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MASTER

Improving the process of configuration registration in the semiconductor industry
a case study

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Improving the process of configuration registration in the semiconductor industry: a case study

Master Thesis

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Abstract

This research is performed at the EUV Factory (EF) at ASML, where highly-complex machines are manufactured. At companies like ASML that manufacture highly-complex machines, there is a need for managing and maintaining the data of the machine's configuration during the entire lifecycle for improving the machine as well as for dealing with the customer preferences. The aim of this research is to analyze and improve the process of registering the data of the product's configuration. We mapped the current configuration registration process by using artifact-centric modeling techniques in order to identify the artifacts flowing through the process, and the activities and decisions that change the status of the artifacts. The data in the process is analyzed and we identified that the introduction of engineering changes (ECs) on critical machine parts resulted in most configuration registration errors. Based on that, we proposed a new way of working where these ECs are embedded in the valid configurations, which are used by the EUV factory as a reference of the machine's configuration. As a result, there will no more configuration registration errors exist at EF due to ECs. Moreover, we found that with our proposed solution design, ASML is expected to decrease the cycle time for EF resulting from increased data and information quality in the process.

Executive summary

Problem Context

This research is about analyzing and improving the current configuration registration process in the EUV Factory (EF) at ASML. The research is carried out within the EUV Factory Breakthrough Projects (EF BP) team in order to support one of the projects focusing on improving the processes regarding configuration management (CM) in general. In the EF, highly complex machines are manufactured and qualified before the machine is transferred to the customer. To install and deliver the machine according to the specifications, the configuration of the machine needs to be managed. The EF performs a check on about 250 critical machine parts, which are called Critical Configuration Items (CCIs). Ideally, all CCIs are manufactured according to the Bill of Material (BOM), and registered in the equipment structure in the ERP system according to the valid configuration, which is the baseline of the machine's configuration. The EF is expected to reach a 99% score on the Configuration As Built (CAB), meaning that 99% of all CCIs are assembled according to the valid configuration. Right know, this target is not always met for several reasons, and ASML aims to get insights in the configuration registration process on how to improve. In addition, ASML increases the scope of configuration items in the CAB from about 250 to 1000 in 2022, and it is not known what it takes to reach this target and be prepared for the future.

Research objectives and methodology

It is expected that ASML itself as well as their customers benefit by reaching this target. The benefits of having 100% configuration registration, meaning that all CCIs are according to the valid configuration, are identified and reaching these benefits is considered as the business objective of this research. A short explanation for these benefits is provided below:

- **Increased transparency with customer**. When the configuration of the machine is 100% registered, it can be fully shared with the customers.
- **Increased reliability**. When everything everything is registered according to the right configuration, the machine works according to its standards, which increases the reliability of the machine (explained in Appendix B.1.1.
- **Increased traceability in part's history**. When all CCIs are registered, the history of the parts can be traced, which has many benefits (presented in Appendix B.1.2.
- **Increased speed of performing upgrades**. The EF Install department profits from 100% configuration registration in the factory, since they are able to better plan and perform the needed upgrades on the machine.

- **No ODRs for configuration control purposes**. An Operational Deviation Report (ODR) is a manually created document that must be created for each configuration registration errors at the transfer of the machine from EF to EF Install. This is not necessary anymore if everything is registered properly.
- **No physical checks for configuration control purposes**. When a CCI is not registered, a check need to be performed sometimes to identify what is assembled in the machine. If everything is registered, this is not needed anymore.

To improve the current way of working, we answer the following main research question:

Main research question:
How can configuration registration in the EUV factory be improved and what impact does it have for ASML?

To answer this research question, we used the problem-solving cycle by van Aken, Berends and van der Bij (2012). The reason for choosing this approach is that the problem solving cycle is a widely chosen approach for optimizing business problems and can easily be aligned with the research questions that we aim to answer. Next, we used the CRISP-DM framework of Sheare (2000). The CRISP-DM framework is used in the second phase of the problem-solving cycle, the analysis and diagnosis phase, since it provides more guidance in the activities that we need to perform in that phase. The fourth phase of the problem-solving cycle (the intervention phase) was not executed in this research. A visualization of the methodology, including all phases, is provided in Figure 1.

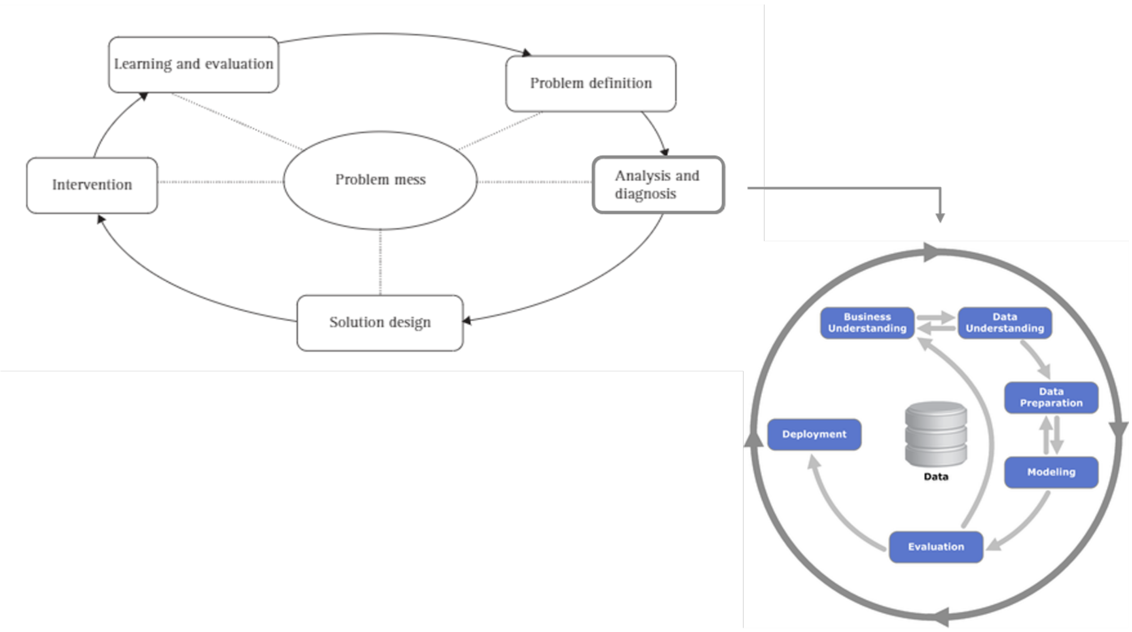

Figure 1: Research Methodology (van Aken et al., 2012; Shearer, 2000)

The problem definition phase of the methodology was covered by interviewing relevant stakeholders at ASML, and by performing literature research. The gathered information in this phases resulted in insights on the objectives of this research leading to the research question that we created. Next, we researched different artifact-centric modeling approaches that we used to model the current way of working, and collected information on data quality dimensions and CM in general, that we used for evaluating the suggested redesign later in this research and determine if this research reaches its objectives.

Analysis and Diagnosis

In the analysis and diagnosis phase, we modeled the configuration registration process by using artifact-centric modeling techniques, which cover the business understanding phase of the CRISP-DM framework. For the current process, the following models were created:

- A context diagram presenting a high-level overview of all interactions of the Configuration Compliance Tool (CCT) with other systems. In the CCT tool, the CAB is created which visualizes the status of the configuration of the machines. The interactions relevant for the configuration registration process act as input for the UML Class Diagram.
- An UML Class Diagram, that presents the relationships between the business artifacts that are present in the configuration registration process.
- An activity-centric process model based on the approach of Kumaran, Liu and Wu (2008), that shows the activities performed in the process that create, edit or remove the business artifacts that are presented in the UML Model.
- An Entity dominance graph that identified the dominant entities available in the configuration registration process. This resulted in two dominant entities: an Order and a Part, which are used to model the current process in a CMMN model. For determining the dominant entities, we used the methods of Kumaran et al. (2008) and Snoeck and Dedene (1998)
- CMMN models of the dominant entities. In here, the decisions made that result in a status change for each of the dominant entities are visualized. These models represent the current way of working of configuration registration in an artifact-centric way.

In the data understanding phase, data was collected on all compliance changes on the NXE: 3400C and NXE: 3600D machine types starting from 01-01-2020 until the day of retrieving the data (18-06-2021). The reason for choosing this machine types are produced in high-volume during that time period, and it is expected that this holds for the upcoming years. We required additional data sources to identify the bottlenecks, and collected data on the shipment date of the machines and the modules where the parts are related to. All data was cleaned to avoid working with missing values in the data preparation phase, and to ensure that the modeling phase contained only data on compliance changes on CCIs that happened in the EF and are thus in the scope of our research. After cleaning the data, we merged all datasets into one final dataset, which is used in the modeling phase. This phases ended with some first insights in the bottlenecks.

Next, in the modeling phase, we analyzed the data and identified that most configuration registration errors occurred at three modules: SRC, DL and BOT. We further investigated these modules by creating an overview of the configuration registration errors of CCIs belonging to these modules. The results were visualized and presented to domain experts in order to explain the results. As a result, we identified three bottlenecks in the current way of working: 1) The introduction of Engineering Changes (ECs) on CCIs leading to late deliveries of parts in the EF, 2) New valid configurations or machine platforms resulting in more configuration errors at the beginning and 3) incomplete serial number registration by suppliers. Since ECs are also introduced at new machine platforms or valid configurations, we combine the first two bottlenecks as one. Next, we held interviews with Supplier Quality Engineers and identified that the collaboration regarding serial number registration has improved. We validated this with the stakeholders in EF who supported this, and therefore concluded that the bottleneck to be eliminated in the redesign phase, should be the introduction of ECs.

Solution Design

To answer our main research question, we propose a new way of working regarding configuration registration. When interviewing stakeholders, we identified that the introduction of ECs is often taken into account when planning an order. Thus, the EF knows about the late deliveries of parts. However, the valid configuration is not changed based on these changes. We therefore propose to edit the valid configuration with the planning of an order. We recommend the EF to take the ECs on CCIs as input for the valid configuration edits, and thereby creating a new valid configuration: valid configuration EF. The number of configuration errors will decrease since the material availability in EF is taken into account. The UML diagram, activity-centric model and the CMMN model for the dominant artifact *Order* are changed accordingly.

The expect that the redesign will reach some of the business objectives of this research and therefore benefits ASML. The new way of working is expected to result in:

- Less Operational Deviation Reports (ODR) for configuration control
- Less support of D&E needed
- An optimized install sequence by enabling EF install to create a first-time right upgrade plan.

Consequently, the cycle time can be reduced which prepares ASML for the future, when the number of configuration items to be registered increases from 250 to 1000. In addition, we expect that the data quality in the configuration registration increases, since the redesign make the data fit for use by reducing the incomplete data in the process. Last, we recommend ASML to focus on cross-sector alignment regarding CM processes, since it takes the processes to the highest CM maturity level according to Myrodia, Randrup and Hvam (2019), in which processes are mature enough for continuous improvement.

Conclusion and recommendations

In this research we analyzed the current way of working regarding configuration registration. We found that the SRC, DL and BOT module caused the most errors in the process, which was a result of a lot of ECs on these modules. We propose a new way of working where the ECs are not only embedded in the planning of the orders, but also in the valid configurations. We recommend to manually edit the valid configurations first, and when the expected benefits are met after a while, we recommend to automate the valid configuration edits. This would save significant time and make the process less subject for manual errors, which would be beneficial in the future when registering more items according configuration management standards.

Preface

This master thesis is the result of my graduation project which I conducted at ASML. With this thesis, I hope to conclude my studies Operations Management and Logistics at University of Technology Eindhoven.

First I want to thank ASML for giving me this opportunity and all of my temporarily colleagues for helping me and let me feel welcome in the organization. It's a pity that we could not meet in person due to the corona restrictions. In specific, I want to thank Sander van der Ploeg in special as my first ASML supervisor. Sander, every week, you spent time to help me with my thesis and you gave me all kinds of great feedback on my work. When I was stuck, you saved some time for me to help me out, which I really appreciate. I definitely learned a lot from you. So again, thank you Sander! Next, I am grateful for the guidance I got from the university. I want to thank Zaharah Bukhsh and Baris Ozkan for being my second and third supervisor. I thank Rik Eshuis for being my first supervisor. We wet each other every two weeks or so and I really appreciated the feedback and direct actionable to-do points for me. Your feedback and suggestions were clear and I always got the opportunity to get an answer for all my questions. Thanks a lot!

Further, I want to thank everyone that I've met during my study period in Eindhoven and my friends in Nistelrode. Six years ago, I never thought that I would enjoy my study period that much. I can now state that I had a great time, met a lot of new people, made new friends and developed myself as a person. Last, I want to thank my parents. Especially during the corona period, studying was hard for me but I made it. Thank you for all the support and I hope that I can make you proud with completing my studies.

Koen Pittens September 28, 2021

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Abbreviations

BOM	Bill of Material
BPM	Business Process Management
CAB	Configuration As Built
CAD	Configuration As Designed
CAI	Configuration As Installed
CAM	Configuration As Maintained
CAS	Configuration As Supplied
CCI	Critical Configuration Item
CCT	Configuration Compliance Tool
CM	Configuration Management
CMMN	Case Management Modeling Notation
CN	Change Notice
CS	Customer Support
CSA	Configuration Status Accounting
CSF	Critical Success Factor
D&E	Development & Engineering
DIP	Decision Intensive Process
EC	Engineering Change Management
ECM	Engineering Change Management
ECN	Engineering Change Notice
EF	EUV Factory
EF BP	EUV Factory Breakthrough Projects
ERP	Enterprise Resource Planning
EUV	Extreme ultraviolet lithography
GSM	Guard-Stage-Milestone
KPI	Key Performance Indicator
ODR	Operation Deviation Report
OMG	Object Management Group
PLM	Product Lifecycle Management
R&D	Research & Development
S&SC	Sourcing and Supply Chain
SQE	Supplier Quality Engineers
UML	Unified Modeling Language

Chapter 1

Introduction

With the technological advances of today, the products that are made become more and more complex. Due to an increasing amount of data generated in each stage of the product lifecycle, companies are faced with the challenge to optimally manage and maintain the configuration their products, especially in industries with highly complex products. In these industries, products consist of thousands individual parts and the effects of changing one part are not directly notable, yet a single part can still impact the overall performance of the end-product. Therefore, having the right data about product's configurations is an important feature to get right, not only for improving the products, but also for establishing the relations with customers. Customer preferences for end-product variants, so different configurations of the products, need to be taken into account for establishing a good relationship with the customer.

A method for managing the configuration of a product throughout its lifecycle is configuration management (CM). It is an important feature to get right, since it allows managers to identify problems and keep track of the process, changes and performance in its lifecycle. Still, CM is often neglected by many organizations in the past years (Quigley & Robertson, 2015). For companies in the high-tech industry with complex products, like ASML, CM is an important function to get right in order to align the quality of the product with the increase in technological advances that make the products even more complex. At ASML, highly complex chipmachines are manufactured and delivered by the end-customers. Managing the configuration of the machine throughout it's lifecycle is therefore crucial. The configuration data of the machine however need to be registered properly and accurately in order to manage the configuration status. In the EUV Factory (EF) at ASML, registering the right configuration data is called configuration registration. This research analyzes the current configuration registration process and aims to optimize the process, so that ASML is able to optimally manage the product's configuration.

1.1 Business Description and Context

1.1.1 Business Description

ASML is the world's leading manufacturer of lithography systems for the semiconductor industry. The headquarters of ASML is located in Veldhoven, the Netherlands. In 2021, ASML has around 28,000 employees where 13,000 are working at the headquarters in Veldhoven, the other employees are spread across more than 60 cities in 16 countries (ASML, 2021). ASML was founded in 1984 and became the global innovation leader in just three decades. In 2010, the semiconductor industry was changed when ASML introduced the first Extreme Ultraviolet Lithography (EUV) machines to the market. These machines are nowadays manufactured at high-volume in ASML's EUV Factory (EF) in Veldhoven, and the next generation of EUV machines is already developed. At ASML, there is always a strive for innovation, which is why ASML spent 2.2 billion euros on R&D expenses in 2020, which is almost 16% of ASML's net sales of 14.0 billion euros in 2020 (ASML, 2021).

The research is carried out in one of the teams within the EF of ASML, the EF Breakthrough Projects (EF BP) team. During this research other departments at ASML are involved to achieve the research goals.

1.1.2 Context

One of the projects managed by the EF BP team is a project on improving the way of working regarding CM. Previous research and projects within ASML showed that CM is a critical function for ASML to improve, since it aligns with at least two business priorities of ASML: 1) decreasing cycle times in the EF and 2) increasing customer trust.

In the EF, the machine is built and qualified such that it can be transported to the customer. During and at the end of the manufacturing activities, the status of the machine's configuration is tracked. It is checked whether the parts that are built in the machine, are registered properly and registered according to the predefined configuration of the machine, which is called the valid configuration. The EF currently performs this activity for about 250 critical machine parts[1], which are called Critical Configuration Items (CCIs). Ideally, all these parts are completely registered and compliant with the valid configuration of the machine, which then result in a Configuration As Built (CAB) score of 100%. If not, several actions should be performed to deal with the parts that deviate from the valid configuration. Next to the CAB, all departments at ASML in the end-to-end process perform these checks the configuration status at that moment and thus have their own report on the status. Tracing and managing the status of a product's configuration is called Configuration Status Accounting (CSA) and is one of the four main activities of CM. Figure A.1 in Appendix A visualizes the CSA activities for each department at ASML. Later in this research, we elaborate on all main activities in the CM field.

This research has been scoped to the manufacturing activities performed in the EF (see Figure 1.1). All activities performed before and after the process in the EF, are considered as out-of-scope. The process starts with receiving the materials from the suppliers. Then, the modules are assembled in the *module build* activity. After that, the modules are integrated with each other to one machine in the *system integration* phase. When the machine is assembled, the *system qualification* activity tests the machine, before the machine is disassembled in the *prepack* phase so that it can be transported to the customers.

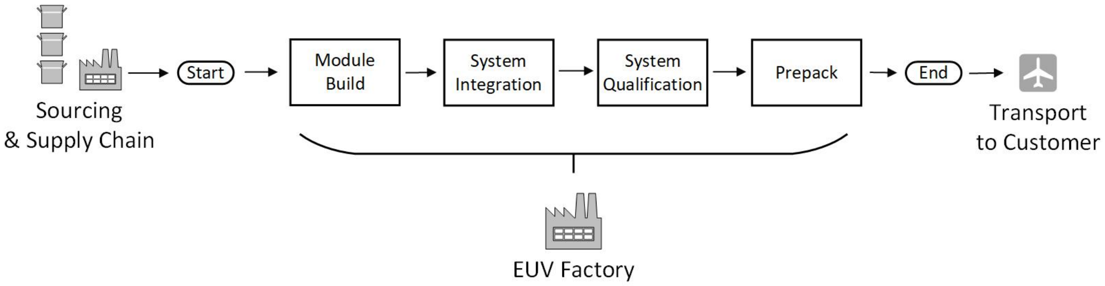

Figure 1.1: Visualization of the research scope

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[1] A valid configuration has approximately 250 CCIs to be checked. The exact number depends on the type of the machine and the related valid configuration. For simplicity reasons, we do not make any distinction in the number of CCIs and always refer to 250 for the current situation.

During the manufacturing activities, ASML's employees complete the orders by assembling the parts from the Bill of Material (BOM) in the machine, and register these parts in the equipment structure in the information system. When the order is completed, the configuration status of the 250 CCIs is checked by comparing the BOM with the valid configuration. This process is called *configuration registration.*

1.2 Problem statement

Right now, ASML is working with 250 CCIs for configuration registration as explained in Section 1.1.2. Ideally, all parts are registered such that the score for each configuration stage equals 100%. However, incomplete or incorrect configuration registration in the EF still occurs, which have a negative impact on ASML's business priorities, customer trust and cycle time. Right now, ASML is on the right track to meet the target of reaching a 99% score for the CAB. However, according to retrieved data, ASML does not meet this target for one out of four machines. It must be mentioned that the scores are close to the target of 99%, however a small deviation for not meeting the target can have enormous impact; if a critical part fails and is not registered according standards, this can increase the downtime at customer site as well as the installation time, since they need to research the machine to register the critical parts.

In situations that the CAB does not reach the optimal 100% configuration registration score, it cannot exactly be known what components are actually embedded in the machine. When installing the machine, the service engineer is thus not provided with all necessary information to successfully follow the installing sequence at customers site, which is not optimal. In addition, when a customer request a report for all materials that should be documented and included in the machine, ASML cannot fully serve the customer. ASML's information systems are then analyzed in order to to find the history of the components, which takes a lot of time.

A similar reasoning holds for the process of manufacturing the machine in the EF. After building the machine, it will be tested. When something goes wrong, in other words, when the test has failed, the digital twin created in the process will be analyzed to see which information is in the machine. When this information, which is configuration data, is not properly registered, the cycle time of this process increases. It is therefore important to get insights in the performance of the process of configuration registration in order to identify possible improvements on the current way of working.

In the future, the EF is expected to increase the number of configuration items of an EUV machine to 1000 in 2022 and even more in the upcoming years (see Figure 1.2). It is expected that customers receive less escalations by registering more configuration items, which can eventually lead to a reduction in downtime costs and therefore an increase in ASML's customer trust will potentially be gained.

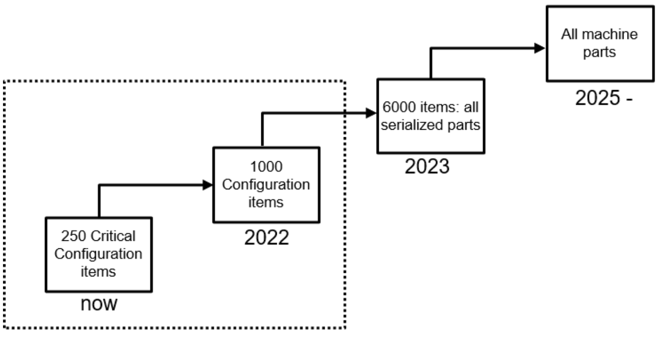


Figure 1.2: Future goals for number of machine items for configuration registration

Another important reason for this research is that ASML currently does not report on the CAB score with 1000 CCIs, and it is not exactly known what it takes to reach to ensure a CAB score of 99% in 2022. As mentioned before, the CAB score can sometimes not be reached in the current situation of registering 250 parts, which implies that there is a need for analyzing the way of working regarding configuration registration in order to be ready for the future. To summarize, the research problem can be stated as follows:

Problem Statement:
In 2022, the EF must reach a CAB score of 99% for 1000 configuration items. Right now for the 250 CCIs, this score is not always reached due to several reasons and it is not known what it takes to reach the target of 2022. We expect that reaching this target benefits ASML itself as well as its customers, but it is yet unknown what that impact is on the current situation, and how to improve that such that most of the benefits can be met in the future situation.

This research aims to *analyze and redesign the current way of working regarding configuration registration, together with the future impact the impact for ASML and its customers.* The current way of working regarding configuration registration as well as the impacts for the future situation are analyzed. For the current situation, we investigate what the process itself, and the quality of the configuration data that is generated in this process are and how the current situation can be improved in order to meet the standards. Moreover, we research on a way for ASML to optimally design their process and data flows in the future, when 1000 configuration items are registered. This is yet unknown.

1.3 Research goals

1.3.1 Business goals

From a business point of view, the research goal is to optimize the way of working regarding configuration registration in the EF. It is believed that improving this would positively impact ASML's customer trust and the cycle time in the EF. To determine the benefits for ASML, we conducted many interviews with stakeholders from various departments at ASML. This resulted in a benefit model (Figure 1.3) that represents all benefits that can be reached when optimizing the configuration registration process. The model is verified by all stakeholders and therefore, reaching the benefits in the model is considered as the business objective of this research. For the link leading towards the increase in reliability, and the decrease in cycle time resulting from an increased traceability in a part's history, additional benefit models are provided in Appendix B.1. The list of stakeholders can be found in Appendix B.2.

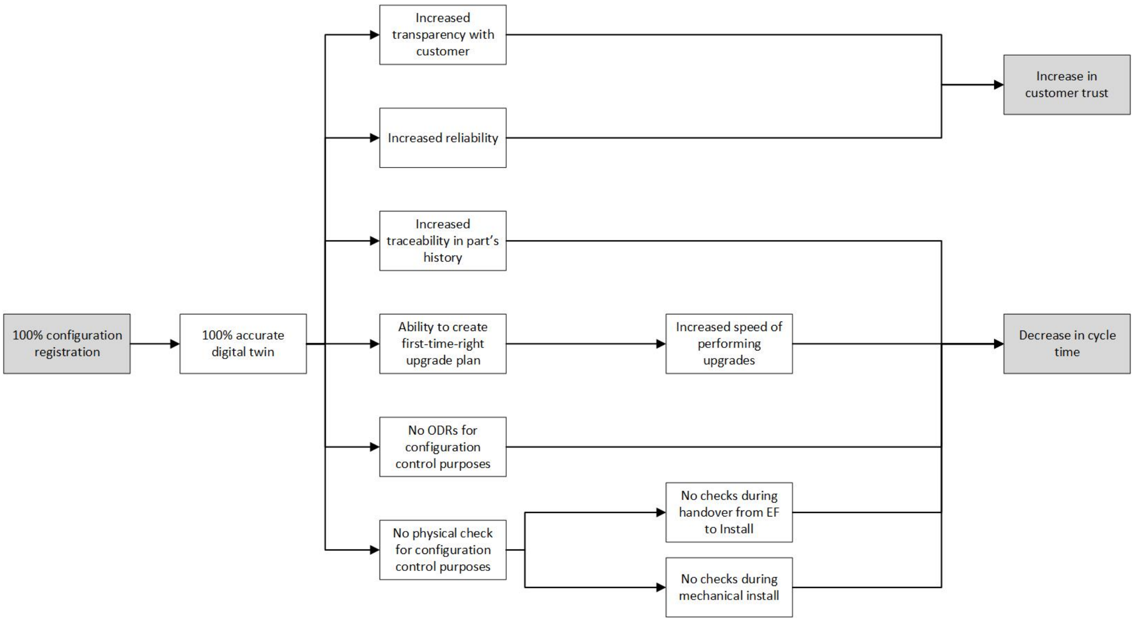


Figure 1.3: Benefits of 100% configuration registration

Next, we aim to assess the impact on the configuration registration process when having more parts registered according CM standards in the future (Figure 1.2). The last years, a lot of effort was taken to optimize the configuration registration process at ASML, and it is yet unknown what need to be done to reach the targets in the future, when registering 1000 parts. Therefore, the data and information in the configuration process are analyzed and subject for improvement. As mentioned earlier in this chapter, data about the part built into the machine must be completely registered, and also compliant with the valid configuration. This comparison results in the CAB score. So, improving the quality of data and information will increase the CAB scores and therefore satisfy the needs of ASML and their customers to deliver the machine in the right configuration.

1.3.2 Scientific goals

At ASML, the term configuration registration is used for mentioning the topic for this research. During literature research, it seems that configuration registration shows a lot of similarities with CSA. One could say that configuration registration enables organizations to perform the CSA activities. Only one research dedicated to CSA is found (Burgess, Byrne & Kidd, 2003). This research does not present a quantitative analysis for this activity. Further, many research state that CM in general is not seen as a critical function within companies (Quigley & Robertson, 2015; Burgess et al., 2003; Kidd & Burgess, 2004), and that CM in organizations is driven by customer requirements (Burgess et al., 2003). Therefore, one of the scientific goals of this research is to provide insights in the benefits of CM, especially configuration registration, for customers as well as organizations.

Second, within the field of CM, there is no literature found that applied artifact-centric modeling processes on CM processes. Earlier research describe the activities to be performed (Kidd & Burgess, 2004) or provide high-level business process models (Quigley & Robertson, 2015). However, there seems to be a gap in literature for optimizing processes regarding CM, since companies currently recognize the importance of CM. Because the process of configuration registration can be classified as a decision-intensive process (DIP), artifact-centric modeling approach like CMMN (Case Management Modeling Notation) is used to fill this research gap. A case study on how to organize configuration registration in a future-proof way is thereby added to the scientific field. To the best of my knowledge, no artifact-centric modeling approaches are used in the field of CM. Moreover, this research can provide insights in how to analyze the performance of their configuration registration process. Insights gathered form these analyses on the current way of working can enhance the CM processes in organizations. Since products become more complex and CM is a method to successfully deal with such complex products, it is useful that there is research providing practical analyses that can be applied in other industries. To the best of my knowledge, this has not been researched yet.

1.4 Research questions

Based on the problem statement and research goals, one main research question is defined as follows:

Main research question:
How can configuration registration in the EF be improved and what impact does it have for ASML?

In order to answer this main research question, the following four sub questions are defined:

1. How is the configuration registration process in the EF currently designed?
2. What are currently the bottlenecks within configuration registration at the EF for registering 250 CCIs?
3. How can the configuration registration process at the EF be redesigned?
4. What is the impact of the proposed solution design for ASML?

