34	-66.64	-66.64	-71.00
	AIC	146.67	135.29	137.27	144.00
	BIC	150.37	137.14	140.97	145.85
MK5R	LL	-54.23	-45.70	-45.58	-46.23
	AIC	112.46	93.39	95.17	94.46
	BIC	116.24	95.28	98.95	96.36

To confirm the goodness of fit of the Poisson distribution, a visual plot is made for both the MK5L and MK5R. These are shown in Figure 42 and Figure 43 respectively. Both show a good fit towards the Poisson distribution and therefore the demand is assumed to be Poisson.

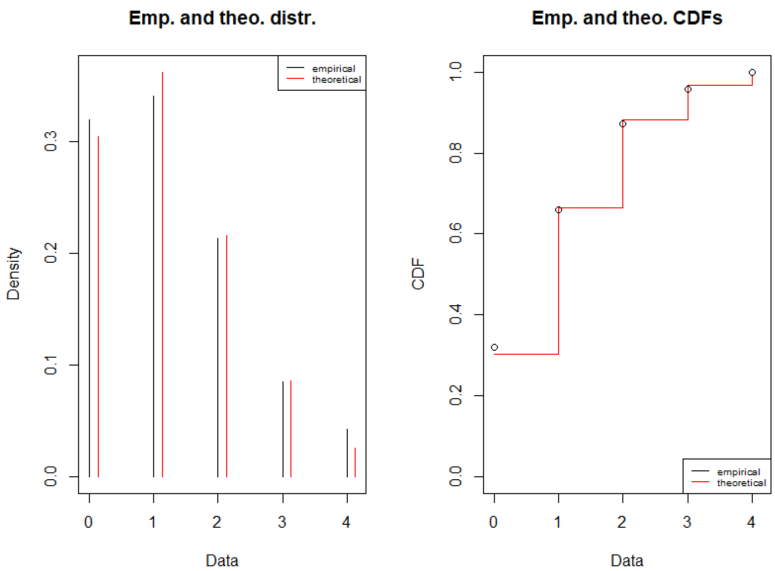


Figure 42: Goodness of fit visual plot MK5L to Poisson (first requested date)

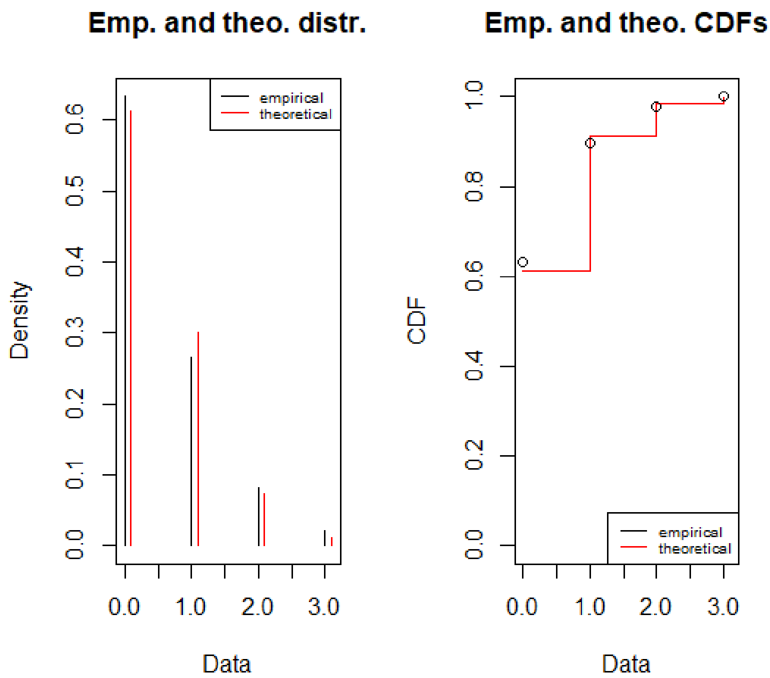


Figure 43: Goodness of fit visual plot MK5R to Poisson (first requested date)

To confirm the Poisson distribution, the delivery date has also been analyzed as a secondary check. As stated above, due to the lack of data of the first requested due dates, the delivery date dataset is larger. Therefore, the results differ from the first requested data. The results of the analysis are shown in Table 17. As can be seen, the Poisson distribution again shows the best fit. As stated before, he numbers differ from Table 16 since the dataset is larger.

Table 17: Demand distribution fitting delivery date MK5L and MK5R

WH	Criteria	Normal	Poisson	NB	Geometric
MK5L	LL	-109.06	-105.44	-105.44	-116.45
	AIC	222.12	212.87	214.87	234.90
	BIC	226.99	215.30	219.73	237.33
MK5R	LL	-100.74	-91.44	-91.44	-96.39
	AIC	205.48	184.89	186.89	194.78
	BIC	210.32	187.31	191.73	197.20

To confirm the demand distribution, a visual goodness of fit plot is again made for the Poisson distribution compared to the MK5L and the MK5R. These are shown in Figure 44 and Figure 45 respectively. As can be seen, the MK5R shows an almost perfect fit. The MK5L shows a slightly worse fit, but it is still the best option. Therefore, the conclusion is that the demand follows a Poisson distribution.