1.5 Outline

With this section, we introduce the structure of this research. In this chapter, we introduced the context of this research and defined the research questions in order to reach the business and scientific goals. Chapter 2 contains a literature review that focuses on the concept of CM in general, artifact-centric modeling techniques and a review on data quality dimensions and information quality in literature. In Chapter 3, we present the methodology that is used to structure this research. Next, Chapter 4 uses the artifact-centric modeling techniques to understand the as-is configuration registration process in order to answer the first sub question. In Chapter 5, we present the data that is used for modeling in Chapter 6 and clean the data according to the scope presented in Chapter 1. In Chapter 5, first insights in potential bottlenecks of the current process are found. The modeling phase in Chapter 6 then analyzes the data in order to find the bottlenecks and thereafter, we are able to answer sub question 2. Based on the bottlenecks identified, Chapter 7 proposes to change the current situation in order to eliminate the bottlenecks and improve the configuration registration process. As follows, we can answer sub question 3. Chapter 8 evaluates on the redesigned model and evaluates if the benefits stated in the business goals in Chapter 1 can be met. In addition, the redesign is evaluated by using the insights on the data quality dimensions we got in Chapter 2, and the fitness for use of information in the process. Finally, this research concludes by answering the research questions. Last, we provide the limitations of this research, insights for future work and recommendations to improve the configuration registration process at ASML.

Chapter 2

Literature review

During the literature research, we retrieve valuable insights and information into the areas of interest for this research. First, literature about the concept and applications of CM is analyzed. Second, since we use artifact-centric modeling techniques for modeling and improving the current situation, such modeling techniques are reviewed and analyzed. Finally, this chapter provides an overview of research on data quality dimensions and information quality and methods for assessing the data quality in business processes.

2.1 Configuration management

CM is defined as the field of management focused on establishing and maintaining the consistency of its system or product performance and its functional and psychical attributes (O-CHART, 2009) Quigley and Robertson (2015) define CM as the plan, or blueprint, for a product, process or a document before, during and beyond its lifecycle.

All-in-all, CM deals with product characteristics throughout the entire lifecycle. In order to do this, the concept of CM in general consist of four activities:

1. **Configuration identification**. The purpose of configuration identification is to name the configuration items to be controlled appropriately based on the information available about the physical and functional characteristics of a configuration item (Quigley & Robertson, 2015). In addition, configuration identification targets to insure the accuracy, uniqueness, integrity and traceability of the items in the product lifecycle (Qiao-Xiang, Ying, Guo-Ning & Shao-Hui, 2011).
2. **Configuration change management**. Configuration change management is the process for managing product changes and variances. This is an important activity in the whole CM process since unmanaged changes of a configuration item can have unforeseen consequences on a company-level (Quigley & Robertson, 2015). This process of controlling the configuration items can be used in order to see what effects changes of configuration items have on the KPIs defined by the organization (Ward, Aggarwal, Buco, Olsson & Weinberger, 2007).
3. **Configuration status accounting**. Configuration status accounting can be defined as the function that records and reports the generated information in other CM functions (Viskari, 1995). These reports can be used in the CM planning in order to see any information like the number of changes for an item and the status of changes for a specific configuration item. This activity can be considered as critical since the traceability of a configuration item can be ensured.

4. **Configuration verification and audit**. Configuration verification activities and audits are performed on two levels (Kidd & Burgess, 2004):
    (a) *Functional level.* Audits are performed to asses whether the performance measures specified in the organization are met during the entire configuration process. Collected data is analyzed and it is identified whether the configuration settings at one state in the product lifecycle are consistent with those of the next state. If deviations or changes are applied somewhere else in the process, these must be appropriately processed such that the different configuration states throughout the product's lifecycle remain consistent. (O-CHART, 2009)
    (b) *Physical level.* Audits are performed on the end of the state and it is verified whether the product configuration items meet the requirements specified by the customer.

During the literature research, most of the papers found were about assessing and improving CM processes in general. Myrodia et al. (2019) developed a general framework in order to assess the maturity level of CM processes in organizations. Figure 2.1 presents the framework with the five different maturity levels. On each of the dimension from Figure 2.1, the classification of each level for each dimension is provided by Myrodia et al. (2019) and is visualized in Appendix C in Figure C.1. Among these levels, organizations can determine the maturity level of their CM activities and processes by assessing the state of each dimension specified in the model.

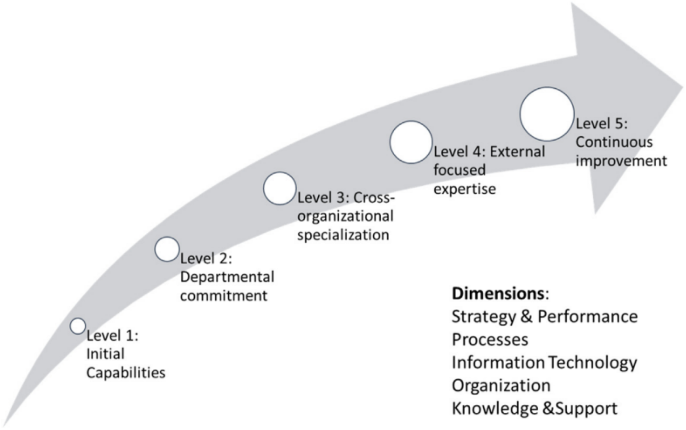
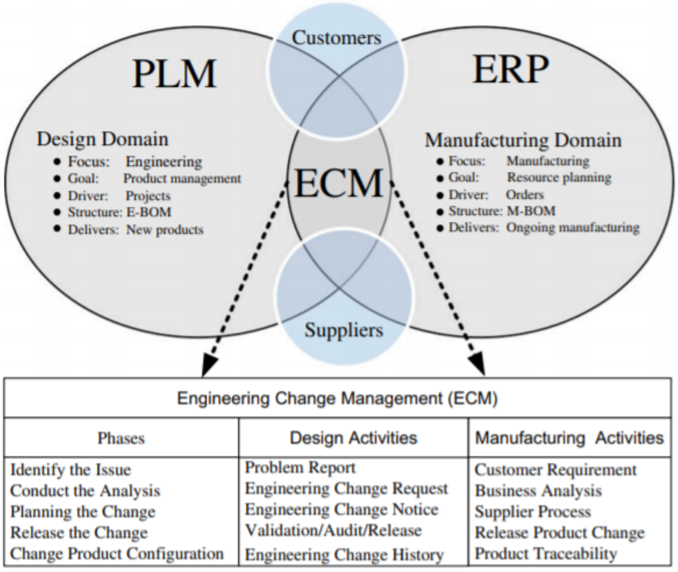


Figure 2.1: CM maturity model (Myrodia et al., 2019)

Next, we discuss the research of (Wu et al., 2014). This research presents an advanced CM-II based Engineering Change Management (ECM) framework, following the CM-II principles. The reason for including this research is that the CM-II industry-standard is used at ASML, and therefore the processes described by Wu et al. (2014) are likely to have similarities with the processes at ASML regarding ECM. In their research, the information exchange and integration between the design and manufacturing activities is visualized, based on the five major ECM stages:

1. Identify the issue
2. Conduct the analysis
3. Planning the change
4. Release the change
5. Change product configuration

In Figure 2.2, the interaction between the design domain (PLM side) and the manufacturing domain (ERP side) can be seen. The application of this framework is tested in the motorcycle industry. The performance was measured before and after the application of the framework, and the researchers concluded that the ECM framework following the CM-II logic can be promoted at organizations, since it leads to significant performance improvement.



Engineering Change Management (ECM)

Phases	Design Activities	Manufacturing Activities
Identify the Issue	Problem Report	Customer Requirement
Conduct the Analysis	Engineering Change Request	Business Analysis
Planning the Change	Engineering Change Notice	Supplier Process
Release the Change	Validation/Audit/Release	Release Product Change
Change Product Configuration	Engineering Change History	Product Traceability

Figure 2.2: Advanced CM-II based ECM framework maturity model (Wu et al., 2014)

2.2 Business process modeling

Configuration Status Accounting (CSA) is the activity that companies use to ensure that the product meets the expected requirements that are documented earlier in the process. These requirements are often set up together with the company's customers. It is stated by Burgess et al. (2003) that reports generated in this activity are used to provide customers more confidence in the final product, especially for highly complex products. In order to keep track of the product status and thus meet the customer requirements, a well-designed configuration registration process should exist in the company. This research aims to identify the information flow in the configuration registration process, since CSA reports solely consists of progress information generated in the corresponding CM stage. The process of configuration registration can be described as a decision-intensive business process (DIP), since the actors need to perform activities for retrieving configuration data in previous stages in the process, together with continuing the manufacturing process. Moreover, when configuration data is found to be incomplete or not according the standards, additional actions should be performed in order to continue the process.

2.2.1 Artifact-centric process modeling

DIPs are described by (Vaculin et al., 2011) as processes that *"provides guidance and support to one or several users in performing information and decision intensive tasks that need to be solved in a collaborative fashion with the help of various information and knowledge resources"*. For such business processes, artifact-centric process models can be representative models (Eshuis, 2021). Artifacts can be defined as "a real-world business entity about which data is processed, and for which activities are performed" (Eshuis, 2021). The concept of business artifacts and the artifact-centric modeling approach is introduced by Nigam and Caswell (2003). There are various names for business artifacts to describe business processes in literature, such as *business entities*, *adaptive documents* and *adaptive business objects* (Kumaran et al., 2008). In this research, we use the term business artifacts.

Business artifact-centric process models can be represented by following the Case Management Model and Notation (CMMN) approach (M. A. Marin, 2017). CMMN is a modeling approach developed by the Object Management Group (OMG) and was introduced in 2014 (OMG, 2014). A visualization of the elements of CMMN is provided in Figure 2.3. CMMN fulfills the request for a modeling standard for managing case management processes (M. Marin, Hull & Vaculin, 2012). Case management at organizations refers to work that is not routine and predictable (Motahari-Nezhad & Swenson, 2013). Where traditional Business Process Management (BPM) approaches standardize and automate structured business processes, CMMN can be used for enterprises to overcome the limitations of BPM to manage unstructured processes (S. Wang, 2017). In addition, artifact-centric models start directly with retrieving business artifacts critical for retrieving a certain business goal, where traditional processes aim to describe the order in which activities are performed (Liu, Bhattacharya & Wu, 2007). When creating artifact-centric models, one starts with retrieving the information structures central to the operations in the business process. With the increasing amount of data in technology-driven organization's business processes, artifact-centric modeling techniques can therefore be useful to (re)design their processes.

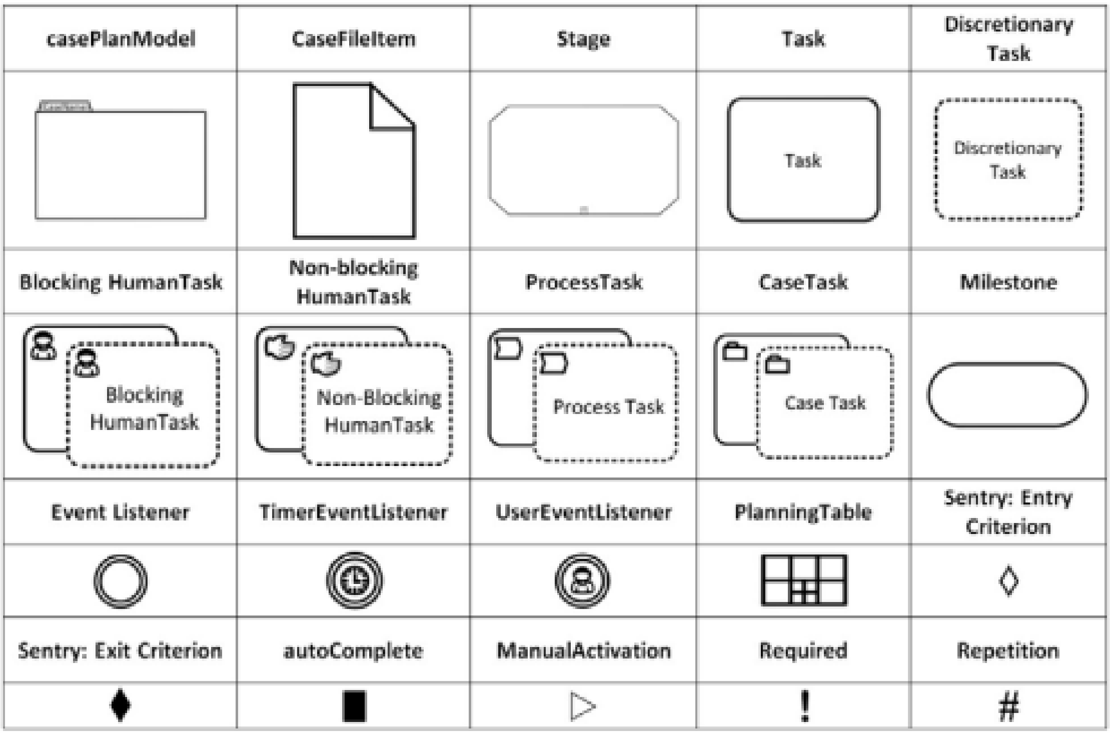


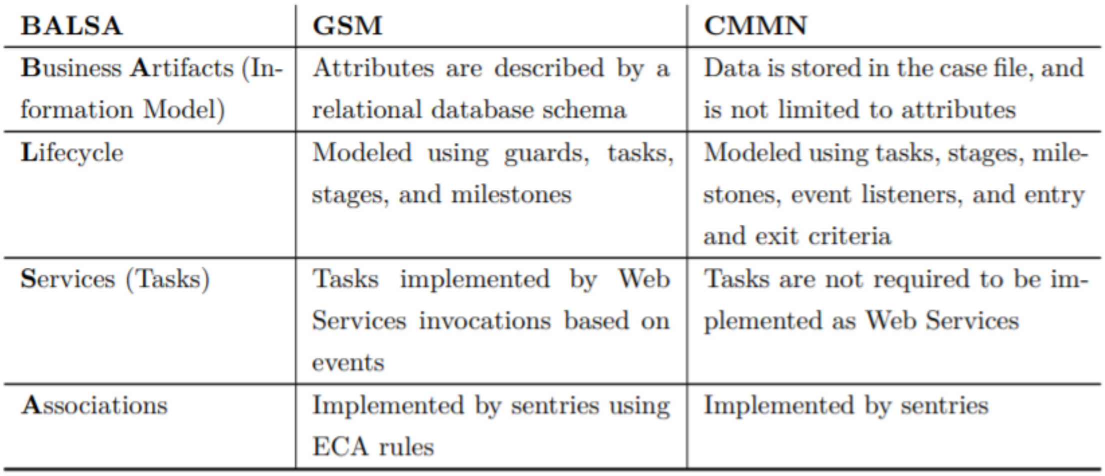
Figure 2.3: CMMN elements (Breitenmoser & Keller, 2015)

CMMN's relationship to Business Artifacts is described by M. A. Marin (2017) using the four BALSA dimensions:

1. BA (Information Model), which record all business-relevant information about the artifact
2. Lifecycle, that specifies the evolution of a case throughout the different stages and tasks in the lifecycle of the case.
3. Services (Tasks). In CMMN, tasks represent the work that has to be done.
4. Associations, which are described by sentries, represent the associations between the case file, tasks, stages and the milestones.

CMMN originates from another artifact-centric modeling notation, namely Guard-Stage-Milestone (GSM) notation. The four BALSA dimensions described above can also be used to characterize GSM (M. A. Marin, 2017), yet in a different context. M. A. Marin (2017) compared both notations using the BALSA dimensions, which can be seen in Figure 2.4. He concluded that GSM is another artifact-centric modeling approach, but differences exist between these two artifact-centric modeling notation. CMMN evolved out of GSM and adds the following important modeling functionalities that are missing in the GSM notation (M. A. Marin, 2017):

1. CMMN supports unstructured data.
2. CMMN adds discretionary stages and tasks.
3. CMMN explicitly models external events, while in GSM, these events are embedded in the sentries.
4. CMMN includes rules that enforce the behavior of a case type, for example, a case type is required or need to be repeated. Next, the interaction with the case workers is embedded. These are not supported in GSM.
5. CMMN supports human interaction to affect the life cycle of the modeled elements, which is not present in GSM.



BALSA	**GSM**	**CMMN**
Business **A**rtifacts (Information Model)	Attributes are described by a relational database schema	Data is stored in the case file, and is not limited to attributes
Lifecycle	Modeled using guards, tasks, stages, and milestones	Modeled using tasks, stages, milestones, event listeners, and entry and exit criteria
Services (Tasks)	Tasks implemented by Web Services invocations based on events	Tasks are not required to be implemented as Web Services
Associations	Implemented by sentries using ECA rules	Implemented by sentries

Figure 2.4: A snapshot of the comparison between GSM and CMMN using the BALSA dimensions, analyzed by M. A. Marin (2017)

2.2.2 Entity Dominance

In the previous Section, we discussed the concept of artifact-centric process modeling techniques. These modeling techniques emerged over the last years and evolves from the need to overcome the limitations of traditional, more activity-centric process modeling techniques such as BPM. However, research is conducted for deriving artifact-centric process models from activity-centric modeling techniques (Kumaran et al., 2008). Kumaran et al. (2008) define activity-centric process modeling as a modeling approach that consists of business activities and connectors that describe the execution sequence of the business activities, with information entities as inputs or outputs of the activities. Such activity-centric process models can be transformed in artifact-centric models by using the concept of entity domination. This concept explains that information entity[1] e_1 dominates information entity e_2 if and only if:

1. Every activity in which information entity e_2 is used as input, e_1 is also used as an input
2. Every activity in which information entity e_2 is used as output, e_1 is also used as an output
3. Information entity e_1 is used in at least one activity that does not use information entity e_2.

With the activity-centric process modeling approach of Kumaran et al. (2008), one can easily determine the entity dominance and therefore construct the entity-dominance graph as input for the artifact-centric process model. An example of the notation of Kumaran et al. (2008) is provided in Figure 2.5, where it can be identified which entities are input and output for a certain business activity executed in the business process. This notation distinguishes the control flow from the data flow by naming the arrows that represent a data flow.

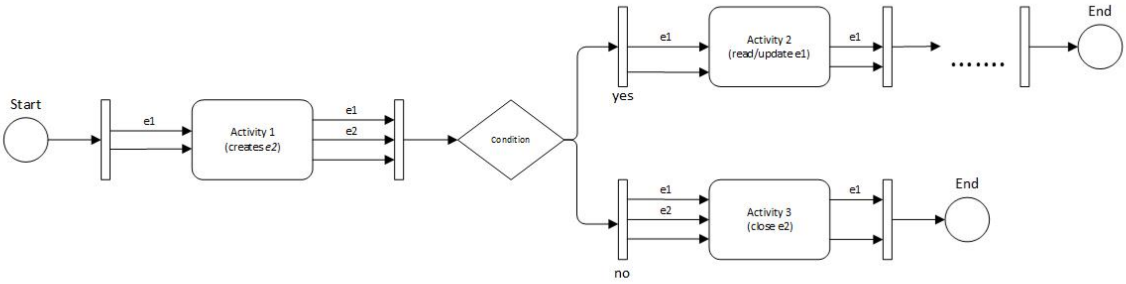


Figure 2.5: Activity-centric modeling notation by Kumaran et al. (2008)

The entity dominance method of Kumaran et al. (2008) shows similarities to a method of Snoeck and Dedene (1998). Where Kumaran et al. (2008) propose a method to find the dominant and dominated information entities with a lifecycle in business processes, Snoeck and Dedene (1998) refer to this as *parent object* and *existence dependent objects*. Existence dependency is explained as follows: *"if each object of class A refers to minimum one, maximum one, and always the same occurrence of class B, then A is existence dependent of B"*. As a result, the existence dependent object can simply not start and end before the parent's lifecycle has started. The method of existence dependency can be integrated with UML Diagrams. Existence dependency relationships between artifacts can be a valuable alternative for "part-of" relationship of UML Class Diagrams. Snoeck and Dedene (1998) even distinguishes two cases of part-of relationships in UML in existence dependent parts and non-existence dependent parts:

---

[1] For explaining this concept, we will follow the original author's naming of business artifacts, namely *information entity*

1. **Existence dependent parts**. For example, an order has many order lines and logically, an order line cannot exist without an order. (see Figure 2.6)

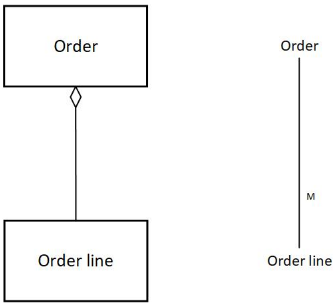


Figure 2.6: Existence dependent parts

2. **Non-existence dependent parts**. A machine consists of multiple parts, for example, a machine consists of three single parts. If the machine is disassembled, the parts could still be used and therefore meaningful exist. In this case, Snoeck and Dedene (1998) would refer to non-existence dependency. (see Figure 2.7)

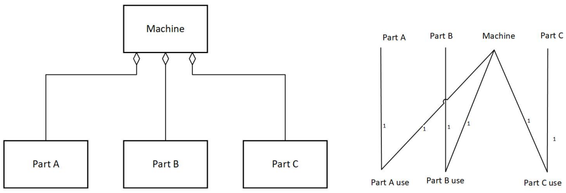


Figure 2.7: Non existence dependent parts

2.3 Data quality

When analyzing data flows in business processes, it is important to assess the quality of the data. High-quality data are the precondition for data analyses, and are needed to ensure that the analyses are valuable for the organization (Cai & Zhu, 2015). Business processes are usually taken as the starting point for assessing the business impact of issues regarding the quality of data (Cai & Zhu, 2015). Data quality is often measured regarding one or more data quality dimensions. In literature, many research is performed on defining these dimensions, and many research provided methods on how to improve the data quality in business processes. This research contains a literature review on relevant papers for assessing the quality of data in business processes, and for defining the most relevant data quality dimensions.

Regarding methodologies for the assessment and improvement of data quality, Batini, Cappiello, Francalanci and Maurino (2009) provide an extensive, systematic and comparative overview of such methodologies. In general, the activity sequence of these methodologies contains of three phases:

1. **State reconstruction**, which refers to the collection of data.
2. **Assessment and measurement**. In this phase, the quality of data along the relevant data quality dimensions is measured and assessed.
3. **Improvement**. This phase is about the selection of steps, strategies and techniques in order to reach the new data quality targets.

Batini et al. (2009) presents an extensive framework which visualizes the reviewed methodology and the quality dimensions that are subject for improvement in these methodologies.

Next, as mentioned before, many research about improving data quality in processes is found (Belhiah, Benqatla & Bounabat, 2016; Cai & Zhu, 2015; Cappiello, Pernici & Villani, 2015; Gürdür, El-khoury & Nyberg, 2019; Sidi et al., 2013; Wand & Wang, 1996; R. Wang & Strong, 1996). All research suggest that determining the data quality dimensions in the process act as input for improving the data quality in the process. Belhiah et al. (2016) present metrics for quantitatively assess the data quality of three dimensions 1) accuracy, 2) completeness and 3) timeliness. These are presented below in respective order.

$$\frac{\text{accurate values}}{\text{total nr. of values}} \quad (2.1) \qquad \frac{\text{non-null values}}{\text{total nr. of values}} \quad (2.2) \qquad \frac{\text{up-to-date values}}{\text{total nr. of values}} \quad (2.3)$$

A method for presenting such data quality metrics is provided by Gürdür et al. (2019). In their research, a method for developing a visual dashboard for companies that represents the quality of linked enterprise data, is presented.

Cai and Zhu (2015) propose a method for assessing the data quality which contain a feedback mechanism, in order to strive for the desired data quality. However, they mention that data quality can only be assessed when having a baseline, or reference values, to compare the retrieved values with. This is in line with statements in the review of Batini et al. (2009).

Cappiello et al. (2015) indicate that a business process characteristics need to be taken into account when changing processes for data quality improvement. Their study contained research on how to improve the data quality of four dimensions: accuracy, consistency, completeness and timeliness. These dimensions are also considered by Sidi et al. (2013), who concluded that these dimensions have a significant relationship with business process improvement. For data consumers, R. Wang and Strong (1996) developed a framework that captures many dimensions of data. After reviewing these papers, it seems that the most important and mostly researched quality dimensions are *accuracy*, *consistency*, *completeness* and *timeliness*. This is in line with statements of Batini et al. (2009) and Wand and Wang (1996). However, both research state that there is no general agreement on which set of data quality dimensions define the data quality. Therefore, validation steps must be done in order to identify the dimensions that are important for organizations to improve on. For that reason, we will interview data users during this research. A complete overview of literature where methods for data quality assessment and improvement are presented, can be found in Table 2.1.

The last research we discuss is of Eppler (2006). Eppler (2006) discusses the concept of information quality. Where most of the research above discuss the quality of data, Eppler (2006) elaborates on the difference between data quality and information quality problems. He mentions that data quality problems can often be resolved by automated process, whereas information quality problems can not. Solving information quality problems often require a fundamental analysis on bottlenecks in the businesses and a process redesign subject to these issues. (Eppler, 2006) defines information quality as *the fitness for use of information* and uses the activation principle of (Garvin, 1988) to explain this. The activation principle states that information should be directly actionable for the information consumers by catching their attention and fulfilling their needs and preferences. Information must be acted upon in order to be of value, otherwise, when the information is simply ignored by the consumers, it is valueless (Eppler, 2006).

Table 2.1: Overview of data quality dimensions in literature

Data quality dimension	Belhiah, Benqatla, & Bounabat (2016)	Cai ad Zhu (2015)	Cappiello, Pernici & Villani (2015)	Gurdur, Elkhoury, & Nyberg (2019)	Sidi et. al (2013)	Wand & Wang (1996)	Wang & Strong (1996)	**Count**
Accessibility		x					x	2
Accuracy	x	x	x	x	x	x	x	**7**
Appropriate amount of data							x	1
Availability				x			x	2
Believability							x	1
Completeness	x	x	x	x	x	x	x	**7**
Concise representation							x	1
Consistency		x	x	x	x	x	x	**6**
Credibility		x						1
Currency						x		1
Fitness		x						1
Integrity		x						1
Interpretability							x	1
Objectivity							x	1
Precision						x		1
Readability		x		x				2
Relevancy							x	1
Reliability						x		1
Reputation							x	1
Reusability				x				1
Security				x			x	2
Timeliness	x	x	x	x	x	x	x	**7**
Traceability				x				1
Understandability							x	1
Usefulness				x				1
Value-added							x	1

2.4 Conclusion

In this chapter we provided insights about the concept of CM in general and briefly described the four main activities of CM. We discussed a CM maturity model that organizations can use to take their CM process to the next level, striving for continuous improvement. Next, we identified what a DIP is and how artifact-centric modeling techniques can help to model such processes. We use these modeling techniques to identify how the current configuration registration process is designed. We performed an extensive literature review on data quality dimensions and how to improve the data quality in organizations. We concluded that there are four data quality dimensions that are the most relevant for organizations. Last, we explained the main difference between data and information quality and introduced the activation principle to explain the *fitness for use* of information in organizations.

At the end of this research, we provide recommendations on how to take the CM processes at ASML to the next level. Moreover, we assess if the artifact-centric modeling techniques are applicable for the process of configuration registration. Last, we evaluate on how the data quality in the configuration registration process can be improved by looking at the four most relevant data quality dimensions. If applicable, other dimensions are considered.

Chapter 3

Methodology

This chapter presents the methodology of this research. Two scientific approaches are chosen For this research, we chose two scientific approaches in order to answer the research questions presented in Section 1.4. We explain both approaches in Section 3.1. After that, we take the phases of the problem solving cycle as the outline of this chapter. Each section of this chapter contains an explanation on how the phase is completed and the research questions are answered.

3.1 Approaches

The first scientific approach that we discuss is the Problem Solving Cycle by van Aken et al. (2012). This method consists of five phases as can be seen in Figure 3.1. The fourth phase, the intervention phase is not part of this research. The reason for choosing this approach is that the problem solving cycle is a widely chosen approach for optimizing business problems and can easily be aligned with the research questions that we aim to answer.

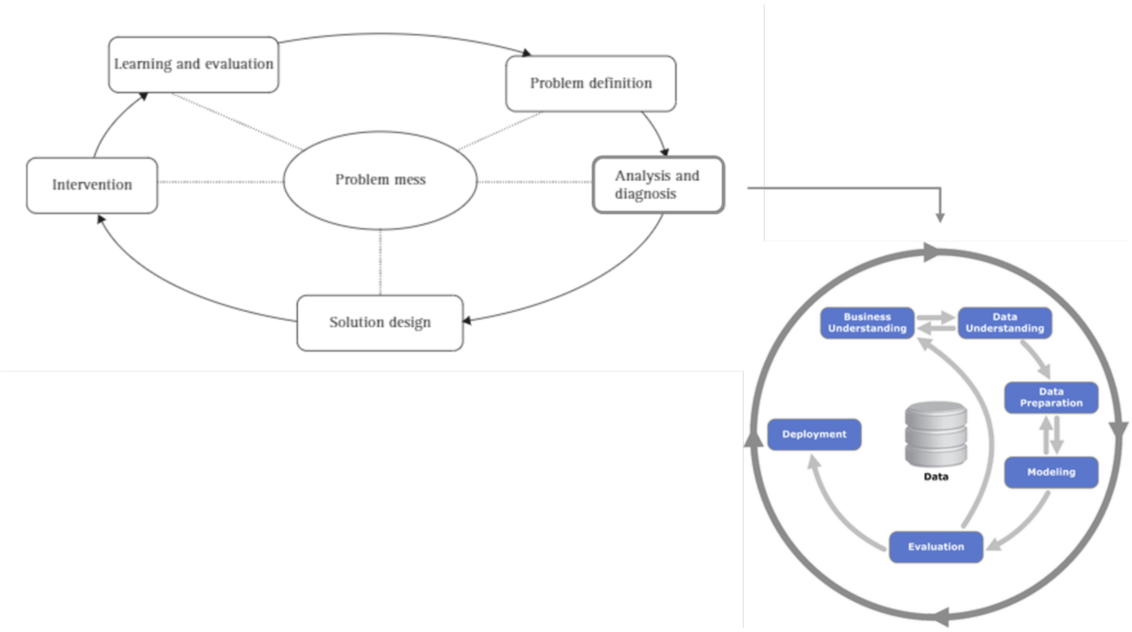


Figure 3.1: Research Methodology (van Aken et al., 2012; Shearer, 2000)

The second approach that is used in this research is the CRISP-DM framework of Shearer (2000). Since this research performs data analyses in order to identify the bottlenecks in the current way of working, this method is chosen. The CRISP-DM framework is also a widely used methodology for research including data analyses parts. In addition, this methodology consists of clear steps that must be executed in order to perform data analysis. The approach can therefore be seen as the guidance for the analysis and diagnosis part of the problem solving cycle. The framework (Figure 3.1) consists of six steps, from which the first five steps are in scope of this research, meaning that the deployment phase is not performed.

3.2 Problem definition

The starting point of any research is to understand the problem to be solved. In Chapter 1, a we provided a problem statement and the context that belongs to the problem to be solved. The first phase of the problem solving cycle is therefore not directly linked to any of the research questions, but is already done prior to this research.

3.3 Analysis and diagnosis

As mentioned, this phase is solved by following the CRISP-DM framework of Shearer (2000). Each stage and the corresponding activities are explained in the next subsections.

3.3.1 Business understanding

This phase is about understanding the process that is subject for this research. This phase therefore covers the first sub question of this research and aims to understand the current way of working regarding configuration registration in the EF. We identified the activities and information flow of the as-is processed by making use of available data, and held interviews with relevant stakeholders at ASML. These interviews were unstructured, since unstructured interviews are mostly appropriate to allow key stakeholders to reveal all important information regarding the topic (Wilson, 2014). The goal of the interviews was to reveal all information about the main process activities, information flow, tools and other information leading towards the creation and status changes of the CAB, since the CAB presents the scores of the configuration status of the machines. With that information, we created:

- A context diagram that provides a high-level overview of the CCT tool, where the CAB is generated
- A UML model representing the links between the relevant artifacts in the configuration registration process
- The activity-centric diagram in order to see the activities that use or edit the artifacts
- The entity dominance graph, in order to identify the dominant artifacts in the configuration registration process
- CMMN models of the dominant artifacts, to visualize the decisions made during the configuration registration process

The business understanding phase is covered in Chapter 4.

3.3.2 Data understanding

First in this phase, stakeholders were contacted in order to collect the required data for the analysis. After that, when we were familiar with the data subject for analysis, we analyzed whether the data is suitable for further data analysis in order to identify the bottlenecks in the configuration registration process. This was done by exploring the data and see if the data covers the configuration registration process. If we were not able to understand the data, the stakeholders that were interviewed during the previous phases were asked for elaboration and explanation. All steps in the data understanding phase were iterative, and we collected additional data in order to cover the research area as good as possible.

During the data understanding phase, we also derived first insights in potential bottlenecks of the configuration registration process. Given the size of the data sources, we decided to use Python for the data analysis. Python is also used in the data preparation phase (Subsection 3.3.3) and modeling phase (Subsection 3.3.4). However, for visualization reasons, we used Microsoft Excel for some cases to visualize the results of the analyses, since this is easier to do in some cases and thus saves time. The data understanding phase is covered in Chapter 5.

3.3.3 Data preparation

In this phase, we cleaned the data such that the data did not contain missing values, and all data was in the scope of this research. Therefore, all empty values, software CCIs, machines not in our time scope, and configuration registration errors that not represent an error in the facotry were removed from the dataset. Last, we merged all data collected in the previous phases resulting in one final dataset that is used in the modeling stage. The data preparation phase is covered in Chapter 5.

3.3.4 Modeling

In this phase, we created the model in order to identify the bottlenecks of the current configuration registration process. We provide an overview of all incomplete and non-compliant registrations in the manufacturing process at EF for our time scope. We presented the bottlenecks on the dominant artifacts identified in the business understanding phase, since these artifacts could potentially be subject for improvement in the redesign phase. The modeling phase is covered in Chapter 6.

3.3.5 Evaluation

The evaluation phase covers the understanding of the quantitative analysis performed in the previous subsection. In here, we assessed the results and validated together with relevant stakeholders if the results are a good representation of the current situation. Additionally, unstructured interviews were held with the relevant stakeholders to get a better understanding of the results, and a direction for the redesign of the configuration registration process. We used unstructured interviews for the same reason as described earlier. The evaluation phase concludes the analysis and diagnosis phase of the problem solving cycle when the bottlenecks of the configuration registration process are identified. This phase is covered by Chapter 6.

3.4 Solution design

During this phase, we optimized the current situation by eliminating the bottlenecks found in the previous phase. Therefore, the as-is process was taken as a reference point and the improvements are implemented in the models created in the business understanding phase. For redesigning the current way of working, we held interviews with stakeholders to collect additional information to validate whether the redesign will not cause additional problems to the process. For the redesign, we briefly analyzed the ECM process at ASML and compared it with literature to identify the points for improvement, since it seemed that the introduction of Engineering Changes (ECs) was the main bottleneck in the current process. We implemented our redesign in the UML diagram, activity-centric diagram and one CMMN model for one dominant artifact. This phase is covered by Chapter 7.

3.5 Learning and evaluation

The final phase of the problem cycle is to evaluate on the suggested redesign implementation. This phase is covered by Chapter 8 and Chapter 9. This phase assesses whether or not the business and scientific goals are reached, and we provide the conclusions, recommendations and the limitations of this research. The assessment is done by contacting the relevant stakeholders that have already contributed to this research. During the conversations with them, we mainly focused on validating on the business goals that can be reached, and the practical implementation of the redesigned suggestion. In addition, we determined the effects on the redesign on the data quality dimensions and the information quality as explained in Section 2.3.This led to a few changes in the documentation and explanation of the proposed redesign, and the business goals.

Chapter 4

Process analysis

This chapter provides an overview of the current way of working regarding configuration registration, and will therefore cover the second research question stated in Section 1.4. As mentioned in Chapter 3, the interest of this research is to identify the process that is leading towards the CAB. This chapter covers the business understanding phase of the CRISP-DM framework and is therefore part of the problem solving cycle. This research focuses on the information flow used in the process and we use an artifact-centric modeling approach to model the current situation. For doing that, different models are used which is leading to the final model in CMMN. Section 4.1 provides an overview of the selected models and reasons for including it in this research. After that, the remaining sections present the actual models corresponding to the as-is situation at ASML. The outline of the analysis of the current situation is provided in Figure 4.1. At the end of this chapter, the current configuration registration process is analyzed, and the information flowing through the process is identified. With that, we can move on to the data analysis phase to identify the bottlenecks in the current process.

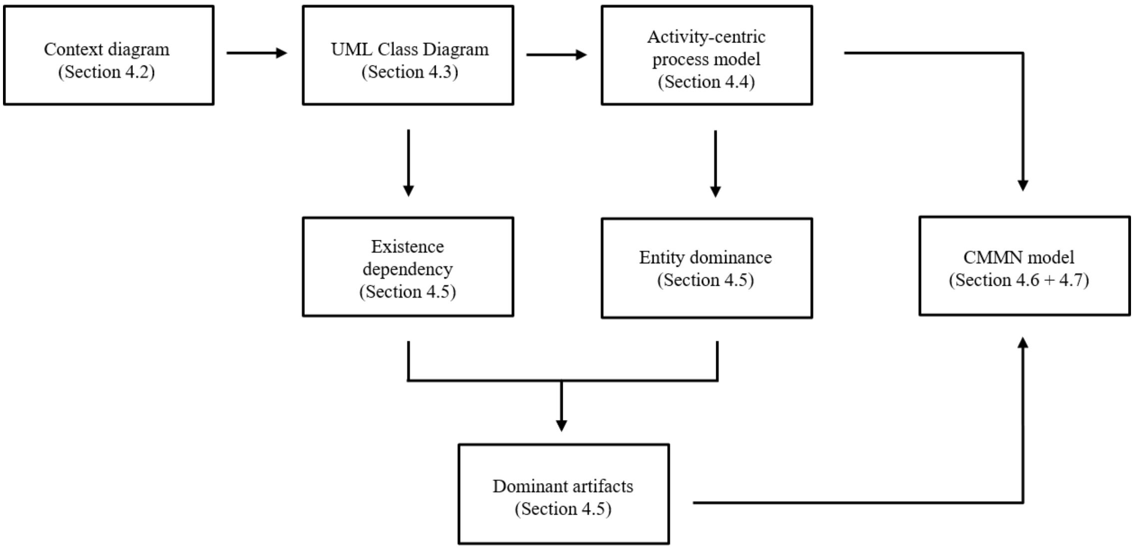


Figure 4.1: Outline of the process analysis

4.1 Introduction

This section introduces the different models that are selected and contribute to the end result of presenting the CMMN model regarding the as-is situation of the configuration registration process. An overview of the selected models and reasons for including these in this research is provided in Table 4.1. While identifying the current situation, the models are continuously changed for improvement in order to provide an actual representation of the current way of working. The actual models (described in the next sections) are based on the gathered information from different stakeholders at ASML. Besides, information available in ASML's databases are used as well. The stakeholders were selected based on their familiarity with the configuration registration process.

Table 4.1: Model selection

Model	**Description**	**Reasons for including**
Context diagram	A context diagram is the highest-level view of a data flow diagram that visualizes the major information flows between the system and external entities	Since the CAB is stored in the CCT tool, it is important to visualize the data this tool uses in order to develop the CAB A context diagram can be decomposed into more explicit data flow diagrams (Ibrahim & Yen, 2010)
UML Class Diagram	Analyzes the content of the relevant information flow presented in the context diagram An UML class diagram visualizes the structure of a system by showing the relationships between artifacts and their attributes	UML diagrams can be used to determine existence dependency between entities (Snoeck & Dedene, 1998) and therefore act as input for determining the entity dominance The relationships between the artifacts used in the process become visible and understandable
Activity-centric process model	Shows the activities performed in the process that create, edit or remove some artifacts presented in the UML model	According to Kumaran et al. (2008), activity-centric process models can be used to determine the dominant entities in the process Used for validating the as-is situation with different stakeholders
Entity dominance	Uses the activity-centric process model to construct the entity-dominance graph to present the dependencies between the entities	Used for identifying the artifacts that are used for the CMMN model
Existence dependency	Uses the UML Class Diagram to model structural relationships between object types in their lifecycle. Follows similar rules as the entity dominance concept of Kumaran et al. (2008)	Used for identifying the artifacts that are used for the CMMN model
CMMN Model	Focuses on representing the current as-is situation regarding configuration registration in an artifact-centric way Shows which activities are responsible for status changes of the artifacts in the process	Represents the artifact-centric process model of the configuration registration process Used as a starting point for business redesign

4.2 Context Diagram

The first model that is explained, is the context diagram as presented in Figure 4.2. This is done to provide a starting point for further evaluation of the current situation. The context diagram presents the highest-level view of how the CAB is created. The CAB is created and edited in a tool that ASML uses for performing the *configuration compliance check* resulting in the *CAB*, the Configuration Compliance Tool (CCT). Since the CAB represents the configuration status of the machine, explaining the interactions of this tool with the outside world is important. These interactions of the tool with the outside world, as presented in the context diagram, can be decomposed into more explicit data flow diagrams (Ibrahim & Yen, 2010), which is done in the remaining sections of this chapter. Right now, we elaborate on the two most important interactions of this tool for this research:

1. **SAP**. CCT retrieves up-to-date information about the status of a machine's configuration out of ASML's ERP system, SAP. While the machine, or a module of the machine, is in one of the manufacturing stages, ASML's employees complete the corresponding order by scanning the parts that they have assembled into the machine or module. When the part has been scanned, the part is registered in the *equipment structure* in the order at the ERP system. This information is synchronized with the CCT tool and used as input to determine the compliance of a part, when the part is classified as a CCI. Eventually, the status of the CCI on its compliancy is visualized in the CAB. Note that the configuration status of a machine or module is a live snapshot of the status on a certain point in time.
2. **Valid Configuration**. Each machine is assigned to a valid configuration. A valid configuration consists of the 250 CCIs for the machine. A machine's valid configuration is administered in the CCT tool and the CAB must be compliant with those CCI values. Thus the up-to-date order information about the parts being built in the machine, need to be compared with the valid configuration. Since a CCI can have multiple parts that are allowed in the machine, the valid configuration contains rules to determine on the status of the CCIs. The valid configuration is created in an earlier stage at ASML (Development & Engineering) and is manually registered in the CCT tool.

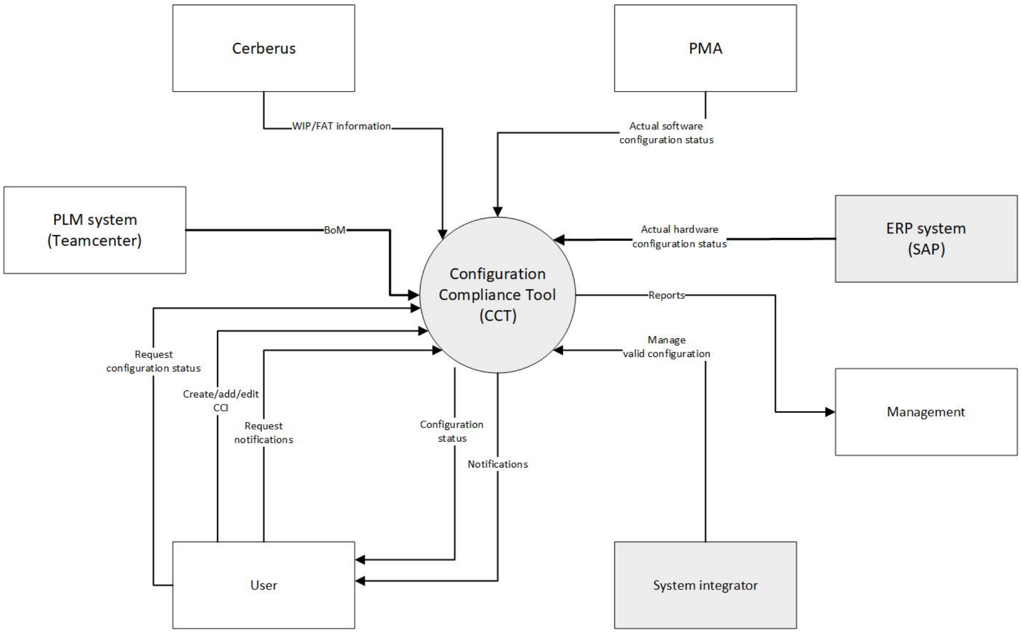


Figure 4.2: Context diagram of the CCT tool used for the configuration compliance check

4.3 UML Class Diagram

This section presents the UML Class Diagram that visualizes all data that is being processed in the configuration registration process (Figure 4.3). The UML class diagram is used to analyze the information entities that interact with the CCT tool in more depth. The diagram is created after having all information collected from the interviews and sources within ASML. The modeling of the diagram started with classes that could be retrieved from the context diagram; the valid configuration and the order (which are in the ERP system, SAP). The interviews and data collection focused on collecting information about the completing the orders for the machines in SAP.

For assembling and qualifying the machine, there are two orders that have to be completed. We have *module orders* and *qualification orders*. Module orders complete a *module*, that consists of integrated *parts*. These modules are then integrated and other parts are added to build the complete *machine*. A machine has a qualification order. Both orders follow a similar way of working and data structure. Each order consists of an *equipment structure*, *planning* and a *work sequence*. An order can be completed by scanning parts in the equipment structure, following all sequence activities and having all parts removed from the order attributes *greylist* and *reservations*. When the order is completed, an *employee* compares the equipment structure with the *valid configuration* in the *configuration compliance check*, which is done by using the *CCT tool*. Multiple checks could be necessary to eventually verify the *CAB*. Ideally, all parts in the machine have the right specifications such that it satisfies the desired situation. However, this is not always the case. When this is noted, employees must decide if this effects the processes at ASML and effect the CAB eventually and, when it does, must create a *deviation notification* for that part. A part can have more than one deviation notification. Deviation notifications can be an output of the verification phase of the CAB, when it is noted that a certain part in the CAB does not match with the valid configuration, which is visualized by a not complete status in the CCT tool for a certain CCI.

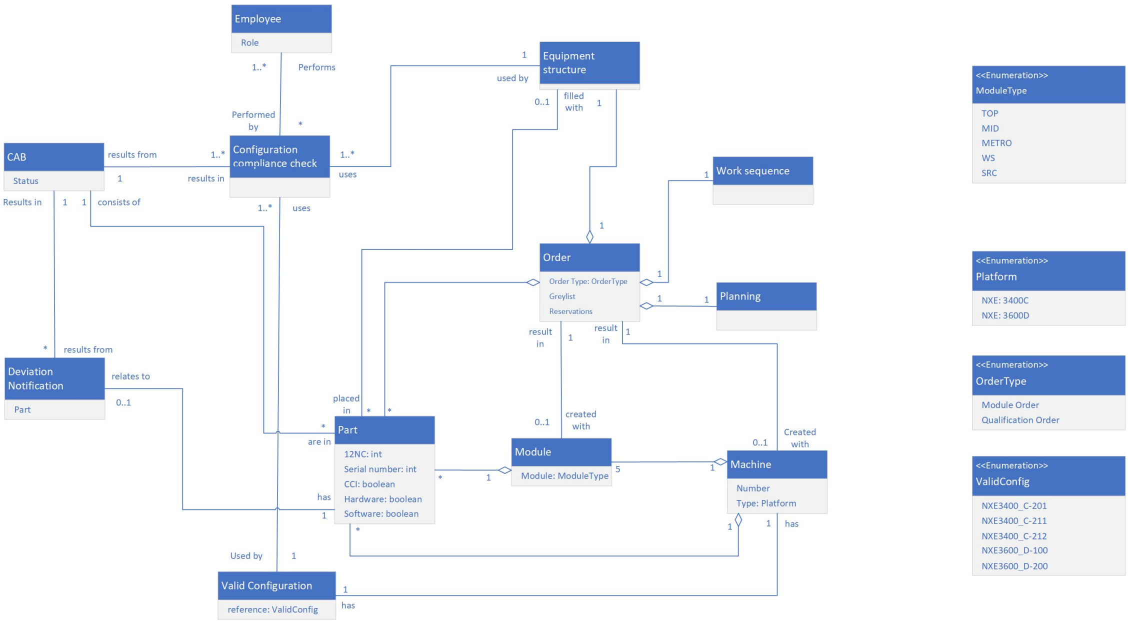


Figure 4.3: UML Class diagram of the configuration registration process

4.4 Activity-centric model

The activity-centric model is created together with creating the UML class diagram. Where the class diagram in Figure 4.3 shows the relationships between the artifacts that are in the configuration registration process, the activity-centric model shows the activities performed in the process that create, edit or delete artifacts in the process. As mentioned before, note that the CCT tool is used for performing the configuration compliance check.

Based on this information, the entity dominance model can be constructed in the next section. Figure 4.4 presents the activity-centric model of the configuration registration process at ASML. It can be seen which artifacts are used in activities performed by ASML employees in the configuration registration process. Again, note that the way of working for each order, so for each module order and the qualification order, is the same on this level of detail. Therefore, the activity-centric diagram can be linked to all orders presented in the UML Diagram in Figure 4.3. A more detailed description of the activities presented in Figure 4.4, can be seen in Appendix D.1.

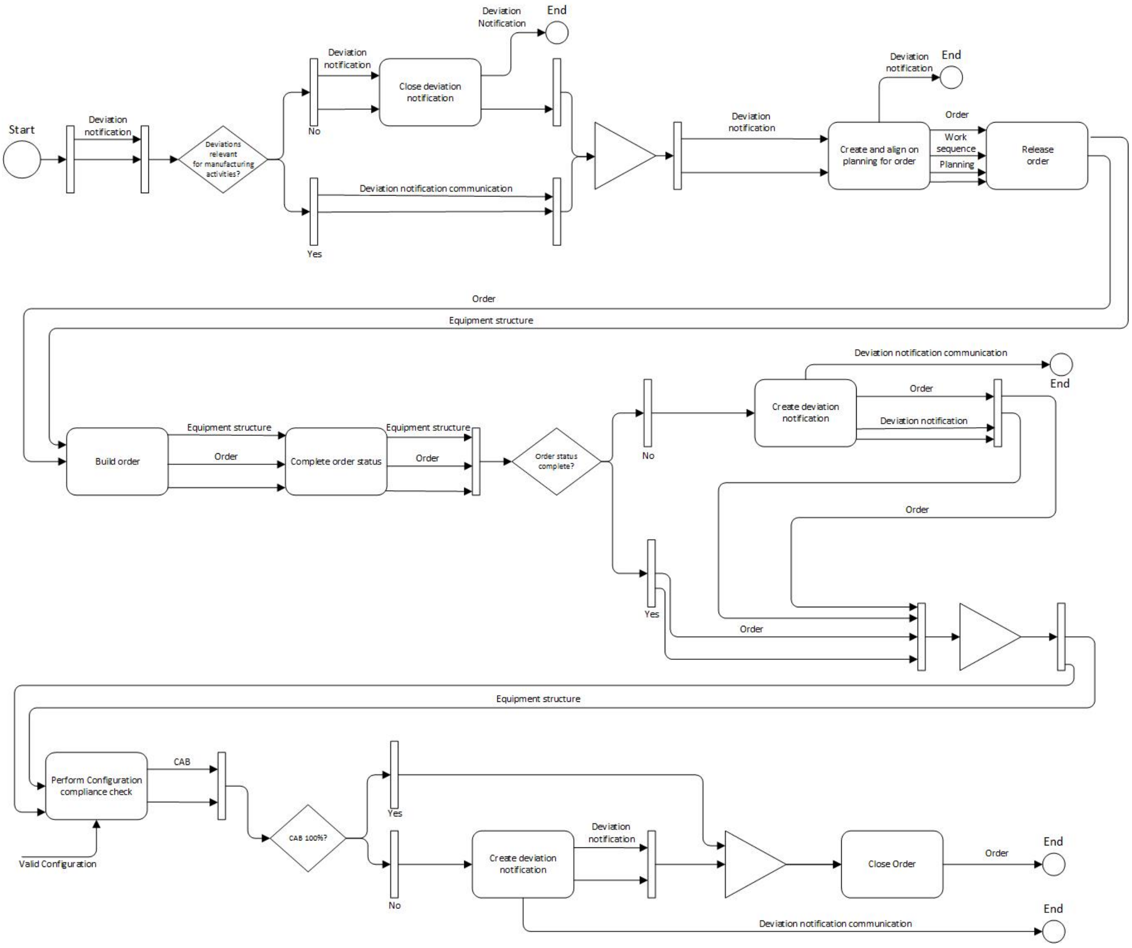


Figure 4.4: Activity-centric model of the configuration registration process

4.5 Entity dominance

In this section, we analyze the dominance between the artifacts (or entities) in the configuration registration process. This is considered as the starting point for the artifact-centric process modeling using CMMN. Dominant entities are considered as the *cases* in the CMMN model, since they represent the crucial entities in the process. In Section 2.2.2, we presented two methods of Kumaran et al. (2008) and Snoeck and Dedene (1998) to determine the dominant and dominated entities in the process. The creation of the Entity Dominance Graph started with the method of Kumaran et al. (2008). With the conditions presented in Section 2.2.2 and the activity-centric process model, we identify that a module order dominated the planning and work sequence, and that deviation notification dominates the deviation notification communication. Yet, there are still two entities that are not connected to any other entity after the first iteration (Figure D.1 in Appendix D.2). In the next iteration, we applied the existence dependency method of (Snoeck & Dedene, 1998). We identified that the two disconnected entities (equipment structure and CAB) were related to the usage of parts in the module order. Therefore, an existence dependence relationship between a part and a deviation notification is found. Based on logic reasoning, all three connections make sense. The equipment structure can simply not usefully exist without parts, and the same holds for the CAB and a deviation notification (because all artifacts are empty without a part). Only one non-existence dependent relationship exists between an order and a part, and therefore, a separate entity *part usage* is included in the entity relationship diagram. After the second iteration, the entity dominance graph is considered as complete and presented in Figure 4.5, where the grey colored entities are the dominant entities in the configuration registration process. For clarification and a visualization of the second iteration, see Figure D.1 in Appendix D.2. In the configuration registration process, an order and a part are the dominant entities and are therefore considered as the cases in the CMMN model explained in the next Section.

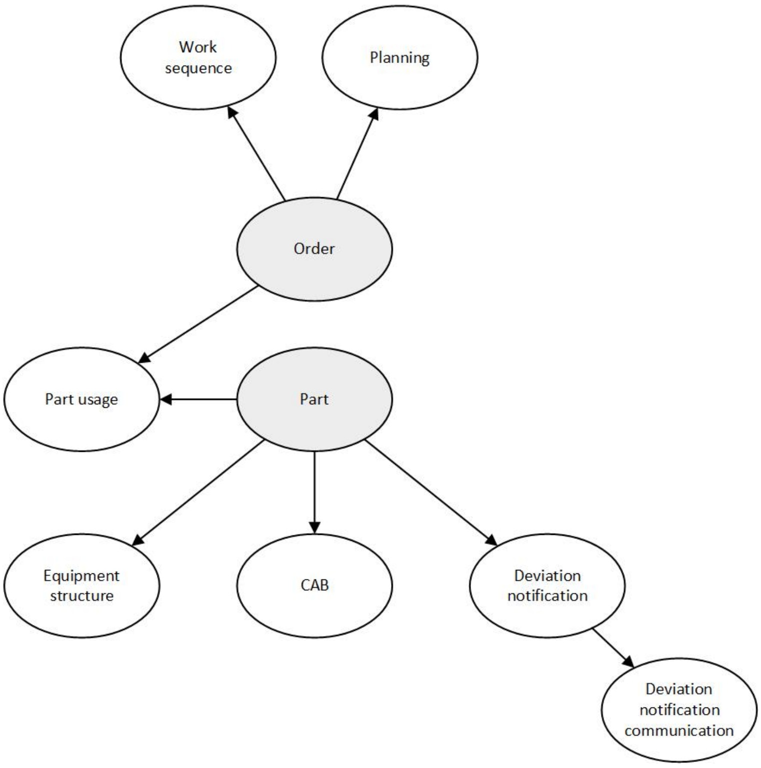


Figure 4.5: Entity dominance of the information entities in the configuration registration process

4.6 CMMN model

The last models and final models that we present in this chapter are the CMMN models. With the entity dominance graph discussed in the previous section, we now know our dominant artifacts that are the cases which will be modeled in the CMMN notation. The goal is to visualize the status changes of the two dominant artifacts in the process of configuration registration. For both artifacts, Order and Part, the CMMN model will be presented and explained in Section 4.6.1 and 4.7 respectively.

4.6.1 Order

The first artifact that is modeled in CMMN is the order artifact (either a module order or the qualification order). Figure 4.6 shows the status changes and links with artifacts within the order case. The status of an order can change in two stages, which are modeled in the CMMN model as expanded stages:

1. During the completion of an order, modeled in the stage *complete order*
2. By means of a deviation notification, modeled in the stage *deviation notification.*

An order artifact is triggered by two events:

1. The parts that are needed to complete the order, must have entered the factory.
2. The deviation notifications on parts necessary for completing that order, which identified in earlier stages at ASML, must be communicated to the ASML employee responsible for the order.

Before the planning and work sequence of the order can be determined and released, the deviation notifications that are input for the order artifact need to be analyzed. A decision on whether or not take actions on the deviation notification must be made. When this decision is made, the employees align on the planning and then create the order that will be completed. This is modeled by the exit criterion on the *analyze deviation notification* task. After creating the order, the order is released and completed. During the completion of the order, deviations on parts could be identified, which is why the *create deviation notification* task is modeled inside the order case. Note that one of CMMN's key feature is that workers on the case can perform any task to modify, create, delete or edit artifact at anytime during the process (M. Marin, 2016), which is why no association between these tasks is modeled. When the order is completed, and thus the milestone is reached, then the status of the artifact will not change anymore and thus the process ends.