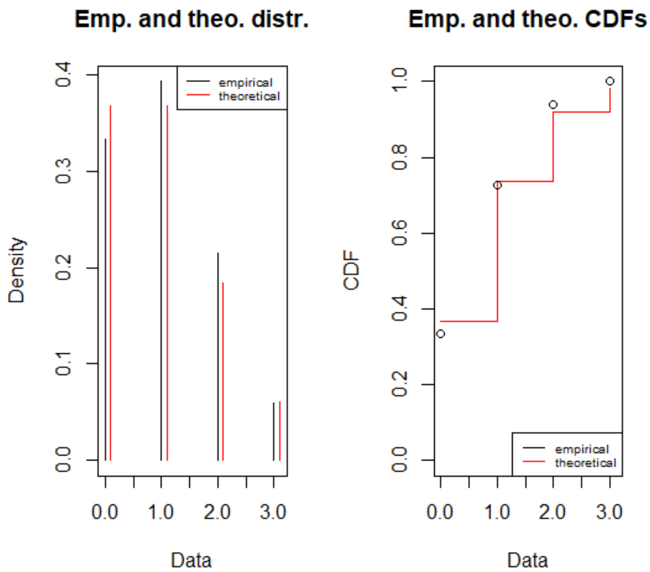


Figure 44: Goodness of fit visual plot MK5L to Poisson (delivery date)

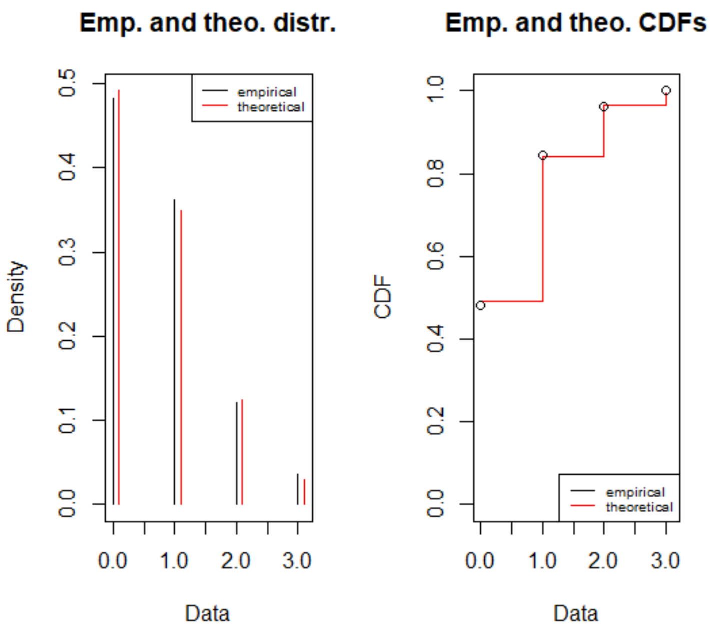
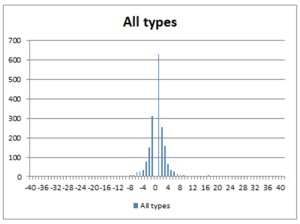
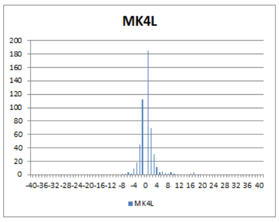


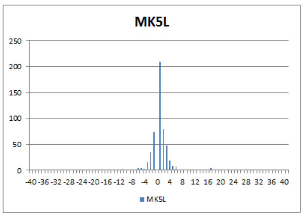
Figure 45: Goodness of fit visual plot MK5R to Poisson (delivery date)

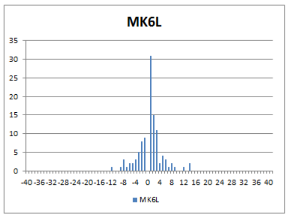
Appendix F. Requested due date differences

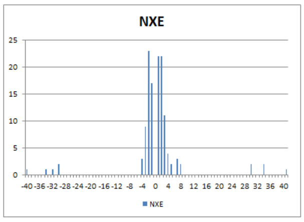
This appendix contains the requested due date differences per item per week.