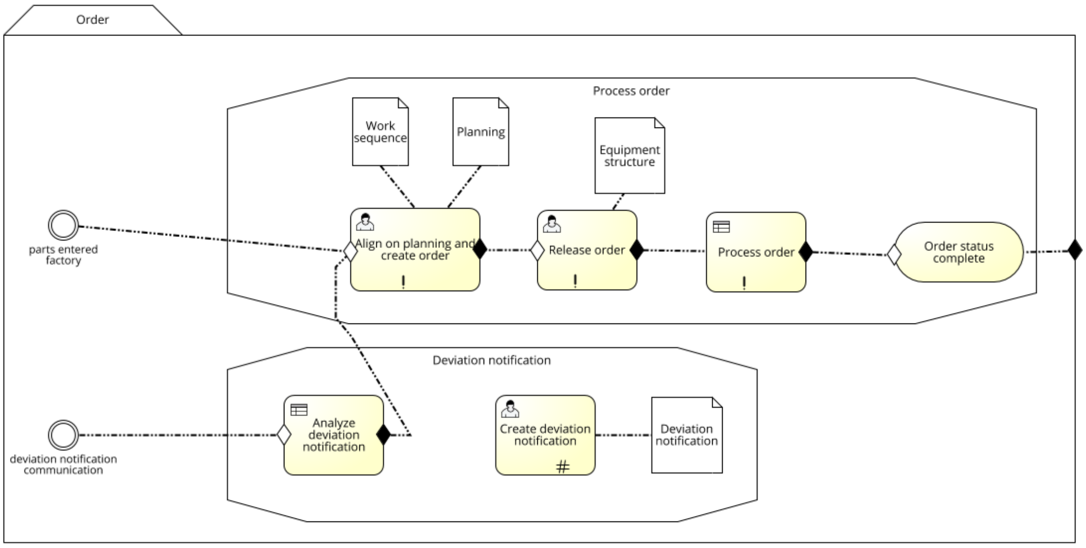


Figure 4.6: CMMN Model: Order

4.7 Part

Figure 4.7 visualizes the second dominant artifact that is modeled in the CMMN notation, a part. In the EF, a part is a physical object that need to be build in the module or machine, however, the CMMN model refers to the *digital twin* of the physical object. A digital twin in the Product Lifecycle Management field is described as a *digital information construct about a physical system, created as an information entity on its own, and linked with the physical system* (Kritzinger, Karner, Traar, Henjes & Sihn, 2018). A part flows through the entire process of configuration registration, since parts form the basis for performing the configuration compliance check, leading to the CAB artifact.

The status of a part can change in three stages, modeled in the same way as in the previous section. Deviation notifications are associated with a part and can be created, closed and analyzed in the process of configuration registration.

Next, when an order is processed, a part's status changes when the part is placed in the equipment structure, which means that an employee scanned the part and has (administratively and physically) built the part in the machine or module. Other status changes for a part that are not modeled in the CMMN model, are when a part is placed on the *greylist*, which indicates that the part is not yet built in the machine or module, or a part is *reserved*, which means that a part cannot be built in the machine at this moment in time. A reservation is then created to build the part in the machine or module at a later moment. These status changes are not modeled in the CMMN model, since they both indicate that the part is not yet in the equipment structure. Since the equipment structure artifact is input for the configuration compliancy check, we are only interested in status changes related to that artifact. This means that it does not add value to model the reservations and greylist attributes.

After an order is completed and closed, the equipment structure artifact is used for the configuration compliancy check. The valid configuration is compared with the equipment structure and after the check, the CAB is created and eventually verified, whereafter the process ends. Note that this check is performed using the CCT tool. During both the *complete order* and *configuration compliance check* stages, deviations on parts could be identified and thus the worker can switch to the deviation notification stage to create one.

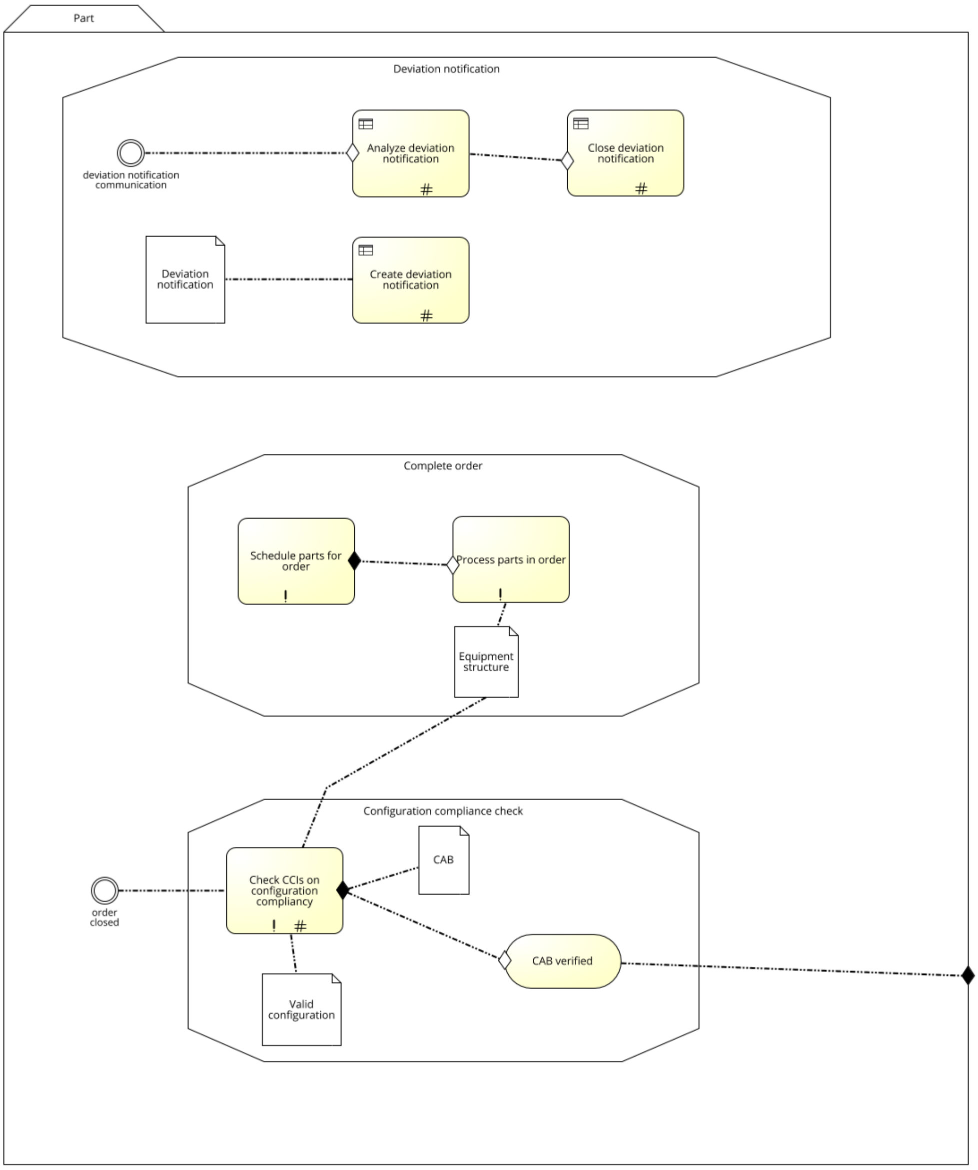


Figure 4.7: CMMN Model: Part

4.8 Conclusion

In this chapter, we identified the current configuration registration process and the information flowing through the process. The activities leading towards the CAB, where the configuration status is traced and managed, are identified. Next, we presented the activities that create, edit or delete artifacts in the business process. This is done by applying artifact-centric modeling techniques. All artifacts and the relations with each other are presented in the UML Diagram. In the activity-centric model, we identified the activities that change the state of an artifact. Based on these two models, we determined the dominant artifacts, (Order and Part) in the process and we used these artifacts to create the CMMN models. The models act as a starting point for the data analyses in order to find the bottlenecks in the process.

Chapter 5

Data understanding and preparation

This chapter is about the data that is used for the data analysis of the current situation of the configuration registration process. The chapter concerns the third and fourth research question where we aim to identify the bottlenecks in the configuration registration process. Before we can do the data analysis, we must be familiar with the data used and prepare the data accordingly. To do this, we followed the CRISP-DM framework of Shearer (2000). The business understanding phase however is already completed in Chapter 4. In this chapter, the data understanding and data preparation phases of the framework are discussed. These phases result in the dataset that is used in Chapter 6. Next, we get a first indication of the possible bottlenecks in the configuration registration process after this chapter.

5.1 Data understanding

In the data understanding phase, we will explain the data that is used for the data analysis. As explained in Section 1.1.2, the CAB is defined and can thus be retrieved out of the CCT tool. Next, additional sources are used in order to retrieve valuable insights in the bottlenecks of the configuration registration process. These will be explained in this section.

5.1.1 Data collection

The data that is used for analyzing the performance of the configuration registration process in the EF is primarily based on the export of all configuration compliance changes of the CCT tool. All information that ASML's employees need to know about the configuration status of a machine, can be derived from the tool. The tool creates and visualizes the CAB per machine and the status of the CCIs for that machine. To identify the bottlenecks, the data export of the CCT tool is therefore subject for the data analysis. The export is not directly extracted from the tool, but all compliance changes are extracted from the tool with a SQL query created by the owner of the tool. The data export contains a total of 9,608,004 records and 9 columns, which are introduced in subsection 5.1.2. This data source is for the remainder of this research referred to as *dataset 1*.

The second export of the CCT tool provides an overview of the module to which a CCI belongs, and if the CCI is a software or a hardware item. In the first export of the compliance changes, this could not be identified. We asked the owner of the CCT tool for this information and he could only deliver textual information with both variables. The data could easily be transformed into column values, which resulted in a total of 4 columns and 219,030 rows. In the next phase described in Section 5.2 the second export is merged with the export of all compliance changes. This export is for the remainder of this research referred to as *dataset 2*.

The third data source used is an excel file containing all shipment dates of the machines. Embedding the shipment dates in the data analysis is important for scoping reasons. The export from the CCT tool does not distinguish the configuration status in the EF from the configuration status during and after the install of the machine at customer site. At the shipment date, the machine is transferred to the customer's site where the installation of the machine starts, and therefore is the ending point in the scope of this research. Next, the excel file contains information about machine's cycle times in the factory and important remarks for the shipped machines are included. In later phases, this information is used to detect and explain outliers and reasons to not include the machines in the analysis. The data file contains a total of 129 rows and 24 columns and is for the remainder of this thesis referred to as *dataset 3*.

5.1.2 Data description and exploration

In this section, we select the data that is needed for further analysis. Since the goal of the data analysis is to identify the bottlenecks in the configuration registration process, the analysis focuses on analyzing incomplete and non-compliant configuration status of CCIs. For each machine, the configuration status of all CCIs can be traced from the moment that the first module order for a corresponding machine is released. From that moment, employees can check the configuration status of a machine and see which CCIs are compliant with valid configuration and which CCIs deviate from the valid configuration, thus having a non-complete status. The status of an CCI is visualized in the tool by using colors. Figure E.1 in Appendix E visualizes the distribution of these status colors retrieved from dataset 1. In this dataset, there are six different colors representing the status of an CCI. With the explanation below, we visualize in Figure 5.1 the configuration registration statuses that are subject for analysis in Figure and explain which color represents a certain status, or is classified as an *other configuration registration status*.

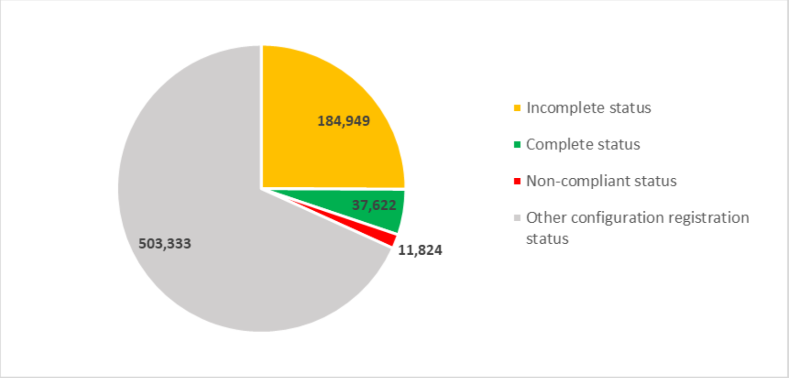


Figure 5.1: Overview of CCI status in CCT export before cleaning

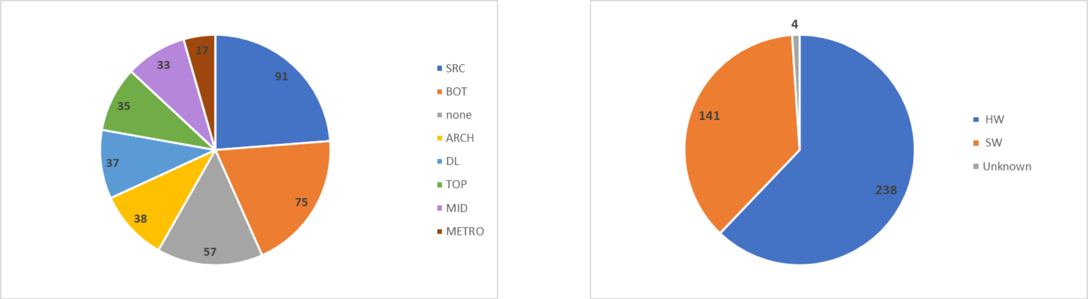
1. Grey, this tells the user that the CCI exist in the equipment structure, but that the valid configuration is not updated yet. CCIs with a grey status do not affect the CAB score. Therefore, in the data analysis, CCIs with a grey status are not considered to be a configuration registration error, and is classified in Figure 5.1 as one *other configuration registration status*.
2. Orange, which indicates that there is no data available in the equipment structure, but the valid configuration suggest that one part of the CCI should exist in the equipment structure.

In this research, an orange status is referred to as an incomplete registration. According to Figure 5.1, incomplete configuration registration errors occur the most.

3. White, which means that the CCI is not in the valid configuration and not in the equipment structure. This only happens when the CCI did not exist in the past and does therefore not add value to the data analysis for identifying configuration registration bottlenecks. Therefore, a white color is classified in Figure 5.1 as one *other configuration registration status*.
4. Green, which indicates that the actual equipment structure in SAP equals the valid configuration, resulting in a *complete* status for the CCI.
5. Red, which indicates on a mismatch between the equipment structure and the valid configuration. CCIs with a red status at a given point in time, is (earlier) in this research referred to as a *non-compliant* configuration registration error.
6. Yellow, which indicates that the actual equipment structure equals the valid configuration, yet with a quantity mismatch. In our analysis, only a few configuration statuses are yellow and therefore, in Figure 5.1 this status is classified as one *other configuration registration status*.

As mentioned before, these status colors present the status of a CCI. Earlier in this research we mentioned that a CCI is a part of the machine. A part is identified by its 12NC number (as can be seen in Figure 4.3), whereas a CCI is named and thus identified by its name. The status of a CCI is determined by underlying rules defined in the valid configuration, which are manually entered by the system integrators. There are many parts with the same characteristics, yet a different 12NC number since they come from, for example, a different supplier. The rule then determines the status of the CCI. For data analysis, it is not possible to analyze which part is actually built in the machine, since the export file of the tool only identifies the status of the CCI, and not the single underlying part. Therefore, the data analysis will be done on CCI level, not on part level.

The second data source used presents the module in which the CCI is embedded in, and if the CCI is a software or hardware item. In Section 5.1.1, we mentioned that the file contains a total of 219,030 records. This is a lot considering that there are approximately 250 CCIs on the CAB. By analyzing the data, we found that there are a lot of duplicates in the data file. The reason for this is that this information was collected for all status logs of the CCIs, where we, in this case, only needed the CCIs name and the corresponding features. After dropping these duplicate entries, the file contains only 383 records, which seems more logical. Over time, CCIs can be renamed, can be added and deleted due to new part or machine introductions, and therefore, it makes sense that there are more than 250 CCIs in the list. To generate the first insights in the distribution of the CCIs among the modules and if a CCI is a software or hardware parts, Figure 5.2a and 5.2b are respectively created.



(a) Distribution of CCIs per module

(b) Distribution of CCIs per hardware and software

Figure 5.2: Data exploration: module and hardware/software before cleaning

From Figure 5.2a it can be concluded that most CCIs are in the SRC and BOT module.[1] This might indicate that most configuration registration errors occur in one of these two modules. However, configuration registration errors have several root causes and it is therefore important to elaborately analyze the results of the data analysis, and not draw conclusions too fast simply because these modules contain most CCIs. Next, we see that their are 57 CCIs in the data file with no module assigned, in the figure referred to as 'none'. There could be two reasons for not having a CCI assigned to a module:

1. The system integrator manually assigns a CCI to a module. It could be the case that the system integrator simply forgot to fill in the corresponding field, resulting in an empty value in the data export.
2. Some CCIs can not be linked to a module. In Chapter 1.1.2, Figure 1.1 visualizes the manufacturing process. In the first phase, module build, all module orders are completed and therefore the modules are finished, before they are integrated with each other in the system integration phase, resulting in the complete machine. Then, the qualification order is released and the system is qualified. In the system qualification phase, there are still parts that are added to the machine, and this could also be CCIs.

Next, one might notice that the modules presented in this section are not the same modules for the module orders as presented in the UML diagram in Figure 4.3. The reason for this is the difference in perspective of the modules from the D&E department, who design the modules, and the EF, where the modules are assembled in the work centers. For example, looking at an EF perspective, the DL and SRC belong to the same module order, whereas D&E distinguish these as two different modules. After consideration, we chose to not integrate the perspectives into one because it does not add value for the remaining part of this research. The identified bottlenecks per module after analyzing the data can easily be linked to the module orders in the different work centers by the relevant stakeholders at ASML. Therefore, we continue the analysis part with the module classification by D&E, on which the CCIs are classified on in the valid configuration.

In Figure 5.2b, it can be seen that most CCIs are hardware parts. However, there are still 141 CCIs classified as a software part. Since the identification of bottlenecks in the configuration registration process mainly focuses on hardware parts, the data must be cleaned for the analyses. Similar to the 'none' classification of the module, there are four CCIs that are not classified as software or hardware part. We remove these entries in the next phase of the data analysis.

Next, the distribution of software and hardware CCIs per module is analyzed. By doing this, we aim to get insight in the possibility of finding registration errors for each module, similar to analyzing the quantity of CCIs per module. Figure 5.3 visualizes this distribution.

Since only hardware parts are embedded in the data analysis and thus subject for redesign, modules with mostly software items are probably not identified as a bottleneck later in the process. In Figure 5.3, it can be seen that the CCIs that are not assigned to a module, are mostly software items. Based on that, the explanation given above, that these parts are mostly added in the system qualification phase, makes more sense. Software CCIs are mostly used for qualifying the machine, and therefore do not belong to a specific module. Next, we see the ARCH and METRO module are both modules that contains more software than hardware CCIs, and see that the BOT and SRC module contain the most hardware CCIs. This, again, might be an indication that the bottleneck analysis in the configuration registration process will be focused on these two modules. Further, the four items not classified as either software or hardware belong to the top module. No further analysis is needed, since we remove these parts later on in the process.

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[1] Please note that the modules are presented with their abbreviation, and not their full name. For this research we will use these abbreviations, and not the module's full name.

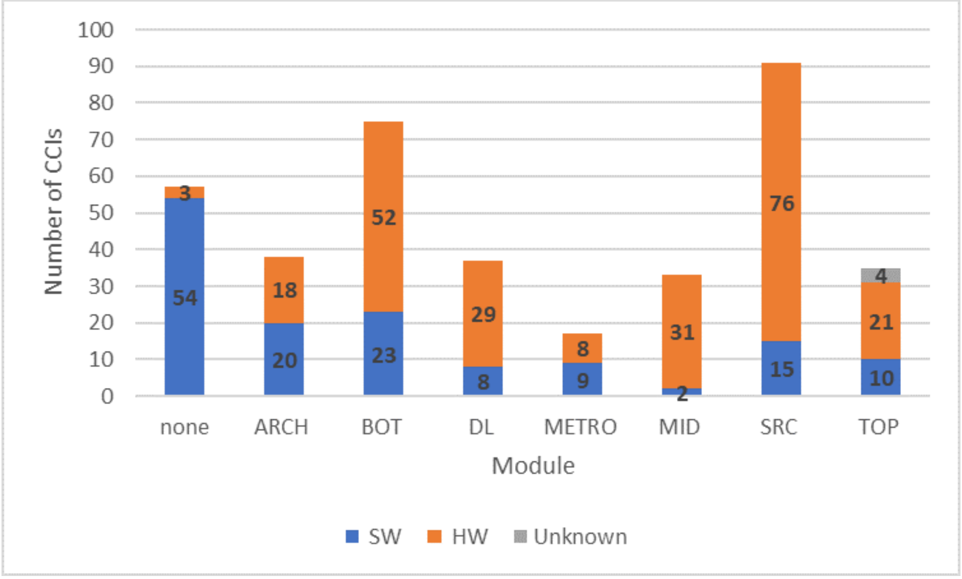


Figure 5.3: Distribution of hardware and software CCIs per module before cleaning

Last, we explore the data source containing the shipment dates of the machines with the relevant information. There are 53 machines that are shipped before 01-01-2020, which are therefore out-of-scope. Next, we found 26 machines that were not shipped yet on the moment of analyzing the data. These machines are also out-of-scope for the data analyses. In the next phase, these entries are removed from the dataset.

5.2 Data preparation

This section is about preparing and cleaning the data such that the data analyses result in insights for the bottlenecks of the configuration registration process. This research focuses on hardware parts that are classified as CCI. As explained in the previous section, the CCT export resulted in an overview where not only status changes for the CCIs were generated. Therefore, the first cleaning step to be executed is to remove all non-CCI entries from the dataset, since those entries do not provide insights in the status of a CCI. After removing these entries from dataset 1, we have a dataset with 122,926 entries.

Next, all software CCIs are removed from dataset 2. In addition, the CCIs that were not classified as a software or hardware CCI and are in that context unknown, are removed. Note that the duplicate values from dataset 2 were already removed in the data understanding phase. After removing the above mentioned entries, we remain a dataset with 238 entries.

Further, the third dataset (dataset 3) is cleaned and prepared for analysis. These cleaning steps are the following:

- All machines with a shipment date earlier than 01-01-2020 are removed from the dataset.
- This research analyzes two machine types: NXE: 3400C and NXE: 3600D. In dataset 3, two machines are from another type, and these entries are therefore removed from the dataset.
- All machines with no shipment date assigned are removed from the dataset.

- All machines with a shipment date after 18-06-2021 are removed from the dataset. As mentioned before, the CAB is a snapshot of the configuration status at a certain moment in time. At 18-06-2021, dataset 1 with all compliance changes was generated and therefore, this dataset is a snapshot of each machine's CAB at that moment in time. Therefore, the reason for removing the entries, is that these machines have not completed the entire configuration registration process in the EF meaning that the CAB for these machines is not verified yet.

After cleaning dataset 3, 47 records remained. This means that we have 47 machines within the scope of this research.

After these cleaning steps, all datasets are merged to *dataset 4*. Figure 5.4 visualizes the merging process together with all variables taken into account for the data modeling. The numbers that can be seen near the arrows represent the steps taken and are the following:

1. Dataset 1 is merged with dataset 3 on the Machine variable. Hereafter, dataset 1 has one added column, namely the *Shipment date* variable. We performed an inner join based on the common variable *Machine*. Compliance changes outside the scope of the research, should be removed anyway. 53,867 entries are left in the dataset after this merging step.
2. Dataset 1 is merged with dataset 2 based on the Name variable (where 'Name' indicates the CCI name). Note that it is not possible to let the datasets join on the *Item* variable, since this variable only contains the value *CCI*, since all other items are removed. Now, dataset 1 has two added columns: *Module* and *SW_HW*. After this step, 30,379 data entries are in the dataset.
3. Next, we remove the columns we do not need anymore: *Machine Type*, *Item* and *SW_HW*. With this step, the dataset containing all necessary variables is constructed.

Next, entries with an *end_datetime* after the shipment date, are transformed for scoping reasons. The *end_datetime* of these entries is replaced with the Shipment date of the machine. This is done because we can now easier create the model and get the insights we want.

After merging the data, we performed the last data cleaning and preparation steps. First, compliance changes of CCIs of a certain machine that happen after the shipment date of the machine, are removed from the dataset. These compliance changes occur during the install process or even during maintenance actions at customer's site. This means that, for each machine, each entry (compliance change) is compared with the shipment date of the machine. If the shipment date is earlier than the start_datetime of the compliance change, the entry is removed. After removing the entries, the dataset 4 contains 25,012 entries.

Last, the final three data preparation steps are performed:

4. First, all *first registrations* are removed from the dataset. It is mentioned before that the configuration registration process starts when the module orders for a machine are released. We also explained that CCIs have an incomplete (Orange) status, if there is no data detected by the tool in the equipment structure in SAP, if the valid configuration expects a certain value for it. This means that after the release of an order, all CCIs are incomplete, thus Orange. This makes sense, since all parts are physical parts that need to integrated with each other and scanned by the employees, to register the part in the (digital) equipment structure. Since we aim to identify incomplete registrations, these first registrations do not represent the bottlenecks during the process, and we distinguish these Orange statuses from the others dataset. In total, there are 7,475 *first registrations* in the dataset, which will not be subject for analysis.
5. Second, the configuration registration that occur in the process and are resolved before the shipment date, are extracted from the dataset. The reason for doing this, is because we

want to get insights in the CCIs that are still not resolved on the shipment date, since that is the moment that the CAB is verified. These compliance changes can be identified by comparing the timestamp *(end_datetime)* with the *Shipment date* variable. If the timestamp does not match with the Shipment date, then the item is resolved earlier in the process. These compliance changes are also extracted from dataset 4 and contain 7,174 entries.

6. Last, the entries with a *end_datetime* equal to the shipment date are extracted from the dataset. This extraction results in 10,363 entries of configuration compliance statuses at the shipment date.

This gives us two datasets extracted from the final set that we are going to use: one dataset with 7,174 entries representing the configuration registration errors in the process, and one dataset with 10,363 configuration registration errors at the shipment date. The process of merging the data is visualized in Figure 5.4

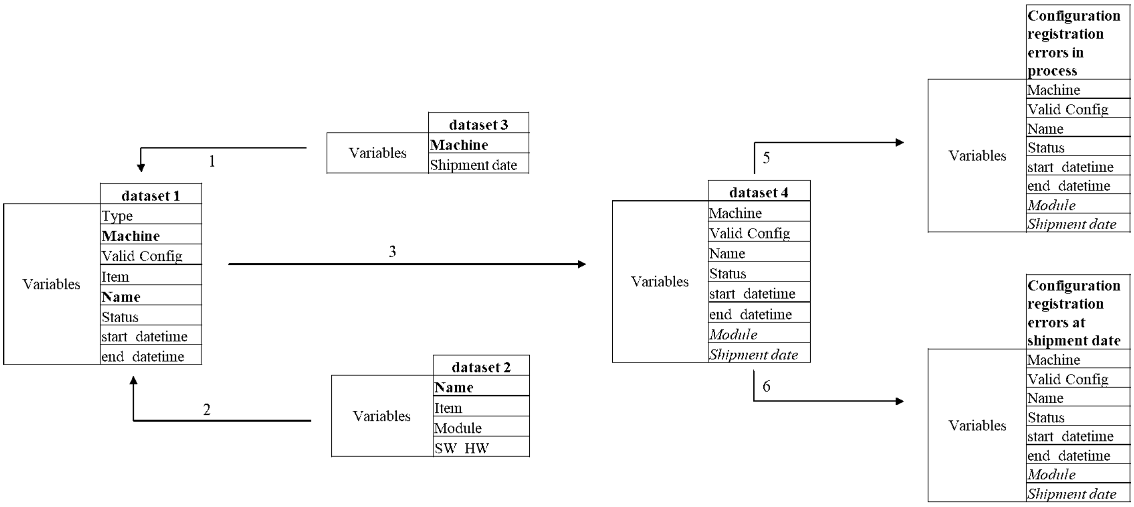


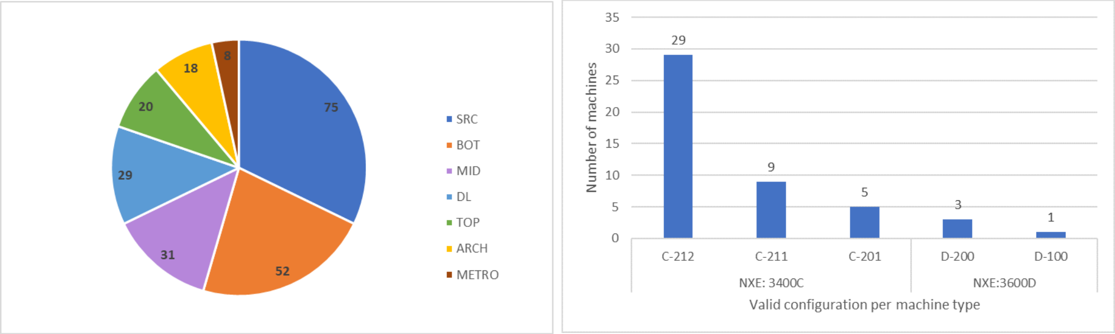
Figure 5.4: Merging the datasets

We explain all the variables in more detail in Table G.1 in Appendix G and visualize a few entries of the dataset in Appendix G in Figure G.1. There, we also visualize and explain how the entries in the dataset are split into the three above mentioned categories.

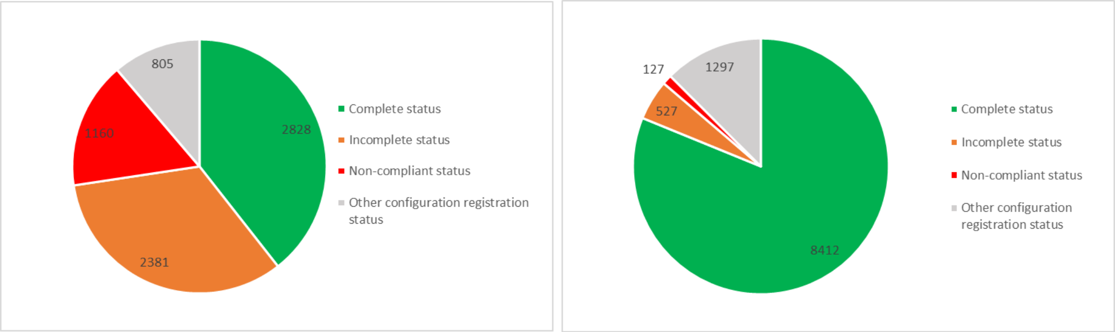
The distribution of the valid configuration assigned to the machine, the statuses of the CCIs in the dataset and the distribution of CCIs per module in the dataset are provided in Figure 5.5. We see in Figure 5.5a is similar to the number of hardware parts per module, which is logical since the software parts are removed. At the SRC and TOP module, one hardware CCI is also removed. Since we removed duplicate values, this is probably the reason.

Next, we see more incomplete registrations compared with the non-compliant registrations in the process as well as at the shipment date in Figure 5.5c and 5.5d respectively. We could hypothesize the bottlenecks might be of having incomplete registrations instead of non-compliant registrations, but we analyze this in the next chapter.

Last, when looking at the valid configurations per machine platform, we see that we only have four NXE: 3600D machines in our time scope. This machine platform is the latest platform released at ASML, and only a few machines are shipped to the customers. Most valid configurations have the C-212 reference as can be seen in Figure 5.5b



(a) CCIs per module after data cleaning (b) Valid configurations after data cleaning



(c) CCI statuses in process after cleaning (d) CCI statuses at shipment date after cleaning

Figure 5.5: Data description after cleaning

5.3 Conclusion

This section was about understanding and preparing the data. We introduced three data sources from which the variables were explained. After cleaning the data and filtering all entries and variables out that are not in the scope for this research, we constructed the dataset that we use for the modeling phase in Chapter 6. In terms of configuration registration statuses, we explored that there are more incomplete registrations comparing it with the non-compliant statuses. Next, we saw that the SRC module contains the most CCIs when comparing it to the other modules. These insights might give us the first indications on the bottlenecks of the configuration registration process. However, this is solely based on the quantity of CCIs and without analyzing the data in detail.

Chapter 6

Modeling

In Chapter 5, we discussed the data used for the data analysis that is performed in this chapter. This chapter discusses the modeling and evaluation phases of the CRISP-DM framework. First, the model is created and results were generated. Second, the results were interpreted and we use the knowledge of domain experts to get a better understanding of the results and thus find the causes for the bottlenecks of the configuration registration process. So, next to quantitatively identify the bottlenecks in the current process, we use qualitative data from the interviews with the domain experts to draw our conclusions. After this chapter, the bottlenecks of the process are identified and therefore be subject for the redesign phase.

The data analysis focuses on the dominant artifacts discovered in Chapter 4: *order* and *part*. As explained in Section 4.3, there are two types of orders:

1. Module orders, which are orders for the modules of the machine
2. Qualification orders, which are orders for the manufacturing and qualification process of the entire machine.

From this, we analyze the performance of the configuration registration for each module, and for the entire machine to get a first indication of the bottlenecks in the process. For the dominant artifact *Part*, we analyze the configuration registration errors per CCI, since it is not possible to analyze on part level. We start with an analysis for all machines, and dive deeper in the BOM by analyzing the errors for each module and per CCI. As mentioned, these results are input for the qualitative analysis which is done by performing interviews. The outline for this chapter is presented in Figure 6.1. The outline is focused on the analysis of the configuration registration errors at the shipment date. Section 6.3 explains the configuration registration errors in the process.

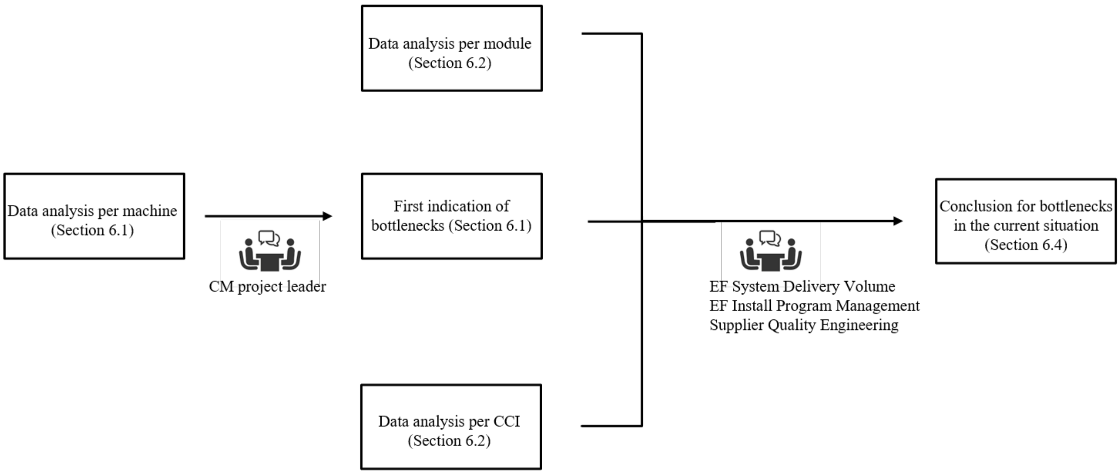


Figure 6.1: Outline for this chapter

6.1 Configuration registration per machine

First, we discuss the configuration registration errors that are presented per machine. In order to see the performance over time, Figure 6.2 represents the number of configuration registration errors sorted on the shipment date of the machine.

It can be noticed that the machines that are shipped earlier, have more incomplete and non-compliant registrations, resulting in lower CAB scores. From this, we can conclude that the configuration registration process over time has improved. However, from Figure 6.2 it can be seen that six machines do not follow the decreasing error pattern. After analyzing additional data and talking to relevant stakeholders, we identified why there are six machines deviating from the overall trend. We held interviews with a project leader for CM projects and the two employees who are responsible for the transfer of the machines from EF to EF Install. An explanation for these deviations for each system is provided below:

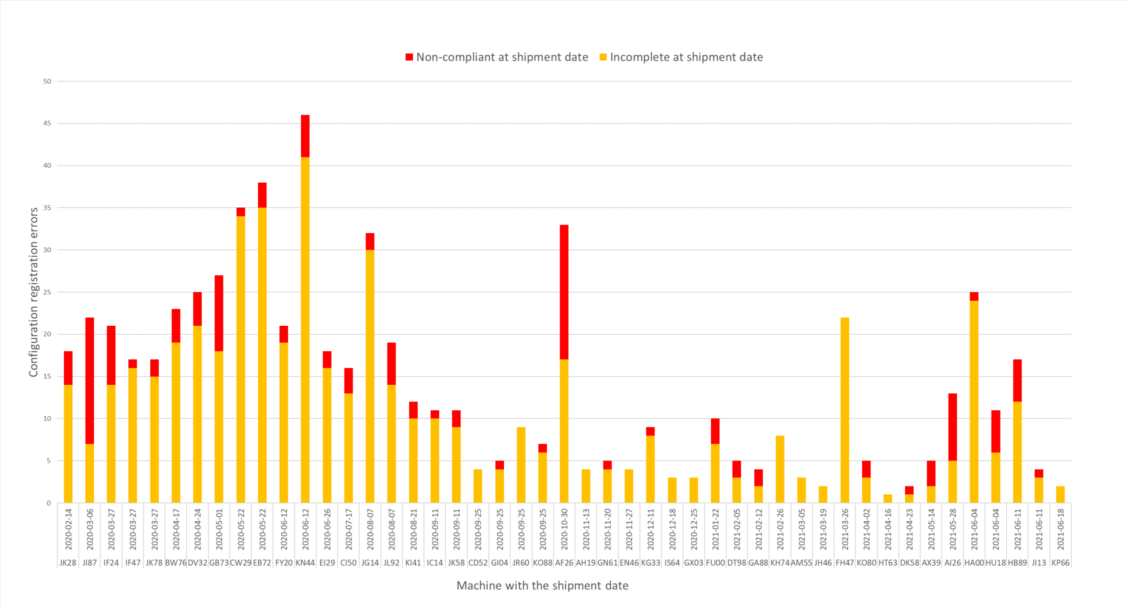


Figure 6.2: Configuration registration errors per machine at the shipment date

- **AF26**. This machine is the first NXE: 3600D shipped to the customer. In Section 5, it was explained that there are two machines in our scope for the data analysis. The NXE: 3600D is the latest machine in the NXE generation, and therefore the successor of the NXE: 3400C system. In agreement with ASML's customer, the machine was shipped earlier and thus did not follow the complete process in the EF. Therefore, some parts are assembled in the machine in the EF according to the valid configuration which resulted in a lot of configuration registration errors.

- **FH47** and **HA00**. These machines are of type NXE: 3400C and contain a lot of configuration registration errors comparing it with similar types shipped during that period. For these machines, most parts of the DL module could not be delivered at the EF on time with the desired quality, and therefore the decision was made to dropship the DL directly towards the customer. The decision was made collaboratively by the supplier and ASML. At customer's site, manufacturing the DL was completed during the install sequence. Since the parts in the DL could not be scanned in the EF and are thus not registered in the equipment structure, the CAB contains a lot of incomplete registrations, as can be seen in the Figure.

- **AI26**, **HU18** and **HB89** are the other three NXE: 3600D systems in our scope. New types of machines require other (or upgraded) parts, which results in configuration registration errors. However, these errors are not caused by the way of working in the EF. According to the domain experts, new parts required for the new machine types, can not be delivered on time. Since ASML's machines and the parts are highly complex, the lead times of these parts are high. When planning the work sequences of the order, these lead times are taken into account, and two decisions can be made in the manufacturing process:

    1. For qualifying the systems, it is sometimes decided to build in an older version of a part. This part is then *swapped* during the install sequence such that the configuration of the machine reaches its baseline on the moment that the machine is up and running at customer's site. However, since the valid configuration of the machine expects another part to be built in the equipment structure, this leads to *non-compliant registrations.*
    2. The second decision that can be made is to dropship parts directly to the customers site, similarly to what is done by the DL that could not be delivered in time. Although

this is an accepted error by the EF, the CAB can still not be completed, since the tool expects a value in the equipment structure to compare with the valid configuration. Since nothing is built in, this results in *incomplete registrations*.

Next, we qualitatively analyze the reasons why there were more configuration registration errors in the past than at the moment, except for the outliers discussed above. There were numerous actions taken in the EF by reducing the number of configuration registration errors. First, the concept of CM at ASML became more mature over time and, according to relevant stakeholders, there was more attention from the management of ASML for shipping the machines in the right configuration. Targets were set and over time, higher CAB scores were set as a target for the EF.

Second, ASML's suppliers did not deliver the required serial number that is needed for the employees to scan the part in order to register the part in the equipment structure. Each part has their own serial number profile, which indicate that the part is a CCI and needs to be registered accordingly. However, suppliers were not aware of this, or simply did not adapt their own processes to attach a serial number on the part. According to the domain experts, this is the reason why there are a lot of incomplete registrations in Figure 6.2 for the NXE: 3400C systems.

Third, a decreasing pattern in configuration registration errors can be explained by the maturity of the system itself. As explained, when a new machine type is introduced, the number of configuration errors increases. Similarly, this can be stated when a machine is shipped according to a new valid configuration. Figure 6.3 shows the number of configuration errors for the machines with the C-212 valid configuration. The reason for showing these machines is that most machines in the dataset have the C-212 as the valid configuration. A decreasing pattern in terms of configuration registration errors can easily be identified. Note that the two outliers, machines FH47 and HA00, had the DL dropshipped as explained above.

Before our time scope, there were only nine NXE: 3400C types shipped to the customers. Therefore, similar to the errors that can be seen for the NXE: 3600D systems in Figure 6.2, parts could not be delivered on time. According to the stakeholders, the CAB scores for the NXE: 3600D machines that are or will be shipped after the time scope of this research, increases over time, meaning that the number of configuration errors will decrease, as shown in Figure 6.3.

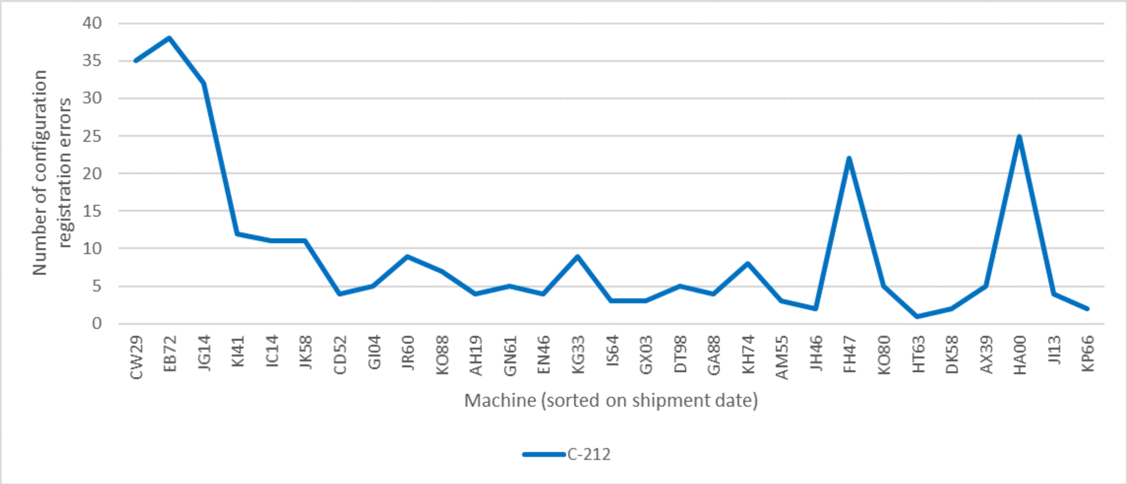


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Figure 6.3: Configuration errors over time for C-212 valid configuration

6.2 Configuration registration per module and CCI

The configuration registration errors per module are given in Figure 6.4. The figure shows the number of incomplete and number of non-compliant registrations on the shipment date over the entire time period. We see that there are four modules with a very few configuration registration errors: MID, METRO, ARCH and TOP. These four modules are therefore not further analyzed, since bottlenecks for not having the right configuration registration will probably not found within one of these modules.

Additionally, we performed additional data analyses to identify the CCIs that are attached to the modules, which statuses are incomplete or not compliant.

It could be the case that one CCI contains significantly more configuration registration errors, that the bottleneck for the each module is not something structural, but a single CCI. The results for the configuration errors per CCI for the SRC, DL and BOT module can be found in Figure 6.5, 6.6 and 6.7 respectively. These figures visualize the CCIs with at least two configuration compliance errors for the time period.

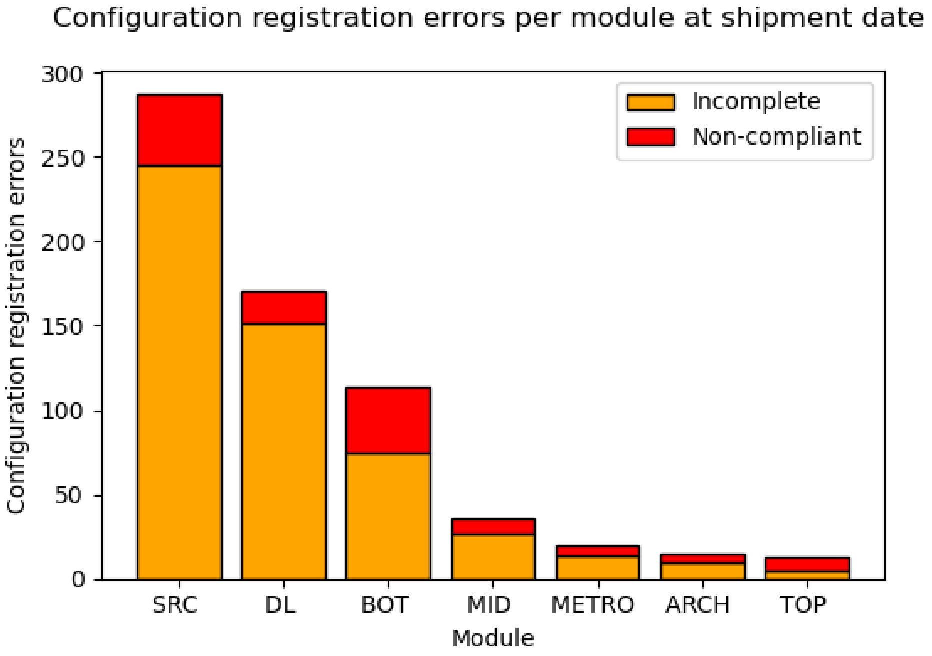

Figure 6.4: Configuration registration errors per module at the shipment date

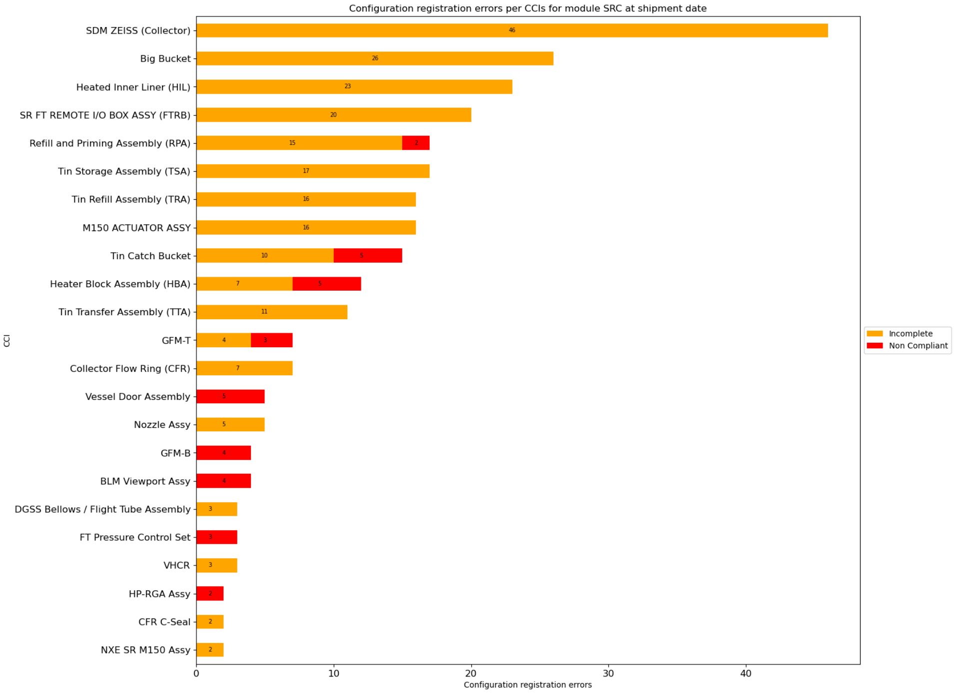

Figure 6.5: Configuration registration errors per CCI for the SRC module

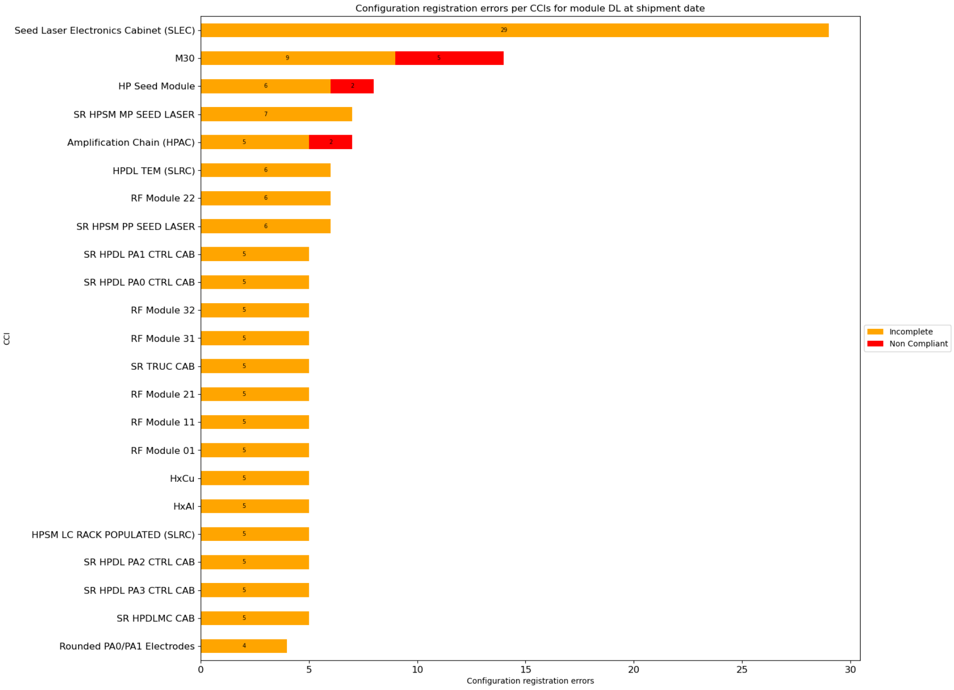

Figure 6.6: Configuration registration errors per CCI for the DL module

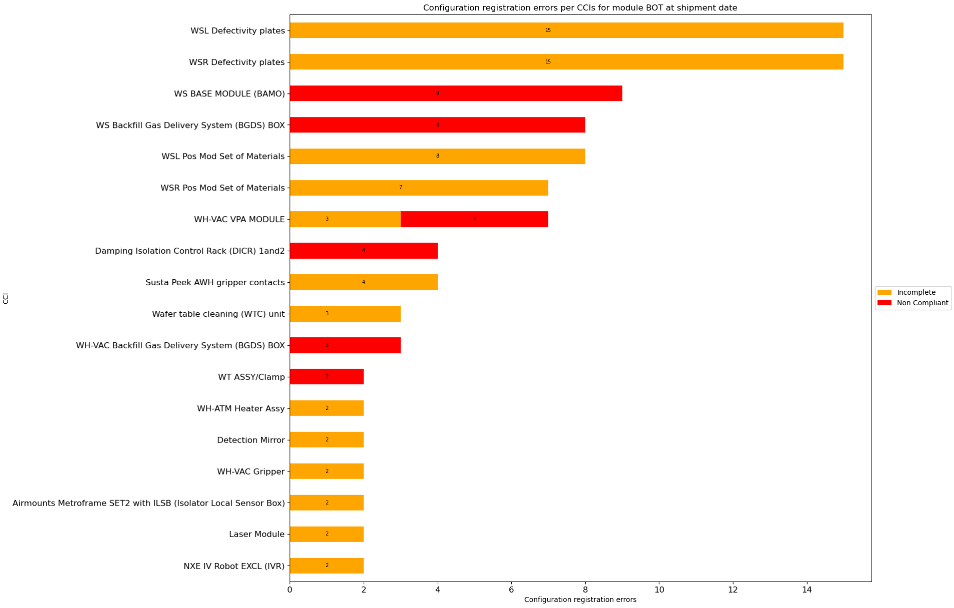

Figure 6.7: Configuration registration errors per CCI for the BOT module

These analyses on CCI (or part) level was done in order to specify the current situation and having concrete results so that they can be used during the qualitative analysis. We expect that detailed results can be easily recognized by the interviewees and thus give us a better insights in the bottlenecks. We therefore held interviews with relevant stakeholders in order to further analyze the bottlenecks in the current process by using the results per module and per CCI. The interviewees were chosen based on the bottleneck indications as explained in Section 6.1. Table 6.1 presents the departments of the employees that were interviewed in order to identify the bottlenecks.

After discussing the results with the stakeholders, the following results were found. First, the CCI named *SDM ZEISS (Collector)* is, except for one machine, always incomplete. This is ASML's working procedure with this CCI, since the CCI is always built in for qualifying the system, and disassembled afterwards, since it is better to ship a new one directly to the customer's site. According to one of the stakeholders, this CCI has nowadays another rule, such that it is not classified as a configuration error anymore on the shipment date.

Second, according to the interviewees, the high number of configuration registration issues has the same reasons as discussed in the previous section. For the NXE: 3400C machine types, there were a lot of engineering changes (ECs) for the SRC module. These ECs resulted in late deliveries by the suppliers due to the long lead times of the highly complex machine parts. In addition, the CCIs of the BOT and DL module were also recognized as CCIs that have been upgraded to newer versions over time, as a result from an accepted EC for the CCIs. Similarly, the same problem holds for introducing a new valid configuration for the machines. A new valid configuration means that there several new or upgraded parts, resulting from ECs. The stakeholders from all departments agreed that most configuration errors in the EF are a result of these ECs.

Table 6.1: Selected departments for the interviews to identify the bottlenecks

Department	**Responsibility**	**Reason for interviewing**
EF MF System Delivery	An employee from this department is responsible for controlling the configuration status during the manufacturing process.	At the end of the process, this employee secures the CAB of the machine and explains the incomplete or non-compliant configuration registration errors to the next department: EF Install. Therefore, the configuration registration errors and the causes can be explained by interviewing this employee
EF System Install Program Management	The employee is responsible for controlling the configuration during the Install process	This employee receives and acts upon the configuration registration errors by EF. Next, the upgrades needed due to ECs are controlled by this employee. Insights on this bottleneck can therefore be gathered.
Supplier Quality Engineering (SQE)	Responsible for serial number delivery from a certain supplier as well as the effective delivery dates of (new) parts to EF.	Multiple SQEs were asked for input regarding incomplete serial number registration, and the effect of ECs at suppliers site.

Third, for the SRC and DL module specifically, CCIs were also recognized by the stakeholders as items with no serial number registration from the supplier. Both modules are almost completely assembled by the supplier, which means that the supplier must take care of the serial number registration. This was already stated in Section 6.1, and therefore, interviews with ASML's Supplier Quality Engineers (SQE) were held. SQEs are responsible for e.g. the serial number registrations by suppliers. It was not considered to not do additional data analysis in order to see which CCI belong to which supplier, but to use the knowledge of the domain experts. Since a supplier delivers a part with a 12NC number and the fact that it can not be seen which part actually determines the status of the CCI, too many assumptions must be made to get an overview of the suppliers of the CCIs, which would potentially lead to a incomplete and unreliable overview. Based on domain knowledge, we know that almost all parts of the DL and SRC module come from a single supplier, and the corresponding SQEs are contacted. The SQEs confirmed that the suppliers used to not properly register the serial number registrations for the CCIs, but that this is improved over time. There are new agreements made between ASML and the supplier, and this agreement seemed to work since there were less incomplete configuration registration errors over time.

All in all, upgrades and wrong serial numbers by suppliers cause almost all the configuration registration errors on the shipment date. After analyzing the results with the stakeholders, we estimated the distribution of configuration registration errors amongst the causes. For this analysis, we excluded the DL module, since the DL is dropshipped a few times resulting in the errors on the shipment date. We analyzed the number of CCIs that were caused by each of the bottlenecks and we see in Figure 6.8 that for both modules, the CCIs with configuration registration errors where equally caused by both identified bottlenecks. Next, when looking at the number of configuration registration errors, we can conclude the same, which can be seen in Figure 6.9. We can therefore conclude that in the past, both the introduction of ECs and serial number issues cause almost all configuration registration errors for EF. However, given the fact that the serial number issues at suppliers site has improved over time (which is also confirmed by the stakeholders from EF), we still consider that the introduction of ECs on CCIs is the bottleneck that EF needs to improve to optimize the configuration registration process.