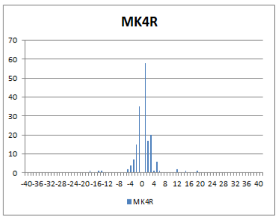


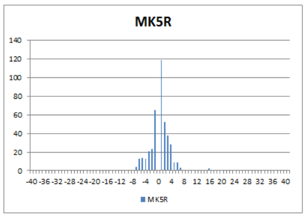


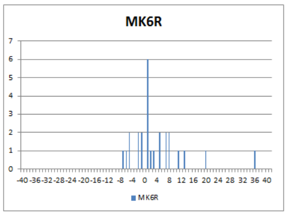












Appendix G. Demand correlation

In this section the demand correlation between end-items is described for the demand as well as for the forecast. The demand correlation is an important factor for *postponement*. Negative correlation allows greater inventory efficiency due to reduced safety stock whereas positive demand correlation results in an increase of safety stock. The solution design focused on the MK5L and the MK5R. However, the table below shows the demand correlation for all end-items with each other. Table 18 shows the demand correlation between the end-items. As can be seen, both positive and negative demand correlation are noticed. Between the configurations left and right there only negative demand correlations. In total, the demand correlation is -0.3 which means that substantial inventory efficiency can be attained.

Table 18: Demand correlation

	MK4L	*MK4R*	*MK5L*	*MK5R*	*MK6L*	*MK6R*
MK4L	1					
MK4R	-0,21380141	1				
MK5L	-0,03521656	0,16604843	1			
MK5R	0,05955838	-0,1227713	-0,17846873	1		
MK6L	-0,06537467	0,14682859	0,10821261	0,14036098	1	
MK6R	-0,13586325	-0,07687251	0,1592465	-0,11621963	-0,07193022	1

To check the correlation between the forecasted demand, the same has been done but for the forecast. These results are shown in Table 19

Table 19: Demand correlation forecasted demand

	MK4L	*MK4R*	*MK5L*	*MK5R*	*MK6L*	*MK6R*
MK4L	1					
MK4R	-0,31444927	1				
MK5L	0,44276633	-0,0766723	1			
MK5R	0,00386257	0,7892016	-0,03749499	1		
MK6L	-0,17376041	-0,07388169	-0,35287702	-0,05022994	1	
MK6R	-0,33884986	0,18313567	-0,46720468	0,23684685	-0,28649093	1

Appendix H. Effect of percentage of commonality on buffer stock

To show the effect of commonality on the safety stock, a situation is assumed with two end items A and B and each item consists of 100 components. The demand follows a Poisson distribution with mean demand of $\mu_A = 1{,}4$ and $\mu_B = 0{,}6$. The standard deviation therefore is $\sigma_A = 1{,}18$ and $\sigma_B = 0{,}77$. To show the effect of commonality on safety stock, the lead time and lead time uncertainty are not included. The percentage of commonality is calculated using formula (1).

The first scenario is to check the relationship under independent demand. It is assumed that every component goes in an end-product only once. Figure 46 shows the relationship between the percentage of commonality and buffer stock under independent demand. This figure shows that increased commonality results in less buffer stock. Figure 46 can be described as exponentially decreasing. The equation for the graph and the R squared test is shown. The exponential decreasing function shows a very good fit. (R^2=0.98)

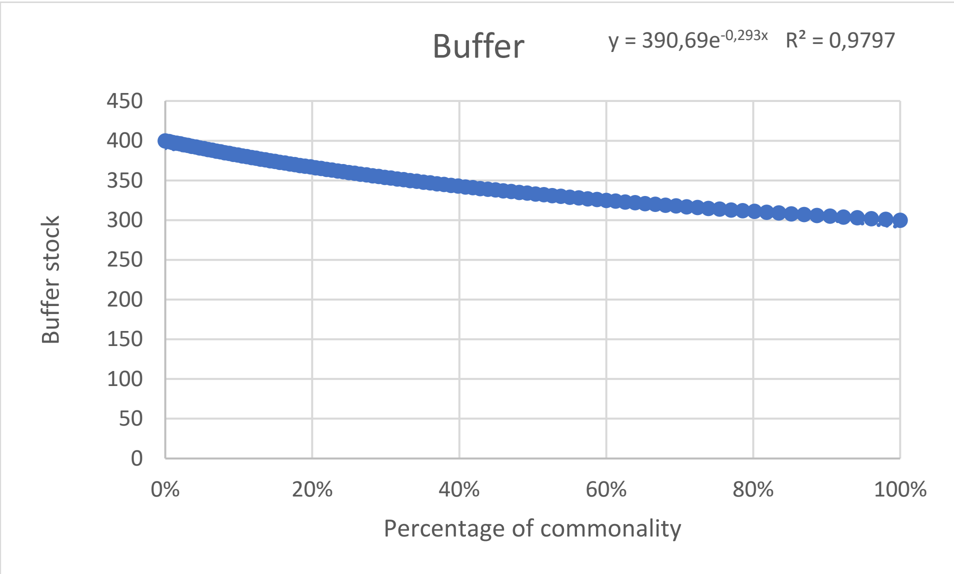


Figure 46: Relationship between commonality percentage and buffer stock under independent demand

Subsequently, this relationship is checked under dependent demand. To check the influence of demand correlation on the effect of the commonality percentage on buffer stock the two extreme values are used: full positive demand correlation and full negative demand correlation. First, a negative correlation of one is evaluated. As can be seen from figure 47, a negative correlation has an enormous impact on the relationship between commonality percentage and buffer stock. Under a fully negative demand correlation, much higher inventory gains can be achieved. Figure 47 again is exponentially decreasing. The equation and R squared are shown at the top. This figure shows an even better goodness of fit (R^2 = 0.99)

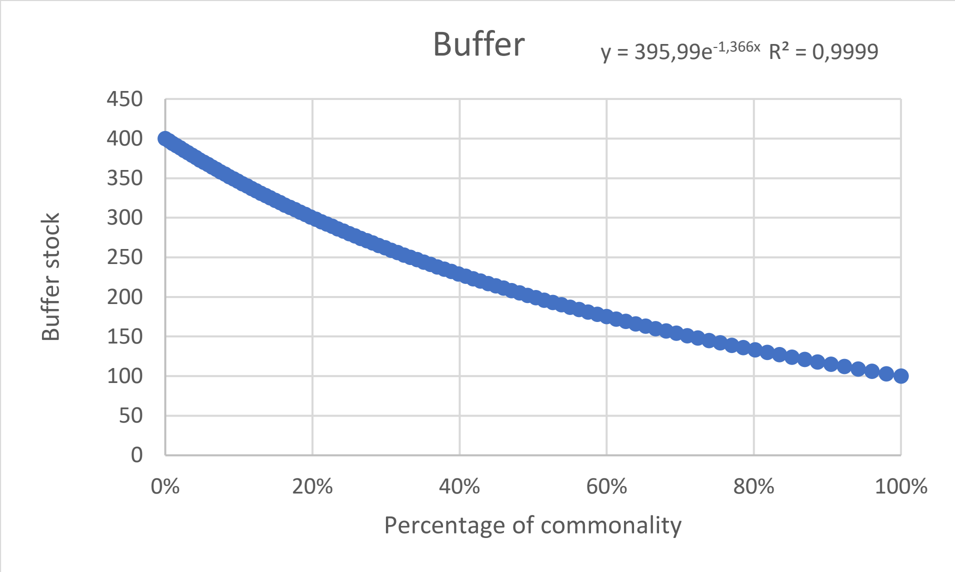


Figure 47: Relationship between commonality percentage and buffer stock under full negative correlation

Since a negative demand correlation increases the inventory gains of commonality percentage, it is expected that less gains are possible with a fully positive demand correlation. This is shown I figure 48. This figure shows no trend since an increase in commonality does not result in reduced buffer stock.

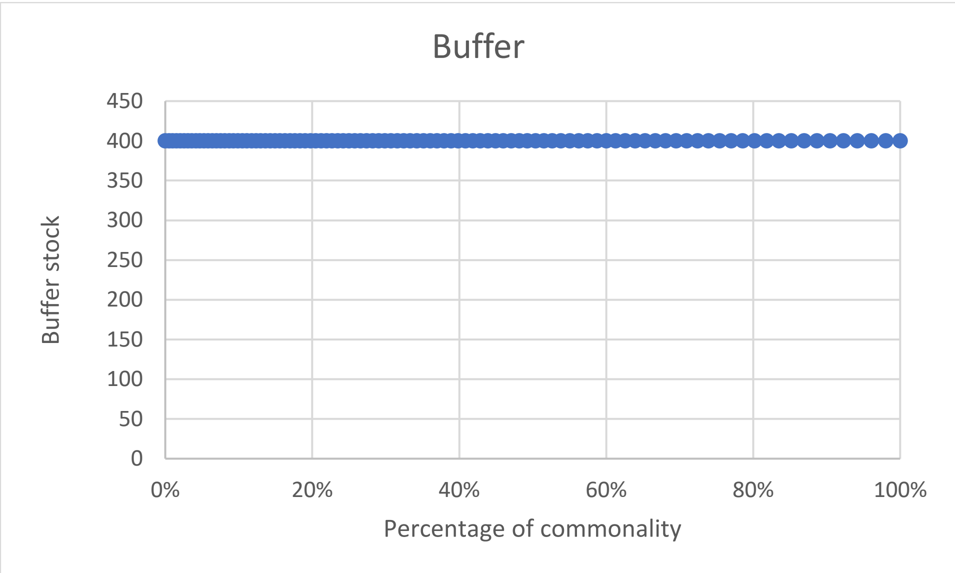


Figure 48: Relationship between commonality percentage and buffer stock under full positive correlation

To conclude, increased commonality percentage results in substantial buffer reduction. Under a fully positive demand correlation, no decrease in required buffer is shown. Under a fully negative correlation, a substantial increase compared to independent demand is shown. Both independent and negatively correlated demand show an exponential decrease in buffer stock as the percentage of commonality increases.