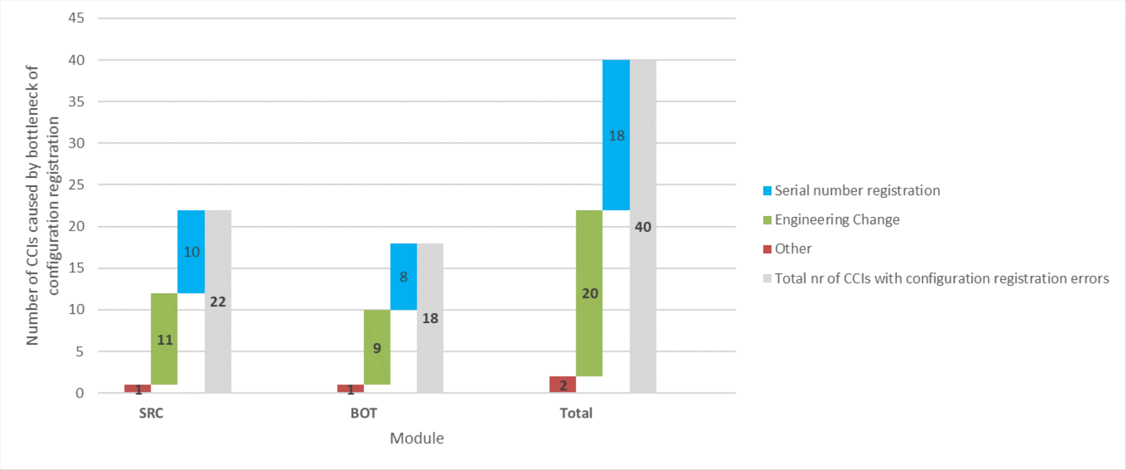

Figure 6.8: Number of CCIs that have configuration registration errors caused by the bottlenecks

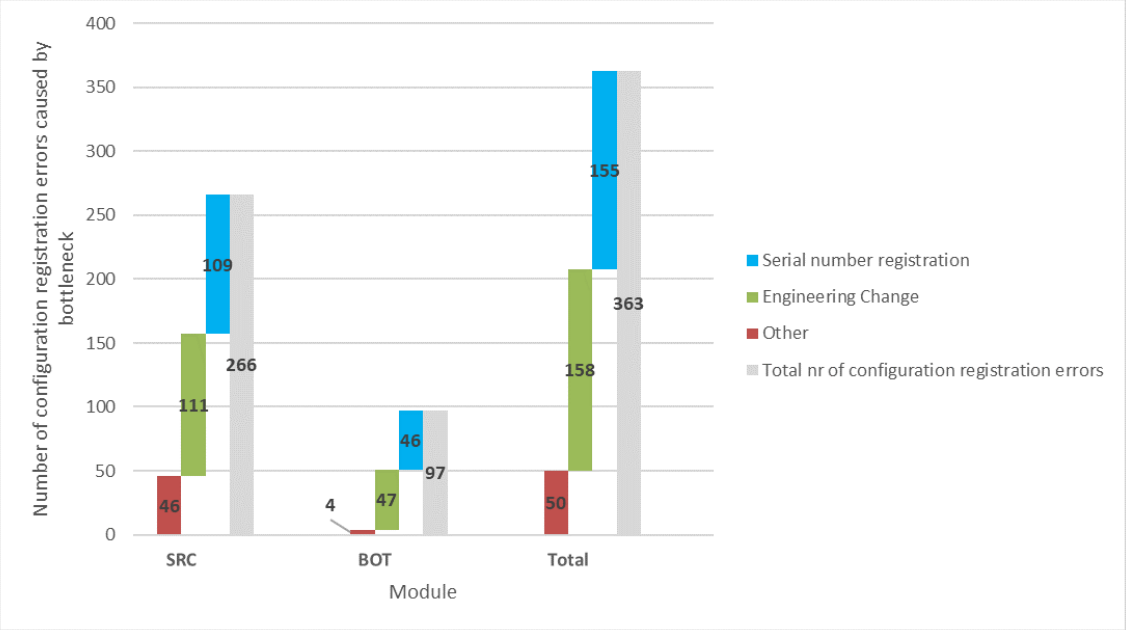

Figure 6.9: Number of configuration registration errors caused by the bottlenecks

6.3 Configuration registration errors in the process

In the previous section, we presented the results for the configuration registration errors on the shipment date per module and CCI. In addition, we elaborated on these results by interviewing the domain experts. Based on the interviews, we concluded that the bottlenecks in the configuration registration process leading to errors on the shipment are the introduction of ECs on CCIs, the introduction of new machine types and valid configurations and no serial number registrations by suppliers. In Section 5.2 we distinguished between configuration errors at the shipment date, and errors during the process, but resolved before the shipment date. The results of these analyses can be found in Appendix H.

We presented the results in the interviews we held with the domain experts, and based on the Figures in Appendix H, the same conclusions on the bottlenecks of the configuration registration process were drawn. Different from the results in the shipment date, the upgrades were performed in the EF and the incomplete serial number registration was communicated with the supplier and a serial number for the part was created before the shipment date.

6.4 Conclusion

Based on both quantitative and qualitative analysis of the configuration errors, the following aspects are identified as the bottlenecks of the configuration registration process in the EF.

The first and probably biggest bottlenecks resulting in incomplete and non-compliant registrations, is the introduction of EC on CCIs. ECs on CCIs require suppliers to develop and assemble these parts. Since parts are highly complex, it takes often a long time until the parts enter the EF. Until then, the manufacturing process continues and the EF uses older versions of the CCI to qualify the system, or simply do not assemble the CCI in the module or machine order when the part expected by the CCI is not available.

Second, we saw that the number of configuration registration errors increased at the introduction of new machine types. After the introduction, a new valid configuration is created and entered in the tool, since these machines need to be build according to the valid configuration. However, because of the high-complexity and long lead times of parts, these parts can not enter the factory in time and thus not be built in the machine. This results in configuration registration errors. The introduction of new machine types can be considered as the same bottleneck as discussed above. New machine types require new CCI versions, or even to new, not earlier introduced, CCIs.

Third, there are several issues regarding the serial number registration from suppliers. Most CCIs are 'buy-parts' and therefore, the supplier is responsible for the serial numbers of the parts. If suppliers do not provide the parts with a serial number, the part can not be scanned and thereby added in the equipment structure, resulting in incomplete registrations.

Chapter 7

Redesign

In this chapter we present our proposal on how to redesign the current configuration registration process. First, based on the conclusions in Chapter 6, the bottlenecks of the current situation are further assessed in order to draw a conclusion for the redesign direction. Next, the redesign suggestion is discussed and explained in more detail. Since the process of the redesign direction is out of the originally defined scope defined in Chapter 1, we did additional research to retrieve insights in that process. After that, we show how the redesign suggestion can be implemented in the current way of working.

7.1 Bottleneck identification

In order to optimize the configuration registration process, the bottlenecks in the current way of working must be eliminated. The previous chapter concluded with three bottlenecks in the current way of working:

1. ECs on CCIs
2. New machine types and valid configurations
3. No serial number registrations on parts by suppliers

The following three subsections elaborate on the three bottlenecks and it is decided whether or not the bottleneck is considered as the direction for the redesigned way of working.

7.1.1 Engineering changes on CCIs

The first bottleneck we discuss is the ECs on CCIs. According to domain experts, this is the main reason why the CAB does not reach its target. Therefore, we can say that we must eliminate the number of ECs on CCIs, however, we already know that this will not happen at ASML. ASML is the market leader in the semiconductor industry and approximately 16% of its net sales are R&D expenses. ASML are in this position since they introduce the newest state-of-the-art technology to their customers, as the very first company in the semiconductor industry. ASML is therefore a technology-driven company where the innovative nature leads ECs on the machines, which make the machine performance even better. Nowadays, there is a global chip shortage so ASML's customer do want the best possible machines as quickly as possible delivered. ASML is pushing boundaries to satisfy the customer's needs and thus continuously improve the machines.

What can be changed is the alignment between ECs and the manufacturing process. Currently, as explained in the previous chapter, the valid configuration is manually changed directly after an EC is released and accepted, if the EC effects a CCI. Although it is known that the part cannot be delivered on time to assemble the machine according to the new configuration, the valid configuration still expects the 'new' part and not an older version. As follows, configuration registration errors occur and the CAB does not reach the target. This is however not a problem that occurs in the factory process, but this bottleneck is caused by external departments, out-of-scope from the configuration registration process in the EF. Therefore, the first redesign direction for optimizing the current situation, is to better align the ECs with the valid configurations that are used to create the CAB.

7.1.2 New machine type and valid configurations

The second bottleneck in the current process are the configuration errors that occur due to new machine type introductions. This bottleneck however has a similar root cause as the bottleneck discussed in Section 7.1.1: ECs resulting in late deliveries of new or upgraded parts. Therefore, we do not elaborate on this identified bottleneck.

7.1.3 No serial number registrations on parts by suppliers

In the past, stakeholders confirmed that there were a lot of problems regarding the serial number registrations at suppliers. However, as stated in Section 6.2, new agreements were made between ASML and its suppliers. As a result, the number of incomplete configuration registration errors decreased, as can be seen in Figure 6.2. Therefore, we consider this bottleneck as resolved and will not take it as a redesign direction for the remaining part of this research.

7.2 Redesign direction

The previous chapter discussed the three identified bottlenecks of the configuration registration process. Moreover, we concluded that the redesign direction should be about the alignment of ECs with the valid configurations that are used to create the CAB.

ASML's engineering change management (ECM) is according to the industry standard for CM that is embedded in ASML's processes: CM-II, which was presented in Section 2.1. For this redesign direction, we briefly discuss on the five phases of ECM presented in 2.1. A description of these phases and a comparison with the ECM stage as documented in ASML's processes can be found in Appendix I.

For this part of the research, the third ECM stage is further analyzed, since this will effect the redesign. The third stage *"plans the detailed implementation of the change through collaboration with the relevant suppliers"* (Wu et al., 2014). In addition, Wu et al. (2014) state that tasks as devising a manufacturing schedule associated with the product data to be changed, including outsourcing to suppliers are included. More complicated changes require proper alignment of tasks between internal manufacturing and technology staff, and suppliers. Since ASML works with complex parts for manufacturing a highly-complex machine, and CCIs are the critical items assembled in the machines, we can assume that the ECs for CCIs are considered as complex changes.

The third stage of the proposed framework by Wu et al. (2014) can be found in the process at ASML as well. In the high-level process of ECM at ASML, one process activity exist which is called *make the implementation plan.* In this activity, a cross-sector team creates the ECN (Engineering

Change Notice) Implementation Plan, where the (Module) configuration calendars are taken into account. This process is leaded by a change specialist who is responsible for the alignment between cross-sector team members. The ECN Implementation Plan contains both the work to be done to release the change in the product documentation for new builds as well as documentation required for upgrades. The information that is generated during this ECM phase is used by the EF when aligning on the order planning and work sequence for that order. In the CMMN model created in Section 4.6.1, the decision on how to deal with these parts is made based on the deviations that are analyzed.

The fourth stage is about releasing the EC. On PLM side, the product change is accepted and new product structure, product model and documentation are edited. If successful, the baseline is changed. This refers to the changes in the valid configuration of the product. At ASML, this activity is also performed in the ECM process. The ECM process includes steps as *commit to the implementation plan* following by an activity where the configuration structure is maintained. As mentioned before, the valid configurations of machines are thus edited in the design domain. However, input from the EF about the effective manufacturing and delivery dates is hereby not taken into account. In ASML's process, it is only stated that the change specialist *monitors the actions that are taken based on the effective delivery date* (Appendix I Table I.1), where it is never stated that the valid configuration should be changed based on these dates. From this, we conclude that our suggestion for redesign is therefore valid and new in ASML's processes. We explain in Chapter 8 why ASML benefits from eliminating this bottleneck with implementing our redesign.

In the case study presented by Wu et al. (2014), it is stated that the actual manufacturing depends on stock availability and business decisions. These business decisions allow the EF to assemble older part versions, or do not assemble a part if there is no stock, which results in most of the configuration registration errors. However, the valid configuration therefore does not represent a representative baseline which the factory must follow. The rules that determine the status of a CCI are already edited such that the newer versions of the parts must directly be implemented, yet this is not reachable. Therefore, we redesign the process and decisions made in the current way of working, in order to change the valid configuration in the EF, based on the business decisions that are taken in the planning stage of an order. From the results in Figure 6.8 and Figure 6.9 we can see that approximately half of the configuration registration errors are caused by ECs. All these errors will be avoided when implementing our redesign. In addition, some of the business goals of ASML will be reached, and it is analyzed why this redesign contributes to be prepared for the future situation, where the number of items in the CAB will increase to 1000. This is further explained in Chapter 8.

7.3 Redesign

The redesign focuses on integrating the decisions made during the planning of an order with the valid configuration. In the UML diagram presented Figure 4.3 in Section 4.3, the planning class and valid configuration class already exist, however, are not linked with each other. Figure 7.1 presents the updated UML Class diagram based on the redesign direction. The added classes with their links are explained below.

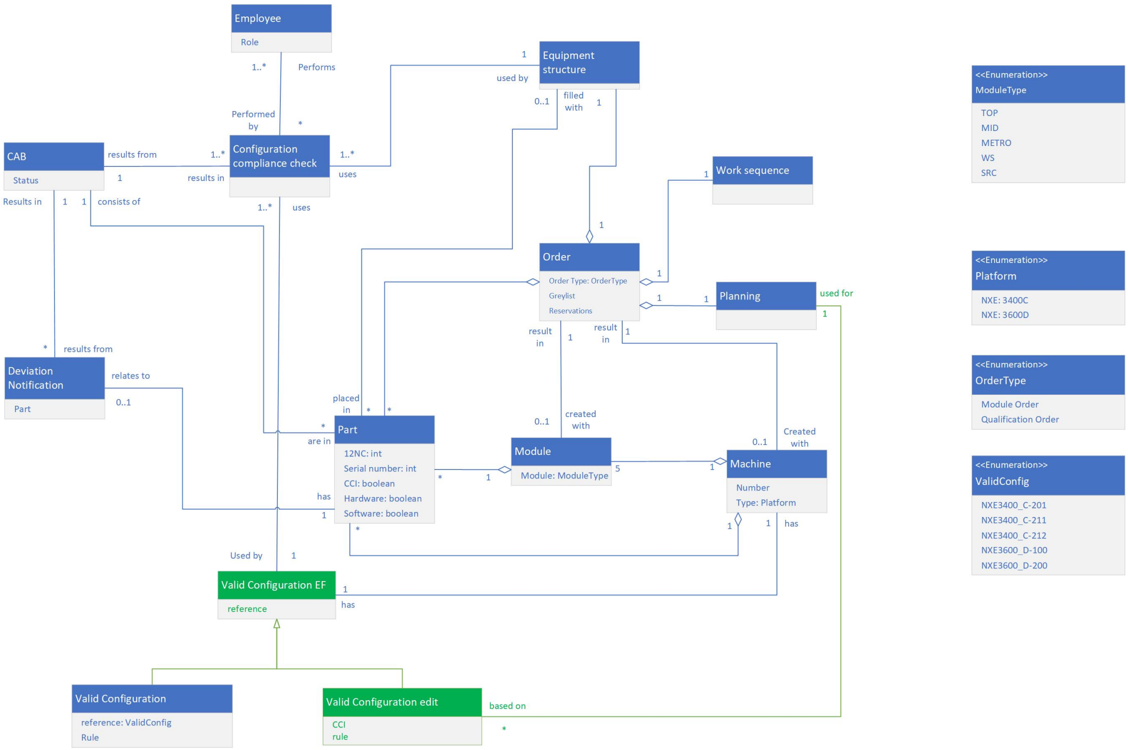

Figure 7.1: Updated UML Class diagram

Their are two added classes in the new UML class diagram:

1. Valid Configuration EF: this class represents the new valid configuration that is used in the EF. As can be seen, this class is linked with the configuration compliance check that is performed which results in the CAB, and is linked with the valid configuration that is created according to the new parts and upgraded parts. Next, the valid configuration EF does not have the same reference as the valid configuration anymore. The valid configuration for the EF is now on machine level, due to the edits that are potentially performed based on the planning. We can say that these valid configurations EF are instances of the valid configurations created by D&E. For example, a machine has valid configuration D-200 as reference, which is edited by the EF, resulting in D-200xxxx as the valid configuration for the EF.

2. Valid configuration edit: this class represents the edits that are made on the valid configuration that is created by D&E. Based on the planning for a module or a qualification order, rules in the valid configuration for the CCIs can be edited resulting in a valid configuration, which represents all the parts that must be assembled into the machine in the EF. When systems become more mature and there are no edits needed on the valid configuration as designed by D&E, there will be no edits and the valid configuration for the EF is the same as the valid configuration designed by D&E. Together with the valid configuration designed by D&E, the valid configuration for the EF can be made.

The updated UML diagram results in another activity-centric diagram and CMMN model. In the activity-centric diagram, there was no activity presented after the order planning. In the new way of working, the deviations where the planning is based on should not only be taken into account for the order planning, but also on the valid configuration. Therefore, a new activity is modeled in the diagram resulting in the updated activity-centric diagram as visualized in Figure

7.2. There, it can be seen that the valid configuration is taken into account during the planning for each order. Thereafter the decision is made if edits are need in order to create the representative valid configuration for the EF. In addition, at the configuration compliance check activity, the valid configuration EF, that is potentially edited during the new way of working is taken as the reference to create the CAB.

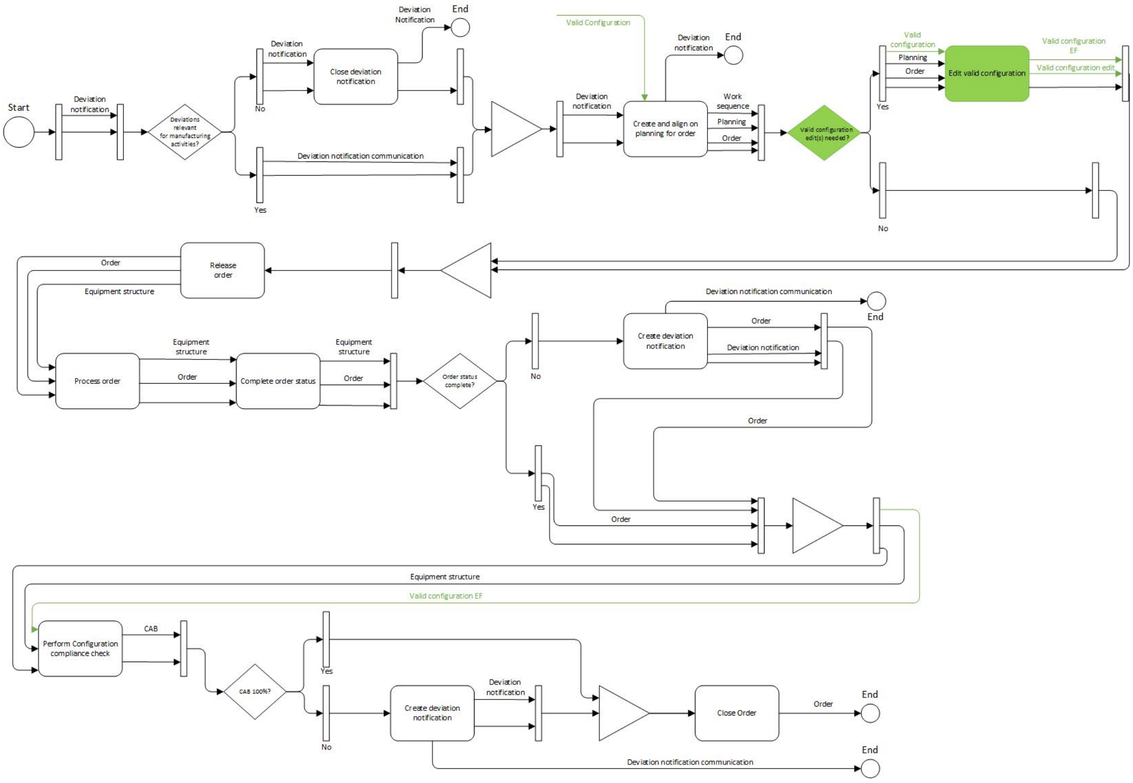

Figure 7.2: Updated Activity-centric diagram of the redesigned configuration registration process

Last, the new way of working is implemented in the CMMN diagram. The decision to edit the valid configuration or not is added to the process and data model, belonging to the planning activity as can be seen above. Since each order has a planning and the activity to edit the valid configuration is based on the planning of that order, the valid configuration for the EF is modeled in the order case. Figure 7.3. In the case, a stage is added where the valid configuration for the EF can be created as a result of the edit valid configuration task. For each case, thus for each order, a non-required task can be executed before releasing the order. This is not a required activity, since it could be the case that the valid configuration designed by D&E can be reached in EF, and thus there is no need for an edit.

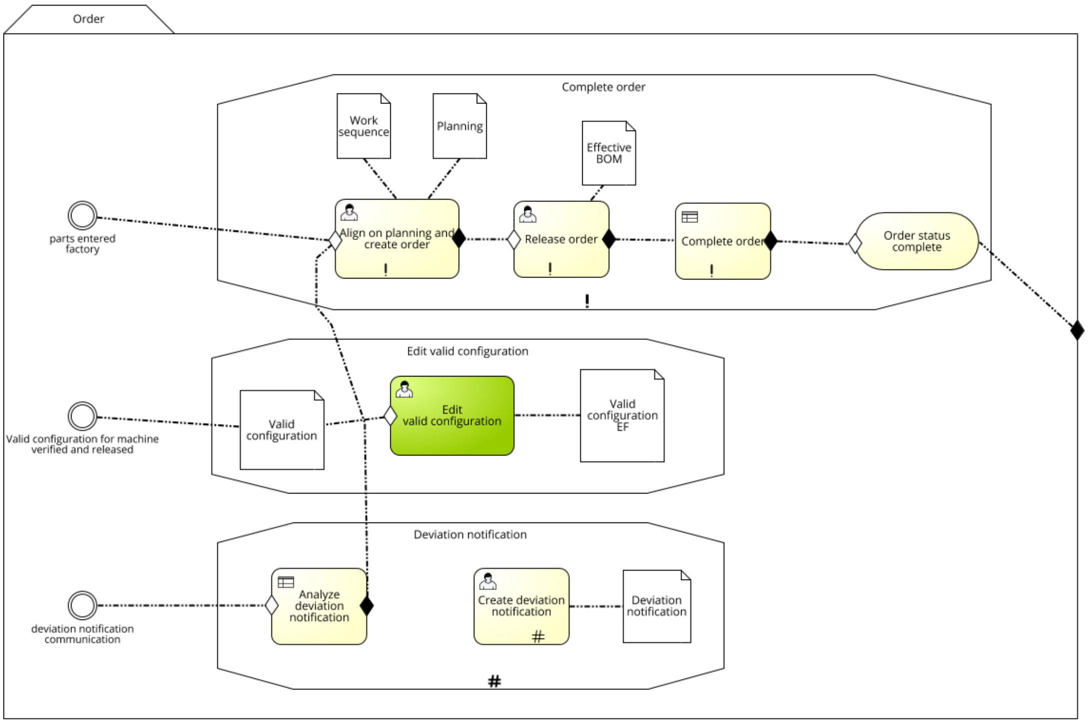

Figure 7.3: Updated CMMN model for an order in the redesigned configuration registration process

7.4 Engineering change notifications on CCIs

In the redesign as created above, there is no direct link visible with the ECs, which was the subject for the redesign. This might seem strange, however, the link is indirectly embedded in the models. We mentioned that an EC is accepted and released earlier than the part that has been changed is delivered at the EF. In addition, we mentioned that the valid configuration is changed after the EC is released and approved. At the cross-sector alignment meeting where the planning and work sequences are created, decisions are made to not follow the new valid configuration. The planners take the delivery dates of the new or upgraded parts into account and are then allowed to schedule the older materials in their planning. These materials are upgraded at customer's site or later on in the process when the new materials have arrived in the EF.

However, to optimize the planning process, there should be a notification to the relevant employees at ASML when an ECN is created by the EC specialists. This process is out-of-scope for this research, yet we recommend to notify the relevant employees when a ECN is created on a part that is flagged as a CCI. As follows, the EF can earlier be involved in the decision making, which optimizes the planning process and decisions on the potential valid configuration edits can be taken earlier.

7.5 Future goal

Right now, the valid configuration is still changed manually by the system integrator in order to report on the configuration status. The new way of working in the configuration registration process still requires manual edits of the valid configuration. It needs more edits than before, since the new way of working requires the employees to edit the valid configuration for each module order and the qualification order. In the future, it is desired to have the valid configuration continuously been changing for each module and thus for each machine, based on the planning that is released for each order. The proposed redesign will still be the same then, however we suggest to automatically edit the valid configuration, where this is no done manually. Right now, there is no integration of the CCT tool with the planning that is created in the ERP system and thus it is not possible yet to automatically change the valid configurations in the tool, in order to optimize the way of reporting on the configurations.

7.6 Conclusion

In this chapter we explained what should be redesigned to optimize the configuration registration process in the EF. The suggestion is to implement edits on the valid configuration as created by D&E based on the planning of an order. By doing this, the bottleneck of ECs leading to configuration registration errors can be eliminated. Since the planning of an order is based on material availability and not on the newest part versions in the valid configuration as a result of the ECs, this will optimize the configuration registration process leading to less incomplete and non-compliant registrations. The UML diagram, activity-centric model and CMMN model for an order have been changed accordingly.

Chapter 8

Evaluation

In this section, we evaluate on the results and the redesign, and see whether or not the benefits can be reached. This is assessed by using the benefit model that is created in Chapter 1. Reaching the benefits of the model is the business goal of this research. Next, we assess if ASML is better prepared for the future, when 1000 configuration items need to be registered in the CAB.

8.1 Future situation (1000 CCIs)

Embedding the planning of an order into the valid configuration eliminates a substantial part of the bottlenecks in the configuration registration process for 250 CCIs. The impact of the redesign on the future situation, when having 1000 configuration items, is not yet assessed. One of this research's limitations is that with the available data, we could not create a prediction model in CAB scores or errors on CCIs. However, with the use of domain knowledge and interviews with stakeholders, we can still assess what the impact of the redesign is for the future situation.

8.2 Business goals

In this section, we assess which benefits identified in the problem definition phase in Section 1.3.1 are reached after the implementation of the redesigned process. These next subsections elaborate on how ASML benefits from the redesigned way of working for the following three benefits out of the model:

1. No ODRs for configuration control purposes
2. No need for D&E assistance
3. Optimized install sequence

In addition, we explain how the increasing scope of 1000 configuration items will lead to less configuration registration problems, by implementing the redesigned model. We discussed the benefits with the same stakeholders from Chapter 6 that were given in Table 6.1. Thereby, we validated which benefits were met according to them, and got additional input on how the redesign helps reaching the business goals.

8.2.1 No ODRs for configuration control purposes

In Figure 1.3, one of the benefits resulting from 100% configuration is that there is no need anymore for having an Operational Deviation Report (ODR) for configuration control. An ODR is manual created document that is created during the transfer of the machine from EF to Install. An ODR is based on incomplete or non compliant registrations in the CAB, and explains why the CCI does not have a complete and compliant status. In the activity-centric model in Figure 4.4, the deviation notification flowing through the process at the end of the sequence, so after the CAB check, represents an ODR. With the redesigned model, there will be less configuration registration errors. Logically, this will lead to less ODRs.

In terms of cycle time, this immediately saves time to write these reports in the EF. Moreover, the reports do not have to be discussed in later stages, which decreases the decisions to be made. Additionally, when moving to registering 1000 configuration items, the number of ODRs that need to be written in the current way of working will definitely increase. So having the valid configuration be added based on what is reachable by the EF, will lead to less ODRs, since deviations that are on beforehand known, are already filtered out of the valid configuration and immediately transferred to install.

Next, manually created documents are sensitive for mistakes. When decreasing the number of ODRs to be written, the chance of making a mistake will decrease. This avoids confusion by the transfer of the machine and rework activities are therefore avoided.

With our redesign, if the order is completed according to the planning and does not have any deviations coming from other factors, for example incomplete serial number registration errors, the number of ODRs to be written equals zero. According to the employee from EF MF Delivery Volume, who writes the ODRs, most ODRs are written due to ECs. However, we do not impact other potential causes that occur in the manufacturing process or earlier with our redesign, so there will always be a need for creating ODRs in the future. However, we can say that our redesign definitely reduces the amount of ODRs.

8.2.2 No need for D&E assistance

Next, the redesigned model leads to less need for having assistance from the D&E department. The implementation of ECs in the valid configuration sets a baseline which aligns with the planning of an order. When doing this, the operators in the EF knows what to do and do not need to contact D&E if they are allowed to assemble older part versions in the machine for the system qualification. We explained that the ECs may lead to newer versions of machine parts in order to improve the machine's performance or reliability. When these parts have not entered the EF, the new way of working includes the decision that for qualification purposes, the older version is allowed. When this is embedded in the valid configuration, the operators and module owners do not have to contact D&E, since their will not be a deviation from the baseline anymore, and thus do not need to align the decision with D&E.

8.2.3 Optimized install sequence

The new way of working in EF also benefits the EF Install department's sequence. In the benefit model in Figure 1.3, we identified the ability for EF Install to create a first-time right upgrade plan when the CAB is 100%. We can not say that the redesign leads to a 100% score for the CAB, however we know that the configuration registration errors decrease which lead to higher CAB scores. When the upgrades that need to be performed are determined at the beginning of the orders in the EF, EF Install knows which parts they need to swap and upgrade and can thus create their sequence according to that. In the current situation, these upgraded parts are not always known while releasing an order, EF Install need to change their upgrade sequence later in the process, which is not optimal.

8.3 Data and information quality

This section elaborates on the data quality dimensions that are effected by the redesigned way of working. The redesign is created in order to eliminate the bottlenecks in the current situation. In this section, we aim to find support from literature for the redesigned method in terms performing better on the data quality dimensions that are discussed in Section 2.3. In that section, we mentioned the four most important data quality dimensions according to Batini et al. (2009) and Wand and Wang (1996): *accuracy*, *completeness*, *consistency* and *timeliness*. However, we found that the redesign does not directly impact on the accuracy, consistency and timeliness dimension. An explanation is provided below. This section ends with Table 8.1 that summarizes the findings on the data and information quality, which are explained in the remaining of this section.