Appendix I. Mathematical derivation safety stock formulas

This appendix explains the mathematical proof for the safety stock formulas (29), (30), and (31)

Safety stock formula (Jacobs et al., 2011):

$$SS = k_\beta \sqrt{LT * \sigma_D{}^2 + \mu_D^2 * \sigma_{LT}^2} \quad (28)$$

$$\sigma_D{}^2 = Demand\ variance$$

$$\mu_D = Mean\ demand$$

$$LT = Lead\ time$$

$$\sigma_{LT}^2 = Lead\ time\ variance$$

$$\mu_D = E[D]$$

$$\sigma_D^2 = V(D)$$

$$SS = k_\beta \sqrt{LT * V(D) + E[D]^2 * V(LT)}$$

I.1. Safety Stock uncommon component

One end item X

<u>Expectation</u>

$$\mu_X = Demand\ end\ item\ X = E[X]$$

$$\mu_D = Total\ demand = \mu_X = E[D]$$

$$E[D] = E[X]$$

Component m is required *a* times in end-item X

$$Demand\ component\ m = E[aX] = aE[X]$$

$$Demand\ component\ m = a\mu_X$$

<u>Variance</u>

$$V(aX) = a^2 V(X)$$

$$V(aX) = a^2 V(X)$$

$$V(aX) = a^2 \sigma_X^2$$

$$substitute\ V(D)\ for\ V(aX)\ and\ E[D]\ for\ E[aX]$$

$$SS = k_\beta \sqrt{LT * a^2 \sigma_X^2 + [a\mu_X]^2 * V(LT)}$$

This can be generalized to end item j and component requirement a_{ij}

$$SS_i = k_\beta \sqrt{LT_i * a_{ij}^2 \sigma_j^2 + [a_{ij}\mu_j]^2 * \sigma_{LT}^2} \quad (24)$$

I.2. Safety Stock common component independent demand

Multiple end-items, independent demand.

Two end items X and Y. one component m

Expectation

$$\mu_X = Demand\ end\ item\ X = E[X]$$

$$\mu_Y = Demand\ end\ item\ Y = E[Y]$$

$$\mu_D = Total\ demand = \mu_X + \mu_Y = E[D]$$

$$E[D] = E[X+Y] = E[X] + E[Y]$$

Component m is required *a* times in end-item X, and *b* times in end-item Y.

$$Demand\ component\ m = E[aX + bY] = aE[X] + bE[Y]$$

$$Demand\ component\ m = a\mu_X + b\mu_Y$$

Variance

$$V(aX + bY) = a^2V(X) + b^2V(Y) + 2abCov(X,Y)$$

$$Cov(X,Y) = 0\ (X\ and\ Y\ independent)$$

$$V(aX + bY) = a^2V(X) + b^2V(Y) + 0$$

$$V(aX + bY) = a^2V(X) + b^2V(Y)$$

$$V(aX + bY) = a^2\sigma_X^2 + b^2\sigma_Y^2$$

$$substitute\ V(D)\ for\ V(aX + bY)\ and\ E[D]\ for\ E[aX + bY]$$

$$SS = k_\beta \sqrt{LT * (a^2\sigma_X^2 + b^2\sigma_Y^2) + [a\mu_X + b\mu_Y]^2 * V(LT)}$$

This can be generalized to multiple end items j and multiple required components a_{ij}

$$SS_i = k_\beta * \sqrt{\sum_{j=1}^{n} a_{ij}^2\sigma_j^2 * LT_i + \left[\sum_{j=1}^{n} [a_{ij}\mu_j]\right]^2 * \sigma_{LT}^2} \qquad (25)$$

I.3. Safety Stock common component dependent demand

Expectation

Assume two end-item: X and Y (dependent demand). And one component m

$$\mu_X = Demand\ end\ item\ X = E[X]$$

$$\mu_Y = Demand\ end\ item\ Y = E[Y]$$

$$\mu_D = Total\ demand = \mu_X + \mu_Y = E[D]$$

$$E[D] = E[X+Y] = E[X] + E[Y]$$

Component m is required *a* times in end-item X, and *b* times in end-item Y.

$$Demand\ component\ m = E[aX + bY] = aE[X] + bE[Y]$$

$$Demand\ component\ m = a\mu_X + b\mu_Y$$

Variance

Variance of demand end-item X and Y is:

$$V(aX + bY) = a^2V(X) + b^2V(Y) + 2abCov(X,Y)$$

$$Cov(X,Y) = \rho_{XY}\sqrt{V(X)V(Y)}$$

$$V(aX + bY) = a^2V(X) + b^2V(Y) + 2ab\rho_{XY}\sqrt{V(X)V(Y)}$$

$$V(aX + bY) = a^2V(X) + b^2V(Y) + 2ab\rho_{XY}\sqrt{\sigma_X^2\sigma_Y^2}$$

$$V(aX + bY) = a^2\sigma_X^2 + b^2\sigma_Y^2 + 2ab\rho_{XY}\sigma_X\sigma_Y$$

$$substitute\ V(D)\ for\ V(aX + bY)\ and\ E[D]\ for\ E[aX + bY]$$

$$SS = k_\beta\sqrt{LT * (a^2\sigma_X^2 + b^2\sigma_Y^2 + 2ab\rho_{XY}\sigma_X\sigma_Y) + [a\mu_X + b\mu_Y]^2 * V(LT)}$$

This can be generalized to multiple end items j and multiple required components a_{ij}

$$SS_i = k_\beta * \sqrt{\left(\sum_{j=1}^{n} a_{ij}^2\sigma_j^2 + \sum_{j=2}^{n}\sum_{k=1}^{j-1} 2\rho_{jk}a_{ij}a_{ik}\sigma_j\sigma_k\right) * LT_i + \sum_{j=1}^{n}\left[a_{ij}\mu_j\right]^2 * \sigma_{LT}^2} \qquad (26)$$

I.4. Mistake Baker (1985) Formula (4) Multiple end-items, independent demand.

Formula (4) of the paper of Baker (1985) states the safety stock level for a common component with independent demand is:

$$SS_i = k_\beta \sum_{j=1}^{n} [a_{ij}\sigma_j^2]^{1/2}$$

Baker (1985) bases this safety stock formula from the general safety stock formula for fixed lead time of one period for a component without commonality (only one end-item). The formula is:

$$SS_i = k_\beta a_{ij} \sigma_j$$

However, if multiple end-items are included with independent demand. The formula becomes

Multiple end-items, <u>independent</u> demand.

Two end items X and Y. one component m

<u>Expectation</u>

$$\mu_X = Demand\ end\ item\ X = E[X]$$

$$\mu_Y = Demand\ end\ item\ Y = E[Y]$$

$$\mu_D = Total\ demand = \mu_X + \mu_Y = E[D]$$

$$E[D] = E[X+Y] = E[X] + E[Y]$$

Component m is required *a* times in end-item X, and *b* times in end-item Y.

$$Demand\ component\ m = E[aX + bY] = aE[X] + bE[Y]$$

$$Demand\ component\ m = a\mu_X + b\mu_Y$$

<u>Variance</u>

$$V(aX + bY) = a^2V(X) + b^2V(Y) + 2abCov(X,Y)$$

$$Cov(X,Y) = 0\ (X\ and\ Y\ independent)$$

$$V(aX + bY) = a^2V(X) + b^2V(Y) + 0$$

$$V(aX + bY) = a^2V(X) + b^2V(Y)$$

$$V(aX + bY) = a^2\sigma_X^2 + b^2\sigma_Y^2$$

$$substitute\ V(D)\ for\ V(aX + bY)\ and\ E[D]\ for\ E[aX + bY]$$

$$SS = k_\beta \sqrt{a^2\sigma_X^2 + b^2\sigma_Y^2}$$

This can be generalized into the following formula.

$$SS_i = k_\beta * \sum_{j=1}^{n} [a_{ij}^2\sigma_j^2]^{\frac{1}{2}} \qquad (26)$$

Therefore, formula (4) of the article of Baker (1985) is not correct and should be formula (26)

Appendix J. Applicability of performance measures to the situation of VDL ETG.

Zhang & Tan (2001) classified the measures as either internal or external. The internal dimension includes 1) total cost, 2) specific costs, 3) customer service, and 4) asset management. A change is indicated by a green fill and no impact is indicated by a grey fill of the third column.

J.1. Environmental performance measures

A change in production process and/or the product may lead to changed customs and duties that have to be applied to certain items. This mostly concerns place postponement (Zhang & Tan, 2001). Environmental measures include average taxes paid to local governments during a fixed period, the value created by local material in the final product, the value contributed by local human resource in the final product (Zhang & Tan, 2001). Because the postponement strategy does not include geographical changes in the supply chain and/or product structure, the KPIs do not change. Therefore, these are excluded from the performance measurement framework. Table 20 provides an overview of the environmental performance measures and their impact on VDL ETG.

Table 20: Environmental performance measures (Zhang & Tan, 2001).