- **Accuracy** is defined as the degree to which data stored in the information system correspond to real-world values (Batini et al., 2009). In order to check this, we must perform physical checks to identify if the parts in the equipment structure match with the assembled part. This is out-of-scope for this research, since such checks disturb the process in the EF. Moreover, we were not allowed to enter all areas in the EF.
- The **consistency** dimension states that all the conventions, symbols and functions used in an information system should follow the same logic and use this logic without exceptions (Eppler, 2006). For determining the status of an CCI, underlying rules are used when comparing the value in the equipment structure with the value in the valid configuration. With the redesign, we do not change the structure of reporting. Therefore, the data consistency will not increase or decrease after our redesign.
- The quality dimension **timeliness** refers to the delay between a change of a real world state and the resulting modification of the information system state (Batini et al., 2009). We know that the CCT tool is synchronized with changes in the equipment structure in SAP. Although it is out-of-scope for this research, we expect that the values are up-to-date and still are in the future. The redesign does not affect this data quality dimension, since the data is still being synchronized by the CCT tool.

The redesign however does affect the **completeness** dimension. Data completeness refers to the degree to which a given data collection includes data describing the corresponding set of real-world objects (Batini et al., 2009). In addition, it is about the meaning of missing values, and it is important to know why values are missing according to Batini et al. (2009). This research showed that incomplete (or missing) values could have two reasons:

1. There was no serial number provided by the supplier, so the part could not be scanned in the equipment structure, resulting confusion since it was not known what was actually assembled in the machine.
2. The part could not be assembled in the machine because the part did not enter the EF (mostly as a result of an EC) and no other part was assembled.

The redesigned method will increase the data completeness since the second reason will be avoided in the future. Right now, the CAB is created on the valid configuration based on the desired situation. With the redesign, ASML can report based on the planning for an order and change the rules of the valid configuration. If it is known that a CCI-part will not be assembled due to, for example, because the part is not on stock, the CAB does not expect a value in the equipment structure which results in a complete status. Completeness of information is considered as complete if all features to represent the reality (Eppler, 2006). With editing the rule in the valid configuration, and thereby creating the new valid configuration, reporting on the data is done on the expected reality, resulting in more complete data. Concluding, the data completeness quality dimension is expected to increase, and thereby, the data quality in the configuration registration process is expected to increase as well.

In addition, the activation principle discussed in Section 2.3 states that information should be acted upon, otherwise it is valueless. With the proposed redesign, the information on the statuses of CCIs represent the work done in the EF, and actors in the process are immediately triggered when seeing a configuration error. In the current situation, most of the errors can be ignored since the EF knows that the incomplete or non-compliant status is a result of an EC resulting in non-availability of the material required by the valid configuration. In the future, configuration registration errors like these are avoided because these are taken into account in the valid configurations edits. Thus, the fitness for use of the information in the new configuration registration process is expected to increase as well.

Increasing the data completeness benefits ASML directly for at least two reasons. First, with less incomplete values in the data, the root causes for data that is still incomplete after implementing the new valid configuration for EF can be found faster. Therefore, problems can also be solved faster. In addition, incomplete data leads to inadequate decision making by the management according to Eppler (2006). In a decision-intensive process like the configuration registration process, decisions will become more adequate, resulting in an improvement for the process.

	Definition	**Effect of redesign**	**Benefits**
Accuracy	the degree to which data stored in the information system correspond to real-world values (Batini et al., 2009).	-	-
Consistency	all the conventions, symbols and functions used in an information system should follow the same logic and use this logic without exception (Eppler, 2006).	-	-
Timeliness	the delay between a change of a real world state and the resulting modification of the information system state (Batini et al., 2009).	-	-
Completeness	the degree to which a given data collection includes data describing the corresponding set of real-world objects (Batini et al., 2009).	↑	less missing values, faster root cause analysis, more adequate decision making
Information quality	The fitness for use of information (Eppler, 2006).	↑	data is representative for work in EF, data understanding increases

Table 8.1: Summary of the effects of the redesign on the data and information quality

8.4 CM Maturity

In Section 2.1, we discussed the maturity levels for the dimensions within CM. This section elaborates on three of these dimensions: Processes, Information Technology and Organization. Specifically, we explain why the proposed redesign bring ASML to a higher maturity level for these dimensions by using the framework in Figure C.1 in Appendix C.

We proposed to include the delivery dates of new or upgraded materials by suppliers in the order planning, and thereby in the valid configuration for the EF. Right now, this information is known, yet not implemented in the current way of working. According to Myrodia et al. (2019), including external stakeholders in the CLM process will bring the process dimension of the CM processes to the fourth maturity level: external-focuses expertise. The same reasoning holds for the Information Technology dimension, by embedding the supplier's information on the delivery dates of parts in the IT system. Next, on organizational level, we proposed to focus on cross-sector alignment, specifically to include the EF when an EC is released for a part that is classified as a CCI. The maturity model states that *any change in CLM communicated to the stakeholders and immediately adopted by the whole organization and its external parties.* One direction for improvement was our redesigned way of working presented in Chapter 7. We suggested to adopt the ECs into the valid configuration, which can according to Myrodia et al. (2019) be seen as a continuous improvement.

8.5 Conclusion

This chapter elaborated on the benefits of the redesign suggestion for the configuration registration process in the EF. First, three of the identified business benefits for ASML can be reached if ASML implements the redesign. We explained why the redesigned leads to less ODRs, less D&E support and an optimized install sequence when implementing the redesigned process. Next, we assessed the effects of the redesign on the data quality dimensions and found that the the completeness dimension will benefit from the new way of working. In addition, the information's fitness for use is expected to increase, which enhance the value of the information in the configuration registration process. With the increased data and information quality, decisions can be made faster and earlier in the process, and root causes for incomplete data after the redesigned process can also be found earlier, which improves the decision-making in the process. Last, we evaluated the proposed redesign with the maturity model of Myrodia et al. (2019) and concluded that the redesign will take the current CM process to a higher maturity level.

Chapter 9

Conclusions

In this research, we optimized the current way of working regarding configuration registration at ASML. To do that, we analyzed the current way of working and provided data analyses to identify the bottlenecks in the current process. Based on data analyses and domain expert's opinions, we found a way to redesign the current process by embedding the engineering changes on CCIs into the valid configuration for a machine. Engineering changes were already embedded in the planning of an order, however the valid configuration was not based on the planning of an order. With the redesigned model, it is expected that ASML will decrease the configuration registration errors which they benefit from in the future, when moving from registering 250 CCIs to 1000 CCIs. In this Chapter, we summarize the key findings on the four sub questions stated in Section 1.4 in order to answer the main research question of this research:

Main research question:
How can configuration registration in the EUV factory be improved and what impact does it have for ASML and its customers?

9.1 Research questions

9.1.1 Research question 1

The first research question was created to identify the current way of working regarding configuration registration. The status of the configuration of the machines and corresponding CCIs is visualized in the CCT tool, therefore we first analyzed the structure of the tool, which was visualized in a context diagram. Next, we visualized the relations between the business artifacts in a UML diagram, and showed the activities that create, edit or remove these artifact in the activity-centric model. With these two models, we identified two dominant artifacts in the configuration registration process: an Order and a Part. For these two artifacts, we created a CMMN model in order to visualize the activities and decisions that change the status of the artifacts. With these models, we gained insights in the current situation leading to the CAB, which is the visualization of the configuration registration status of the machines and parts at ASML. This research question was covered in Chapter 4.

9.1.2 Research question 2

With the second research question, we provided insights in the bottlenecks of the current configuration registration process. The first part of the research question, covered by Chapter 5, was about the collection, understanding and preparation of data. We identified three data sources that were needed to find the bottlenecks for the current situation:

1. An export of the CCT tool with all compliance changes on CCIs, starting on 01-01-2020 until 18-06-2021. This export was our main data source since it contained the insights in the status changes of the CCIs.
2. A data file containing the module belonging to the CCI, for getting better insights in the bottlenecks, and with if the CCI is a software or hardware item, for scoping reasons.
3. A data file with the shipment date of the machines, needed for scoping reasons and insights in the configuration registration performance over time.

The data was prepared such that the incomplete and non-compliant configuration registration statuses could be analyzed. Next to cleaning, preparing and merging the data sources into the final dataset, we also got first insights in the bottlenecks of the current process. Moreover, we identified that our data contained status changes of CCIs only, and not the underlying parts. Therefore, it was difficult to link the data with other sources, since the CCI name is only used for configuration registration purposes.

In Chapter 6 the data analyses was performed. We visualized the performance per machine, per module and per CCI. To get a better understanding of the results, we held interviews with domain experts. With the insights gained, we concluded with the three bottlenecks of the current configuration registration process:

1. The introduction of Engineering Changes (ECs) on CCIs
2. New machine types or new valid configurations
3. Incomplete serial number registration on the parts from suppliers.

9.1.3 Research question 3

After we found the bottlenecks in the previous research question, we proposed a redesigned model in Chapter 7. First, we concluded that the redesign should focus on eliminating the first bottleneck identified, so the introduction of ECs. We looked at the current process and concluded that all ECs are already taken into account in the planning of an order. However, the valid configurations are not edited based on the order planning. When an EC is released, the valid configuration is immediately edited by D&E and the delivery times of the changed parts at EF is not taken into account. This leads to a valid configuration that could not be met, which is not representative for the work performed in the EF. We therefore proposed to create a new valid configuration for the EF by editing the valid configuration based on the planning for an order. By doing this, the number of configuration registration errors will decrease. The UML diagram, activity-centric diagram and the CMMN model are changed by including the valid configuration edits in the models. In addition, we briefly analyzed the ECM process at ASML and recommended, with support from literature, to notify the relevant stakeholders when an EC is released for a part that is a CCI. Last, we proposed to automatically change the valid configuration by integrating it with the planning of an order, but this should be investigated further in the future.

9.1.4 Research question 4

In Chapter 8, we evaluated on the redesigned model and see if the benefits in the benefit model, which are the business goals in Section 1.3.1 could be met. We concluded that the with the redesigned model, three of the benefits could be reached with the redesigned model:

1. Less ODRs for configuration control purposes have to be created by EF. First, this saves time to create and align on the ODRs and second, since ODRs are handwritten documents, the probability of mistakes decreases.
2. There is less need for support of the D&E department, which reduces the amount of rework, and thus saves time.
3. The upgrade plan of parts during the install phase of the machine can be created right at the first time. This improves the working sequence at EF Install in terms of cycle time.

Next, we assessed the data quality in the configuration registration process after the redesigned model, and concluded that the data completeness dimension will increase. This leads to:

1. Faster decision making in the new configuration registration process.
2. Faster root cause analyses on errors made by EF or earlier in the process, in the new configuration registration process

9.2 Conclusions

What we can conclude from a business point of view is that we provided a solution design for the current configuration registration process. We suggested that ASML edits the valid configuration based on the planning of an order, such that ECs are embedded and do not lead to configuration registration errors that cannot be solved in EF. We also showed that the new way of working leads to reaching at least three business benefits for ASML, which all three focus on reducing the cycle time. In addition, we explained that the data completeness and the information quality in the process will improve by our solution. Due to the data availability constraints, we could not build a prediction model in order to predict the future CAB scores when registering 1000 configuration items. However, with the use of domain knowledge, we expect that EF benefits from this solution.

From a scientific point of view, we have shown in this research that the configuration registration process can be modeled by using artifact-centric modeling techniques. We believe that this study therefore contributes to the scientific field, especially given the increasing importance of CM at organizations. We also provided an in-depth analysis of the process of configuration registration, which currently did not exist. We believe that this study can be used as a method for other studies regarding configuration registration, but we want to emphasize on the need to carefully structure the data on beforehand, so that the data in the process becomes self-explaining.

9.3 Limitations

This section discusses several limitations that are subject to this research. First of all, there is a limitation regarding the availability of data. As mentioned before, the export of all compliance changes was on CCI-level and not on part level. A CCI is a name that is only used for configuration registration purposes, and is not used in other data sources at ASML. The identifier of a part is a 12NC number. These were available in the export, yet not with information about the status. Therefore, we could not see which of the allowed parts for the CCI were actually assembled in the machine. For that reason, we could not use the 12NC number for extracting data of features out of the data sources to identify the bottlenecks of the configuration registration process, because we simply did not know which 12NC number we should take. The original idea was to extract related features of these parts to cluster the current bottlenecks and create a prediction model with the added configuration items in the future, in order to predict the future CAB scores. We could not do this due to the data availability constraints. As a result, we generated our results on a CCI level and used the input of domain experts to identify the bottlenecks. We could not quantify and visualize these bottlenecks and got only an explanation of the relationship between the results in Chapter 6 and the identified bottlenecks.

Next, the business goals that were created in Section 1.3.1 and later evaluated in Chapter 8 can not be quantified. The benefits that will be reached after implementing the redesign effect activities that are not quantified. Moreover, the benefits are all manual activities the completion times are not stored in the information systems at ASML. Additional research about the quantification of the benefits is required to better evaluate on the business goals that can be reached. Right now, this is only an indication based on the interview sessions with the stakeholders in Chapter 8.

A third limitation is about the bottleneck identification phase. We know that the parts have to be scanned by the employees of the EF to register a part in the equipment structure. From the interviews with relevant stakeholders, we know that employees sometimes do not always correctly administrate these parts in the equipment structure. Since we only have data from the CCT tool and no data from SAP where the employees (de-)register the parts, we cannot quantify this at all, and therefore have no insights in the number of workmanship errors happening at the process. Due to time and scoping constraints, this was not possible in this research.

Last, there is a limitation about the scope of this research. We scoped this research to the situation in the EF. However, it seemed that the identified bottlenecks were not a result of the performance in the EF. The scope is therefore limited in sense that the processes behind the bottlenecks are not analyzed in detail. This may lead that we did not cover the entire field where the bottlenecks arise. In addition, changing the way of working in the EF also effects the next department, EF Install. Similarly, the processes at EF Install are not analyzed in details.

9.4 Recommendations

This section presents the recommendations for ASML based on this research.

9.4.1 Redesign implementation

The first recommendation we provide is to implement our redesign suggestion into the processes. This means that ASML should change the valid configurations designed by D&E into valid configurations for the EF. The changes should be based on the ECs on parts that are classified as CCI. The EF should actively participate in the ECM processes so that the delivery dates of the new or upgraded parts are known. Based on that, the rules that determine the status of an CCI can be edited such that they are representative for the work that can be done in the EF.

9.4.2 Future tooling

Our second recommendation is to change the tooling that is used in the current way of working. First, we recommend ASML to also visualize the status changes on a part level in the CCT export.

At the start of implementing the redesign, we suggest to manually change the valid configurations and the underlying rules in the CCT tooling. However, when the new way of working seems to be successful and is more mature, we recommend to automate these changes and create a direct link between the order plannings and the rules in the valid configuration. This could possibly be a direction for future research. Especially when registering more configuration items in the future, this would save significant time and will decrease the probability of manual errors.

9.4.3 Cross-sector alignment

Last, we recommend ASML to focus on the alignment between all sectors for CM. Since CM is an area that requires work and data from many departments in the company, it is important that all departments are aware of the effects for the next departments regarding configuration registration errors. We showed in this research that the serial number registration by suppliers and the ECs initiated by D&E resulted in most bottlenecks in the EF. As Myrodia et al. (2019) states that any change in the entire CM lifecycle should be immediately adopted by the internal and external stakeholders in order to continuously improve the CM processes and reach the highest maturity level regarding CM, we advise ASML to clearly define all roles and relevant stakeholders for achieving this maturity level. On all dimensions, cross-sector alignment is key and we therefore suggest to include all relevant parties, both internal and external parties, in the CM processes.

9.5 Future research

This section provides some interesting directions for future research.

As mentioned in Section 9.4.2, we recommend to automate the rule editing for the valid configurations. Even if the redesign implementation does not seem to be successful, or is not implemented, automate this manual action will save time, especially when the scope is increased for registering more configuration items in the future.

Second, it could be interesting to apply process mining techniques on the completion of an order in the EF. We mentioned that workmanship errors (e.g. scanning parts into the equipment structure) could not be identified in this research. When applying process mining techniques, it can be identified where in the process a part or module is not correctly administrated in the ERP system. When structural patterns are found, ASML might consider to improve the work instructions, or consider additional training for the employees.

Third, the new way of working is not validated yet. Further research is require to assess on the performance of the redesign suggestions. When the new way of working is successful in the EF, ASML could consider to provide research on applying a similar solution for the S&SC department. Further research can follow the methodology used during this research and assess whether or not S&SC also benefits from a similar solution.

Finally, the identification of the bottlenecks is performed with the help of domain experts. Therefore, this part is rather explorative. We suggest to implement the redesign in order to eliminate the bottlenecks regarding the ECs. In the future, ASML could consider to incorporate more features of the parts responsible for the CCI status, in order to more elaborately assess the as-is situation and identify other bottlenecks. However, the history export of the CCT tooling should include the status changes on a part level by then.

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Appendix A

Configuration Status Accounting at ASML

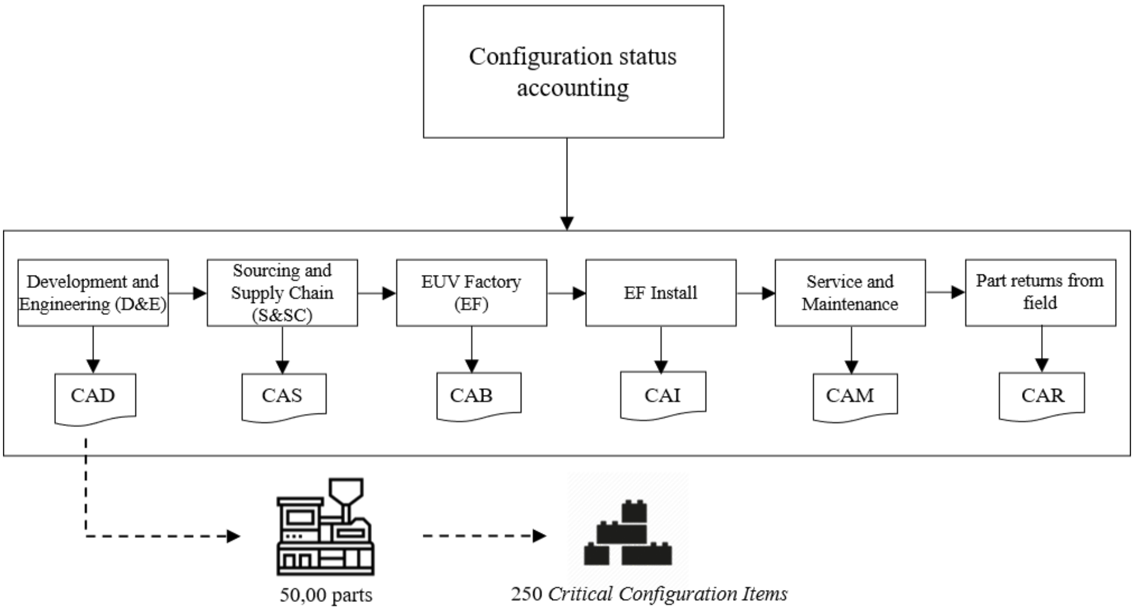


Figure A.1: Configuration Status Accounting at all departments

Appendix B

Benefit models

B.1 Benefit models

B.1.1 Benefits of having a 100% accurate digital twin leading to an increased reliability

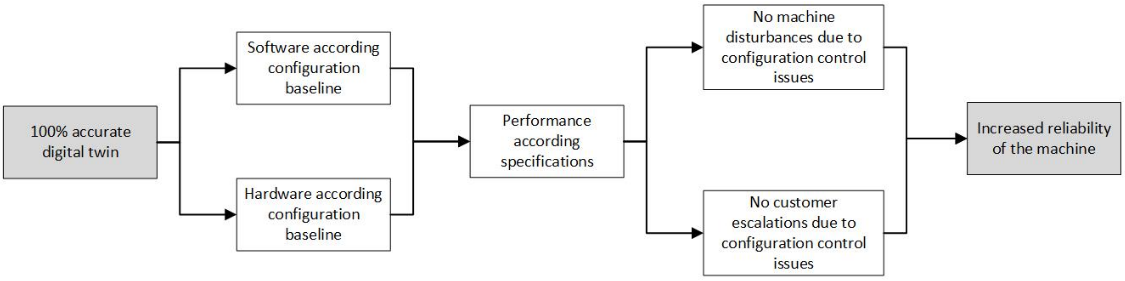


Figure B.1: Benefits of having a 100% accurate digital twin leading to an increased reliability

B.1.2 Benefits of Increased traceability in a part's history

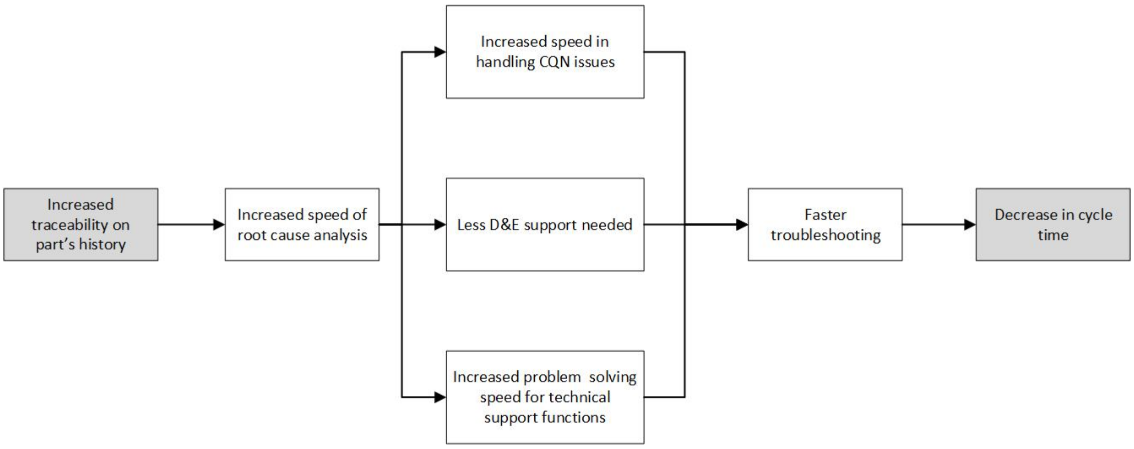


Figure B.2: Benefits of having an increased traceability on a part's history

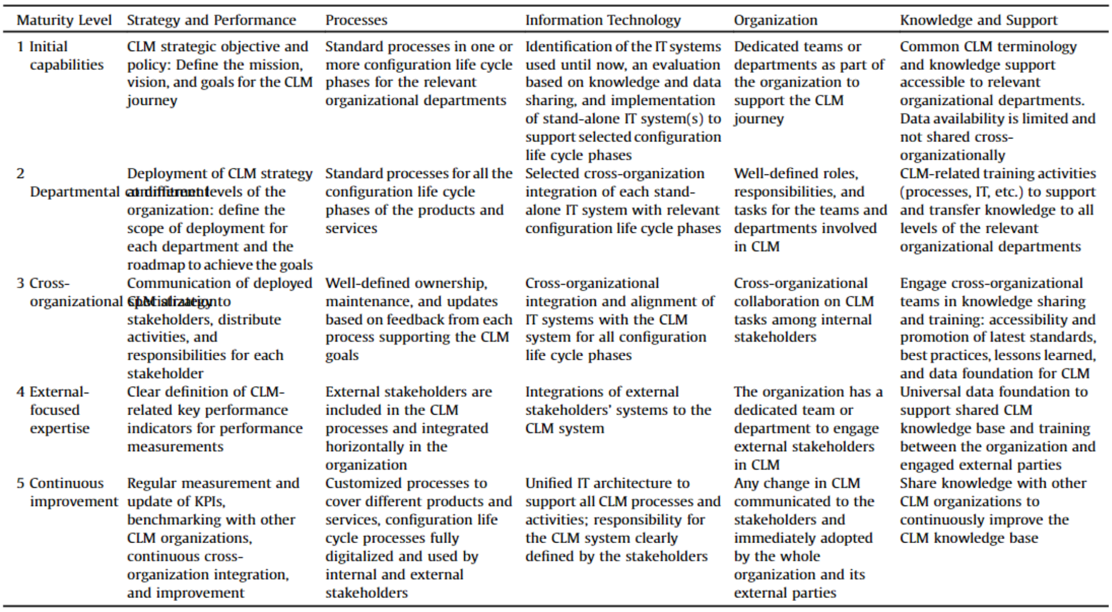
B.2 Stakeholders benefit analysis

Table B.1: Interviewed stakeholders for benefit analysis

Name stakeholder (ASML abbreviation)	**Department**
SPLP	EF OE Project Organization
TOMJ	EF PS Business Engineering
PGRK	EF PS Project organization
RKBE	EF systems install projects
NHAX	QP GQ Customer Quality Care
PDPB	EV EUV Systems Delivery Upgrade
GERO	MD DE CM C Conf Def Execution
EJON	EF PS FLS Team 4
EDWB	MD DE CM C Config Mgmt Architecture
LGEM	EF System Install Korea
EOMM	EF System Install US
XIAY	CN CS EUV Operations Design
RHBC	EF MF System Delivery Volume
TROR	EF MF Program Management
MHFB	EF PS FLS Team 4
NBRA	PI_EUV DE SI E Mgmt & Verif AdvSys
BJAZ	EF MF System Delivery Volume
WISP	MD DE CM C Config Mgmt Architecture
MMPB	EF MF System Integration

Appendix C

Configuration Lifecycle Management Maturity model



Maturity Level	Strategy and Performance	Processes	Information Technology	Organization	Knowledge and Support
1 Initial capabilities	CLM strategic objective and policy: Define the mission, vision, and goals for the CLM journey	Standard processes in one or more configuration life cycle phases for the relevant organizational departments	Identification of the IT systems used until now, an evaluation based on knowledge and data sharing, and implementation of stand-alone IT system(s) to support selected configuration life cycle phases	Dedicated teams or departments as part of the organization to support the CLM journey	Common CLM terminology and knowledge support accessible to relevant organizational departments. Data availability is limited and not shared cross-organizationally
2 Departmental coordination	Deployment of CLM strategy at different levels of the organization: define the scope of deployment for each department and the roadmap to achieve the goals	Standard processes for all the configuration life cycle phases of the products and services	Selected cross-organization integration of each stand-alone IT system with relevant configuration life cycle phases	Well-defined roles, responsibilities, and tasks for the teams and departments involved in CLM	CLM-related training activities (processes, IT, etc.) to support and transfer knowledge to all levels of the relevant organizational departments
3 Cross-organizational specialization	Communication of deployed CLM strategy to stakeholders, distribute activities, and responsibilities for each stakeholder	Well-defined ownership, maintenance, and updates based on feedback from each process supporting the CLM goals	Cross-organizational integration and alignment of IT systems with the CLM system for all configuration life cycle phases	Cross-organizational collaboration on CLM tasks among internal stakeholders	Engage cross-organizational teams in knowledge sharing and training: accessibility and promotion of latest standards, best practices, lessons learned, and data foundation for CLM
4 External-focused expertise	Clear definition of CLM-related key performance indicators for performance measurements	External stakeholders are included in the CLM processes and integrated horizontally in the organization	Integrations of external stakeholders' systems to the CLM system	The organization has a dedicated team or department to engage external stakeholders in CLM	Universal data foundation to support shared CLM knowledge base and training between the organization and engaged external parties
5 Continuous improvement	Regular measurement and update of KPIs, benchmarking with other CLM organizations, continuous cross-organization integration, and improvement	Customized processes to cover different products and services, configuration life cycle processes fully digitalized and used by internal and external stakeholders	Unified IT architecture to support all CLM processes and activities; responsibility for the CLM system clearly defined by the stakeholders	Any change in CLM communicated to the stakeholders and immediately adopted by the whole organization and its external parties	Share knowledge with other CLM organizations to continuously improve the CLM knowledge base

Figure C.1: Configuration Lifecycle management maturity model (Myrodia et al., 2019)

Appendix D

Process Analysis

D.1 Activity-centric model

Table D.1: Activity-centric model: Explanation of activities and conditions

Activity or condition	Name	Description
Condition	Deviations relevant for manufacturing activities?	Workers decide whether or not a deviation notification should be taken into account while processing the order, or not.
Activity	Close deviation notification	Deviation notification is considered as closed, if it not affects the further operations of the order
Activity	Create and align on planning for order	ASML employees create the planning and work sequence for the order, and thus create the order that can be released. Deviation notifications on parts are taken into account.
Activity	Release order	The order, created in the previous activity, is released. Hereby, the equipment structure is also released, in which the parts are registered by the workers to complete the order
Activity	Process order	the order (a module order or a qualification order) is processed in the EF.
Activity	Complete order status	The order need to be completed, deviations should be handled and all sequence steps must have been executed.
Condition	Order status complete?	When an order cannot be completed in the given period, deviation notifications must be created and communicated with the next department. If the order is complete, the order can be closed.
Activity	Create deviation notification	An employee creates and communicates a deviation notification regarding a part in the order.
Activity	Perform configuration compliance check	The equipment structure and the valid configuration are compared in this activity in order to create the Configuration As Built (CAB)
Condition	CAB 100%?	If the CAB is 100%, which indicates a perfect match between the equipment structure and the valid configuration, the order can be closed. Otherwise, a deviation notification is created and communicated, and the order can be closed after that activity.
Activity	Close order	The order status is complete and thus the order can be closed.

D.2 Entity dominance

D.2.1 First iteration

In the first iteration to construct the entity dominance graph, the method of Kumaran et al. (2008) was followed. An entity dominates another entity if and only if:

1. Every activity in which information entity e_2 is used as input, e_1 is also used as an input
2. Every activity in which information entity e_2 is used as output, e_1 is also used as an output
3. Information entity e_1 is used in at least one activity that does not use information entity e_2.