KPI	Equation	Impact postponement
Taxes to local government	Taxes per year	No Impact
Localizing degree of the product	Average value of local materials and component per unit/average value of the finished product	No Impact
Localizing degree of labor	Average local labor value in the finished product/average value of the finished product	No Impact

J.2. Costs

These KPIs entail the costs incurred with the implementation of postponement. No change occurs in the *transportation costs* with the implementation of postponement. The same amount finished products are produced and shipped to ASML. There are also no geographical changes in the supply chain. Therefore, this cost is removed from the framework. *Warehousing costs* contains the fixed costs (buildings, equipment, and fixed payroll) and variable costs (contract manpower, variable utilities) of a warehouse. There are also no changes in these costs: there is no extra buildings or equipment required as well as manpower. Therefore, this KPI is removed from the framework. The *labelling and packaging costs* are also not impacted and removed from the framework. Packaging and labelling will have the same input and output in the postponed supply chain as it had in the current situation. *Assembling labor cost* and *Manufacturing labor cost* are also not impacted because the processes of PRE-ASSY and FASSY do not change. The only change is that the product is either produced on an actual order or an MPS order, which does not matter for the assembling and manufacturing costs. The only change is in the order processing. This is currently allowed in two weeks whereas this will be reduced to one week in the new situation. This is plenty of time for the acceptance of an order according to *order management* and *integral planning*. However, only the timeframe changes, not the tasks. Therefore, no order acceptance cost changes are expected. *Reverse costs* are costs associated with diagnosing and repairing orders. The RS&S department is out of scope for this project. Moreover, nothing changes with respect to the current situation. Finally, the *material costs* are also unchanged. There are no product changes required for the implementation of postponement. Therefore, the *material costs* are unchanged. The *direct labor costs* are an accumulation of all the above-mentioned costs. To conclude, since all costs stay the same, this category can be dropped from the framework. Table 21 shows the KPIs with their definition and the impact postponement has.

Table 21: Cost breakdown performance measures (Zhang & Tan, 2001)

KPI	Definition	Impact postponement
Transportation cost	Measure cost of moving goods	No Impact
Warehousing cost	Measure the cost effectiveness of operating a warehouse	No Impact
Labelling process cost	To measure the production cost during labeling stage	No Impact
Packaging process cost	To measure the production cost during packaging stage	No Impact
Assembling process cost	To measure the production cost during assembling stage	No Impact
Manufacturing process cost	To measure the production cost during manufacturing stage	No Impact
Order process cost	To measure the cost for order information sharing passing along the supply chain	No Impact
Reverse cost	The cost to diagnose, repair, and rework returned products	No Impact
Material cost	The cost of raw materials	No Impact
Direct labor cost	To measure the total production cost	No Impact

J.3. Asset management

These performance measures focus on the utilization of capital investments as well as working capital application of inventory (Zhang & Tan, 2001). The only cost factor that is not impacted with the implementation of postponement is *one-time asset investment*. Because the postponement strategy can be implemented within the current boundaries of the supply chain design, a one-time investment in assets is not necessary. The change that is necessary concerns an ERP-based change regarding the standardization of processes. However, the asset requirements for the processes remain the same. Therefore, there is not one-time asset investment required. This is removed from the framework. The three KPIs related to inventory measures will all change accordingly to the expected inventory level. Since the inventory turns and the inventory holding costs are directly dependent on the inventory level, the performance measures will show similar results.

Table 22: asset management performance measures (Zhang & Tan, 2001)

KPI	Definition	Impact Postponement
Inventory turns	The number of times inventory turned over during the year. It is useful to evaluate the speed of goods moving through a company	Impact
Inventory holding costs	Cost for holding product in the warehouse	Impact
Inventory level	The average inventory level in the supply chain	Impact
One-time asset investment	The effect of strategy implementation on cooperation's asset	No Impact

J.4. Customer service

These KPIs concern measures that evaluate the customer service in the postponed situation. Table 23 shows the customer service KPIs proposed by Zhang & Tan (2001). The new situation has an impact on all KPIs and therefore, no measures are removed. However, not all measures will be included in the analysis. The stock-out delivery rate is the inverse of the fill rate and will therefore, not be included in the analysis. Only the fill rate is incorporated. The on-time delivery rate is not possible to estimate for the new concepts. This is dependent on yield and other miscellaneous factors that are not in the scope of the project. Therefore, even though postponement will have an impact on this KPI, it is not included as it is immeasurable within the scope and time frame of this thesis. Furthermore, the back-order cycle time is expected to be equal to the total lead time. Consequently, only the lead time is included.

Table 23: Customer service performance measures (Zhang & Tan, 2001)

KPI	Definition	Impact postponement
Fill rate	To measure them proportion of demand met from inventory on hand. Important indicator for service level	Impact
Stock-out rate	To measure the unavailability of goods	Impact
On-time delivery rate	To measure the rate of deliveries finished in the promised time	Impact
Back-order cycle time	The average time from when a back order is generated to the time when the shipment is received by the customer	Impact
Total Lead time	The average time from when an order is generated to the time it arrives to the customer	Impact

J.5. Total cost

These KPIs contain measures that evaluate the system wide costs. These are further divided into: total cost, total cost per unit, and total cost as a percentage of sales. Table 24 shows the total costs performance measures. Since the costs for the production and assembly of a WH do not change, implementing postponement does not have an effect on the costs and therefore, this dimension is not included in the performance evaluation of VDL ETG.

Table 24: Total costs performance measures (Zhang & Tan, 2001)

KPI	Definition	Impact postponement
Total Cost	To identify the change in systematic costs brought about by decisions	No Impact
Total Cost per unit	Total cost per unit	No Impact
Total cost as a percentage of sales	To measure the return of total cost	No Impact

Appendix K. ChainScope explanation

ChainScope is used for the determination of the fill rate performance measure. This appendix provides a deeper understanding of ChainScope. This section is based on an earlier thesis which used ChainScope and provided a detailed explanation and the user manual of ChainScope (Alatas, 2017).

K.1. Introduction to ChainScope

ChainScope is a program which is specifically designed to analyze a complete supply chain of an organization from a multi-echelon perspective. This entails the entire production to the distribution of the product (transportation time from the last stock point is not taken into account). The program can analyze the current performance of a supply chain based on the current parameters. Subsequently, the program also has an optimization mode which analyzes what the stock division should be in an optimized version of the supply chain. In the evaluation mode, the average stock is taken as a fixed input data whereas the average stock is ignored in the optimization. This done so the program can determine the optimal stock levels per tier. The expected demand and standard deviation of end-items have to be inserted into the program combined with a target fill rate. The main objective of ChainScope is meet a specified target fill rate for end-item demand against a minimal capital investment in inventory. It is important to note that ChainScope is based on mathematical models and is therefore not a Discrete Event Simulation.

K.2. Model solving technique

The program uses the Synchronized Base Stock (SBS) policy. The SBS policy extends the concept of Rosling for pure assembly systems. This a system where an item always has only one successor which allows for the transformation into a serial system. The method is composed of allocation rules and base stock policies to guarantee order releases that are feasible concerning material availability. The main difference between pure base stock policies and the SBS policy is that the pure base stock policies only include an order mechanism whereas the SBS policy contains both an order mechanism as well as an allocation mechanism. This allocation mechanism of the SBS policy is that it allocates the shortages in fixed fractions to successive stages. Moreover, the SBS policy allows specific end-item service level to be defined and multiple base stock levels for one item. Ultimately this leads to flexibility regarding the achievement of required service level for each end-item.

A large part of the SBS policy is synchronization. This refers to the combination of coverages of future demand as WIP, in transit stock and actual stock, which depends on the control policy. Synchronization can be done by Linear Programming (LP) or by SBS. De Kok and Fransoo (2003) found out that SBS outperformed the LP allocation for all 12 test cases significantly: 8-18% less inventory capital. Although SBS splits the coverage of future demand for common items already before it is needed, the model appeared to be tractable and control appeared to be more effective due to the inclusion of demand uncertainty.

SBS relies on a finding in De Kok and Visschers (1999). Partially based on Diks' and De Kok's (1999) close-to-cost-optimal periodic echelon order-up-to-policy *(R,S)* for divergent systems under stochastic stationary demand and linear holding and penalty costs, De Kok and Visschers (1999) proposed a decomposition method for general assembly systems. This method decomposes assembly networks into pure divergent multi-echelon systems by pre-allocating common components to end products. This entails establishing an artificial hierarchy which is based on the specific BOM structure and Planned lead times of items. The decision node network is constructed based on this artificial hierarchy. Then the divergent network can be translated into cost-optimal Newsvendor equations, which synchronize order release decisions of items over time. Therefore, the Newsvendor equation, as described in Diks and De Kok (1999), is solved recursively. Then, those order releases are converted back to the original network structure.

K.3. Model input

This subsection explains the input that the program requires.

Item input

- Item lead time
    - The throughput time between the moment of order release until the ordered item is available for usage
- Added value
    - The value that is added during the transformation process that creates the item. It is the monetary value of the item minus all the values of the input items. For purchased items the added value is the purchase price.
- Release costs
    - Costs of releasing an order. Can be fixed or transportation costs.
- Yield
    - Ratio of items that do not get broken during the transformation process.
    - The yield ratio is an input for every individual item.
- Review period
    - The review period is the period between subsequent release decisions for an item.
- Item target stock
    - The item target stock is the targeted average number of items in the stock point.
- Order size
    - The number of items that are ordered simultaneously
- Max stock
    - The maximum stock allowed in the supply chain for an item

Relation input

- Structure
    - Number of items necessary to complete the successor transformation
- Successor
    - In ChainScope a successor of item i is an item for which item i is needed during the transformation process to create the item (the successor).

Item customer input

- Customer
    - Name of the customer
- Demand
    - The number of products per period the customer wants to receive
    - The standard deviation of the expected demand
- Customer order lead time
    - The customer order lead time are the number of periods between the moment a customer places an order and wants to receive the ordered items
- Margin
    - Profit margin
- Target P1
    - The target value for the ready rate service level
- Target P2
    - The target value for the fill rate service level