According to the activity-centric model presented in Figure 4.4, the entity dominance graph can be drawn as presented in Figure D.1.

D.2.2 Second iteration

The second iteration includes the method to determine existence dependency between information entities. From the UML Class diagram in Figure 4.3, it seems that an order contains of multiple (*) parts. However, this relationship is non-existence dependent, since parts have an useful existence without having an order. Therefore, a separate entity *part usage*, referring to the use of parts to complete an order, is created in this second iteration. Further, I identified the association links between a part with 1) deviation notifications, 2) CAB and 3) the equipment structure. Using the theory of Snoeck and Dedene (1998), logic reasoning and domain knowledge, it can be stated that these three entities are existence dependent on a part. Simply put, all three entities do not have a meaningful existence without the existence of a part in the configuration registration process. Following the method of Snoeck and Dedene (1998), the entity graph of the second iteration is created and visualized in Figure D.1. Together, these two models form the entity dominance graph as presented in Section 4.5.

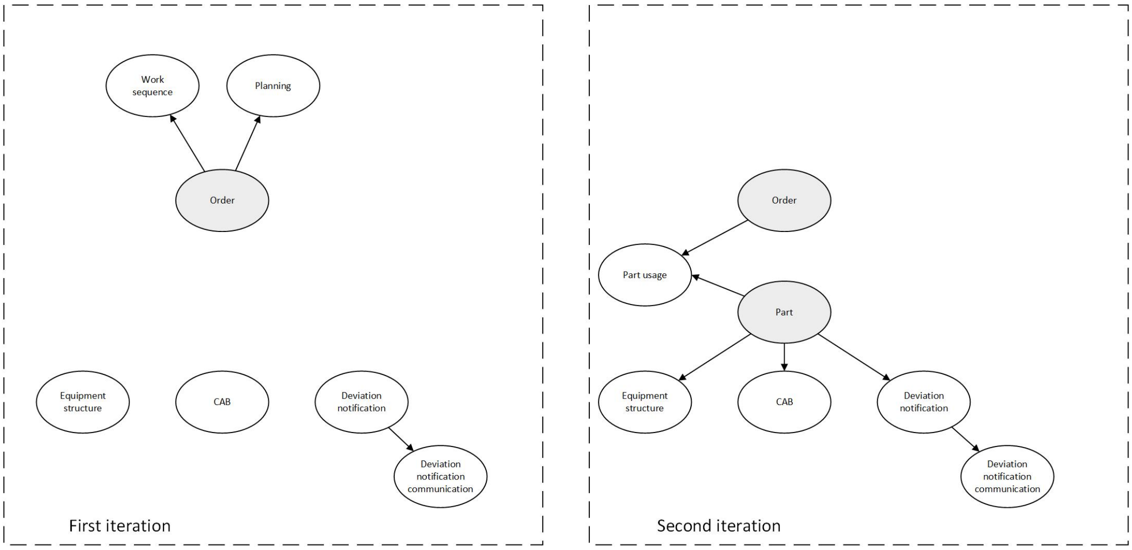


Figure D.1: Entity dominance: iterations

Appendix E

CCI status export per color

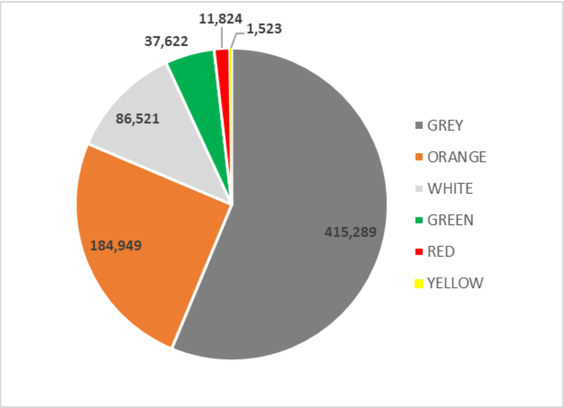


Figure E.1: Overview of CCI status per color in CCT export before cleaning

Appendix F

Machines in scope

Table F.1: Machines in scope

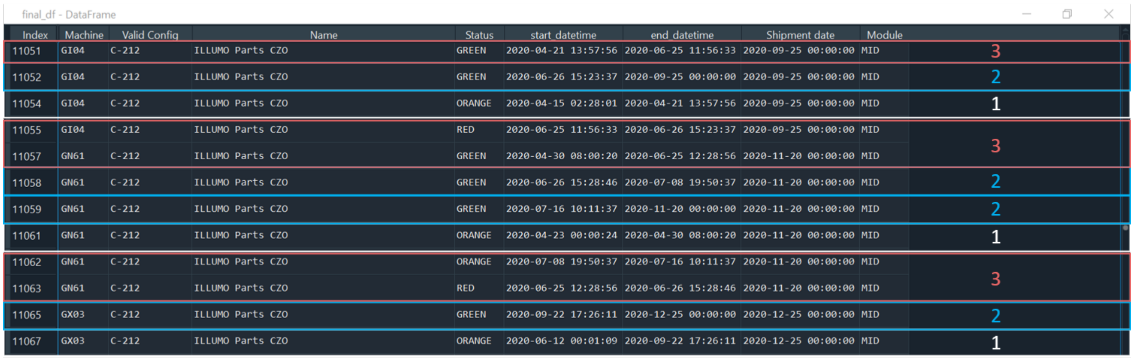
Machine	Type	Valid configuration	Shipment date
JK28	NXE: 3400C	C-211	2020-02-14
JI87	NXE: 3400C	C-201	2020-03-06
IF24	NXE: 3400C	C-211	2020-03-27
IF47	NXE: 3400C	C-201	2020-03-27
JK78	NXE: 3400C	C-211	2020-03-27
BW76	NXE: 3400C	C-211	2020-04-17
DV32	NXE: 3400C	C-211	2020-04-24
GB73	NXE: 3400C	C-211	2020-05-01
CW29	NXE: 3400C	C-212	2020-05-22
EB72	NXE: 3400C	C-212	2020-05-22
FY20	NXE: 3400C	C-201	2020-06-12
KN44	NXE: 3400C	C-211	2020-06-12
EI29	NXE: 3400C	C-211	2020-06-26
CI50	NXE: 3400C	C-211	2020-07-17
JG14	NXE: 3400C	C-212	2020-08-07
JL92	NXE: 3400C	C-201	2020-08-07
KI41	NXE: 3400C	C-212	2020-08-21
IC14	NXE: 3400C	C-212	2020-09-11
JK58	NXE: 3400C	C-212	2020-09-11
CD52	NXE: 3400C	C-212	2020-09-25
GI04	NXE: 3400C	C-212	2020-09-25
JR60	NXE: 3400C	C-212	2020-09-25
KO88	NXE: 3400C	C-212	2020-09-25

AF26	NXE: 3600D	D-100	2020-10-30
AH19	NXE: 3400C	C-212	2020-11-13
GN61	NXE: 3400C	C-212	2020-11-20
EN46	NXE: 3400C	C-212	2020-11-27
KG33	NXE: 3400C	C-212	2020-12-11
IS64	NXE: 3400C	C-212	2020-12-18
GX03	NXE: 3400C	C-212	2020-12-25
FU00	NXE: 3400C	C-201	2021-01-22
DT98	NXE: 3400C	C-212	2021-02-05
GA88	NXE: 3400C	C-212	2021-02-12
KH74	NXE: 3400C	C-212	2021-02-26
AM55	NXE: 3400C	C-212	2021-03-05
JH46	NXE: 3400C	C-212	2021-03-19
FH47	NXE: 3400C	C-212	2021-03-26
KO80	NXE: 3400C	C-212	2021-04-02
HT63	NXE: 3400C	C-212	2021-04-16
DK58	NXE: 3400C	C-212	2021-04-23
AX39	NXE: 3400C	C-212	2021-05-14
AI26	NXE: 3600D	D-200	2021-05-28
HA00	NXE: 3400C	C-212	2021-06-04
HU18	NXE: 3600D	D-200	2021-06-04
HB89	NXE: 3600D	D-200	2021-06-11
JI13	NXE: 3400C	C-212	2021-06-11
KP66	NXE: 3400C	C-212	2021-06-18

Appendix G

Final dataset variables

In Figure G.1 we present a snapshot of the final dataset constructed in Section 5.2. This could provide more insights in the data we used in this research.



Index	Machine	Valid Config	Name	Status	start_datetime	end_datetime	Shipment date	Module	
11051	GI04	C-212	ILLUMO Parts CZO	GREEN	2020-04-21 13:57:56	2020-06-25 11:56:33	2020-09-25 00:00:00	MID	3
11052	GI04	C-212	ILLUMO Parts CZO	GREEN	2020-06-26 15:23:37	2020-09-25 00:00:00	2020-09-25 00:00:00	MID	2
11054	GI04	C-212	ILLUMO Parts CZO	ORANGE	2020-04-15 02:28:01	2020-04-21 13:57:56	2020-09-25 00:00:00	MID	1
11055	GI04	C-212	ILLUMO Parts CZO	RED	2020-06-25 11:56:33	2020-06-26 15:23:37	2020-09-25 00:00:00	MID	3
11057	GN61	C-212	ILLUMO Parts CZO	GREEN	2020-04-30 08:00:20	2020-06-25 12:28:56	2020-11-20 00:00:00	MID	
11058	GN61	C-212	ILLUMO Parts CZO	GREEN	2020-06-26 15:28:46	2020-07-08 19:50:37	2020-11-20 00:00:00	MID	2
11059	GN61	C-212	ILLUMO Parts CZO	GREEN	2020-07-16 10:11:37	2020-11-20 00:00:00	2020-11-20 00:00:00	MID	2
11061	GN61	C-212	ILLUMO Parts CZO	ORANGE	2020-04-23 00:00:24	2020-04-30 08:00:20	2020-11-20 00:00:00	MID	1
11062	GN61	C-212	ILLUMO Parts CZO	ORANGE	2020-07-08 19:50:37	2020-07-16 10:11:37	2020-11-20 00:00:00	MID	3
11063	GN61	C-212	ILLUMO Parts CZO	RED	2020-06-25 12:28:56	2020-06-26 15:28:46	2020-11-20 00:00:00	MID	
11065	GX03	C-212	ILLUMO Parts CZO	GREEN	2020-09-22 17:26:11	2020-12-25 00:00:00	2020-12-25 00:00:00	MID	2
11067	GX03	C-212	ILLUMO Parts CZO	ORANGE	2020-06-12 00:01:09	2020-09-22 17:26:11	2020-12-25 00:00:00	MID	1

Figure G.1: Snapshot of the final dataset

In the Figure above, we distinguish the entries as follows:

1. The entries with number 1 represent the 'first registrations' as explained in Section 5.2. We see an orange status which tells us that the part is not registered in the equipment structure. In most cases, the part is simply not handled yet and is assembled in the machine at the *end_datetime* for that entry. In the column *Machine*, we see three machines. Correspondingly, we have three 'first registrations'.
2. The entries with number 2 represent the configuration registration status at the shipment date. For the CCIs of these machine instances, we can see that there are no configuration errors for these CCIs at the shipment date. Similar to the first registrations, we see three entries representing the status of an CCI on the shipment date.
3. The rest of the registrations represent the status changes that got another status during the process, but were solved on the shipment date. On the entries with number 3, we see that the *start_datetime* and *end_datetime* change before the shipment date, but after the 'first registration'.

Next, Table G.1 explains the variables in more detail.

Table G.1: Explanation of the variables in the final dataset

Variable	**Description**
Machine	The number for the machine is a random number generated that is associated with a machine instance.
Valid Config	The valid configuration variable represents the valid configuration reference on which the machine instance is assigned to.
Name	This variable displays the name of the CCI.
Status	The status shows the configuration status of the CCI, classified by the color codes from the CCT tool.
start_datetime	This variable is the date representing the moment when the CCI changed in the status related to the same entry.
end_datetime	This variable is the date representing the moment when the CCI changed into another status related to another entry (and thus leaving the status of that entry).
Module	This variable is a string variable showing the module to which the CCI is related to.
Shipment date	This is the shipment date of the machine instance.

Appendix H

Results configuration registration errors in process

Per Module

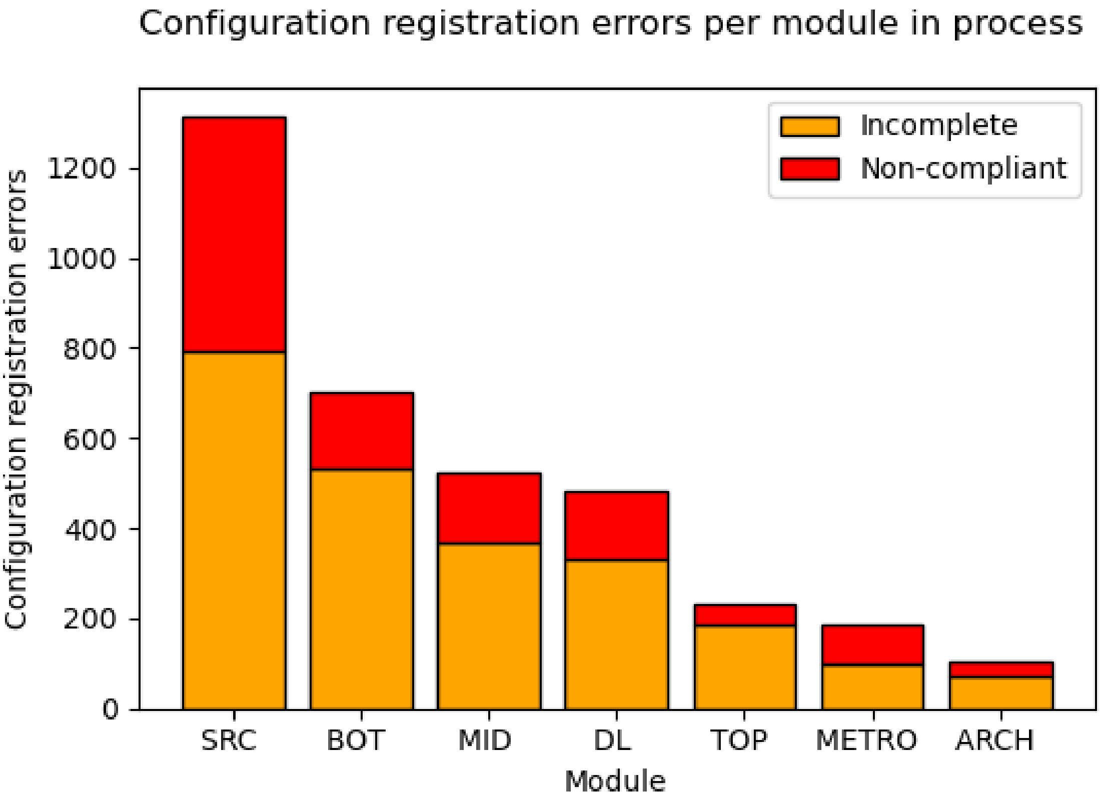


Figure H.1: Configuration registration errors per module in the process

Per CCI

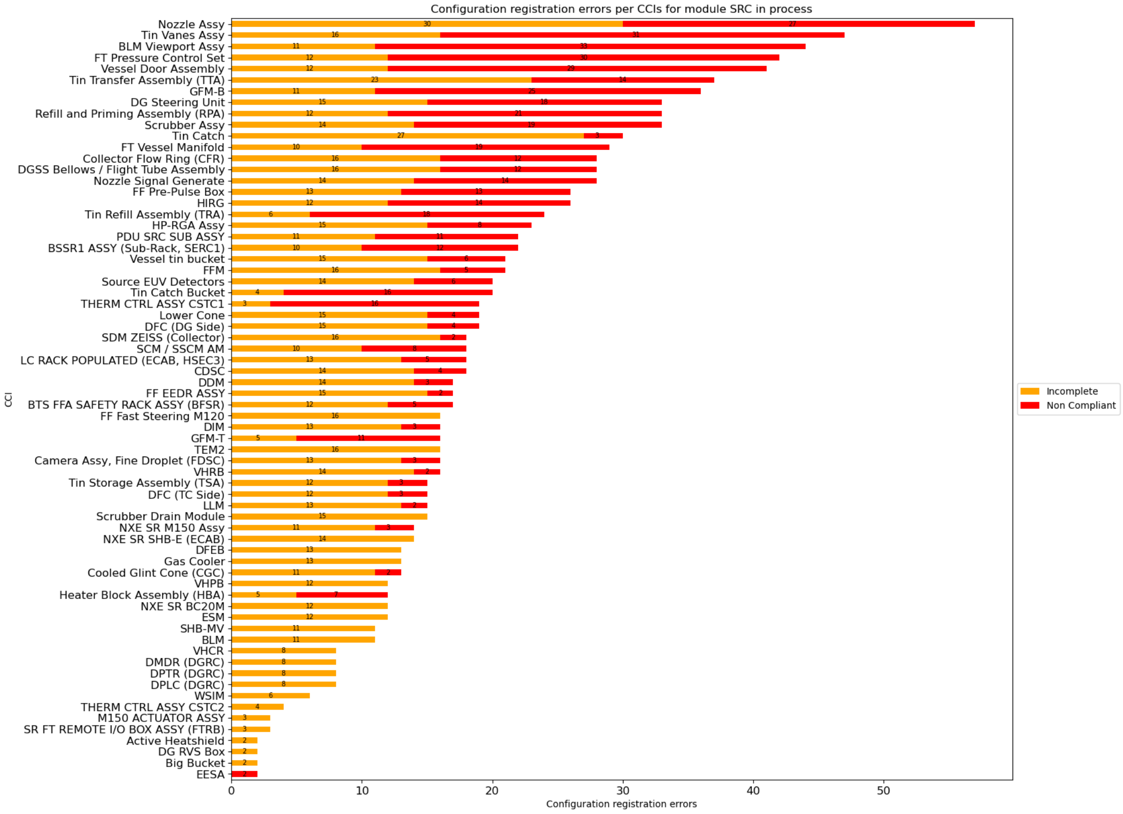


Figure H.2: Results configuration registration errors SRC module in process

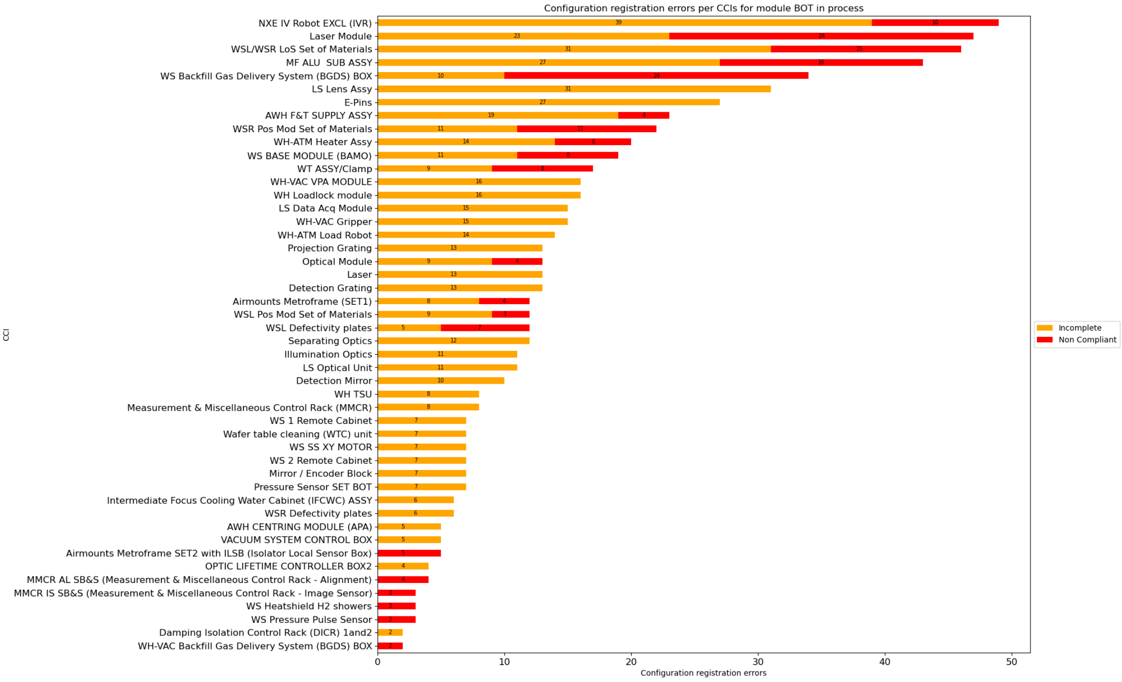


Figure H.3: Results configuration registration errors BOT module in process

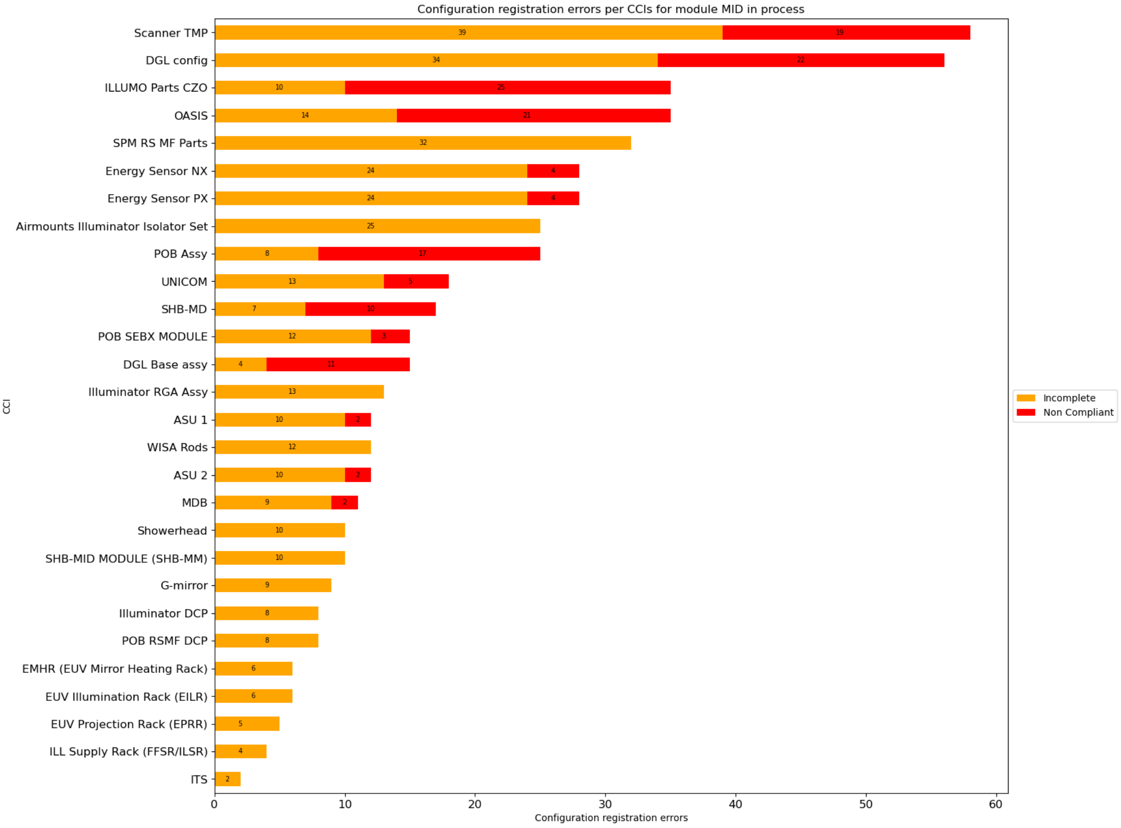


Figure H.4: Results configuration registration errors MID module in process

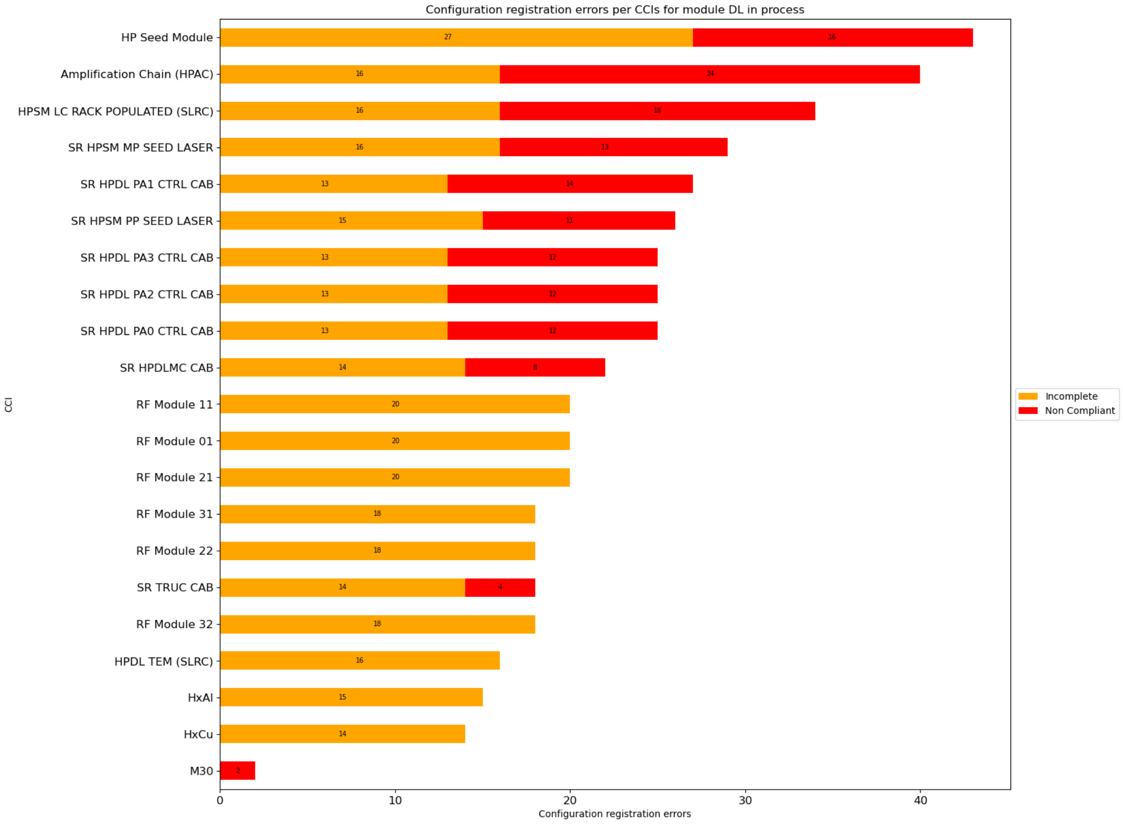


Figure H.5: Results configuration registration errors DL module in process

Appendix I

Engineering Change Management

Table I.1: Comparison of the ECM framework presented by Wu et al. (2014) and the ECM process at ASML

ECM phase	Wu et al. (2014)	ASML[1]
Identify the Issue	In this phase, requirements or problems from ERP side are checked, and reported to the PLM side, where the issue is analyzed and a problem report is generated.	This phase is the input of the change management processes at ASML. The change specialist at ASML creates the change request and enrich it with information gathered at earlier processes.
Conduct the Analysis	This phase is about conducting a change identification and business analysis, and result in an approval or rejection of the problem report. If the report is approved by the PLM side, the ERP side perform a business analysis of the change.	At ASML, an analysis is conducted in three phases. In the first phase, a cross-sector team (including EF) analyze on the boundaries for the EC to be implemented, for example, if older parts can still be used. Next, the conceptual design of the new part can be made and based on that, suppliers and customers are involved in the process by analyzing the impact of the EC. In that phase, a proposal is made on how to manage misalignments regarding the configurations of machines, and the business impact for the EF is also assessed. Last for the analysis phase, the EC is accepted and a ECN is created.

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[1] At ASML, there are two ECM process flows, where one ECM process flow is specific for the SRC module. Since most ECs are related for the SRC module, we compared that workflow with the framework of Wu et al. (2014)

Planning the Change	This phase plans the implementation of the change by collaborating with the relevant suppliers. If accepted, an ECN records the plan on PLM side. For the ERP side, the activity is described as *devising a manufacturing schedule associated with the product data to be changed, including outsourcing to the suppliers on the ERP side*	This phase has several similarities with the description provided by Wu et al. (2014). On a high-level, the steps are the same, and we therefore do not go into details for this step. Before releasing the EC, ASML has an additional step *commit to plan*, where the scheduled delivery dates of the new or upgraded parts are managed.
Release the Change	When an ECN and the implementation plan are approved, the product structure and the documentation are upgraded on the PLM side before releasing it to the ERP side. At the ERP side, a small volume is manufactured and afterwards, the gap between actual vs. planned change is reviewed.	The description by Wu et al. (2014) is a good description of the process at ASML. At ASML, a *release package* is released and the gap between the actual vs. the planned change is reviewed in the *secure implementation* activity in the process.
Change Product Configuration	In this phase, the history of the EC of new product versions are made traceable, so that the end-products can be recalled when an issue is identified.	In ASML's process description, it is stated that the configuration baselines are changed. The change specialists then monitor if these actions take place based on the effective delivery dates of the parts. By changing the baseline, the history can be reviewed.