Data-driven Priority Setting for Improvements on Service Procedures and Sequences

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Management summary

This research is executed within the Customer Support Extreme UltraViolet (EUV) Service Engineering Department at ASML in Veldhoven. The solutions are scoped for the installed base of the New Generation TWINSCAN with EUV (TWINSCAN NXE machine).

The **service procedure and sequence** improvements are implemented because the Service Engineering organisation aims to diagnose, repair, and recover systems with minimal customer downtime and at maximum quality. A procedure is a so-called work instruction, and a sequence is a series of these work instructions. Due to the complexity of the NXE machine, one or more sequences are required to perform a complete service action. These procedures and sequences are part of the **Service Mix**, which encompasses everything required to service a system in a customer's factory.

The Customer Support EUV Service Engineering department processes different types of **Service Mix Feedback** or feedback on procedures and sequences; **procedure comments, sequence comments, auto-comments and de-nesting work**. On one hand, procedure or sequence comments are provided by Field Service Engineers stationed around the world, working directly with the machines. On the other hand, auto-comments, created by scripts, identify issues such as incorrect information within procedures. Additionally, automated feedback highlights when procedures are interlinked, causing delays in service action execution. These interlinked procedures require de-nesting to streamline the process.

The Service Engineering department is processing almost **14,000** of those different Service Mix feedback items per year. All those reviewed feedback result in a certain gain. The competence engineers are processing comments on a first come, first served basis. Nonetheless, in the coming 5 years, ASML will introduce multiple new machine types within the field. With the introduction of new machine types, there is a rise in feedback from Field Service Engineers as they go through a learning curve. **This increases the overall workload**, yet the number of engineers remains the same. Additionally, the lack of an accurate global overview of the number and actual execution time of service activities in the field means that Service Mix Feedback prioritisation relies largely on intuition and the experience of competence engineers, **resulting in inefficient use of resources**.

However, ASML has access to global data on procedure opens, sequence exports and spare part usage, which collectively reflect the number of service activities executed in the field, resulting in the following research question:

How can the prioritisation of procedure and sequence improvements be effectively enhanced within the CS EUV Service Engineering Department?

The literature review and deeper context analysis provide knowledge essential for identifying methods to measure comment impact. This work was further supported by a survey completed by eight competence engineers and seven group and product leads, which enabled the application of the **Analytical Hierarchy Process (AHP)**. In this survey, participants were asked to rank the prioritisation factors based on procedure and sequence characteristics and to rank Service Mix feedback types and their respective comment types and priorities.

The result of the Analytical Hierarchy Process (AHP) method is used to set the factors for both the prioritisation factors based on procedure and sequence characteristics and the Service Mix feedback types.

A service mix feedback ticket always has a corresponding **Service Mix Feedback Type** consisting of a procedure comment with comment type human safety, technical, configuration, and typographical, a sequence comment with comment type technical, configuration, and typographical and priority from low, medium, high to critical, an auto-comment, or a de-nesting task.

The impact of a ticket can be based on the following five factors based on procedure and sequence characteristics:

1. **Frequency**: Procedure or Sequence executed per week in the field.
2. **Comments**: The total number of comments per procedure or sequence since release.
3. **Execution Time**: The execution time of a procedure or sequence.
4. **Also Used in New Product Introduction (NPI)**: A procedure or sequence is used in both existing and new products.
5. **Field Service Engineers**: The number of Field Service Engineers involved in the particular procedure or sequence.

The **Simple Impact method** takes into account only the frequency; the **Medium Impact Method** considers the frequency and execution time, and the **Advanced Impact method** considers all five factors by using the AHP method and normalisation.

The total value of a ticket is a combination of the impact of a ticket depending on the sequence and procedure characteristics and the weight of a ticket depending on the Service MIX Feedback type.

$$Value\ of\ a\ Ticket = Impact\ of\ a\ Ticket * \text{Weight of a Ticket}$$

When it is possible to measure the ticket value in a data-driven way, it is possible to make a prioritisation model to further enhance the research. This model includes historical data on procedure comments and historical data on the arrival rate of sequence comments, auto comments and de-nesting work.

Conclusions

- Figure 0.1 illustrates that, after 13 weeks, the new Advanced Impact method achieves a cumulative ticket value that is 59% higher than that of the historical approach. While the historical method reaches a total ticket value of 4.85 by the 13-week mark, the Advanced Impact method achieves this same value in under 9 weeks. This indicates that the Advanced Impact prioritisation method **accelerates ticket processing**, reaching the total ticket value nearly a month faster.
- With a 20% engineer capacity, three clusters face a rising backlog due to fully utilised capacity. Similarly, at a 10% engineer capacity, five clusters experience an increasing backlog, while the remaining eight clusters have sufficient capacity. This imbalance in resource allocation highlights **an unbalanced division of capacity across clusters**. The cluster-specific model underscores this difference, as some clusters are unable to keep up with demand, leading to rising backlogs.
- The Advanced Impact model **performs more effectively under conditions of limited capacity**. As more machine types are introduced in the field, this will increase comments, and the available capacity will become tighter. With a constant number of engineers, prioritisation will become increasingly valuable, allowing resources to be directed where they are most needed and enhancing overall efficiency.

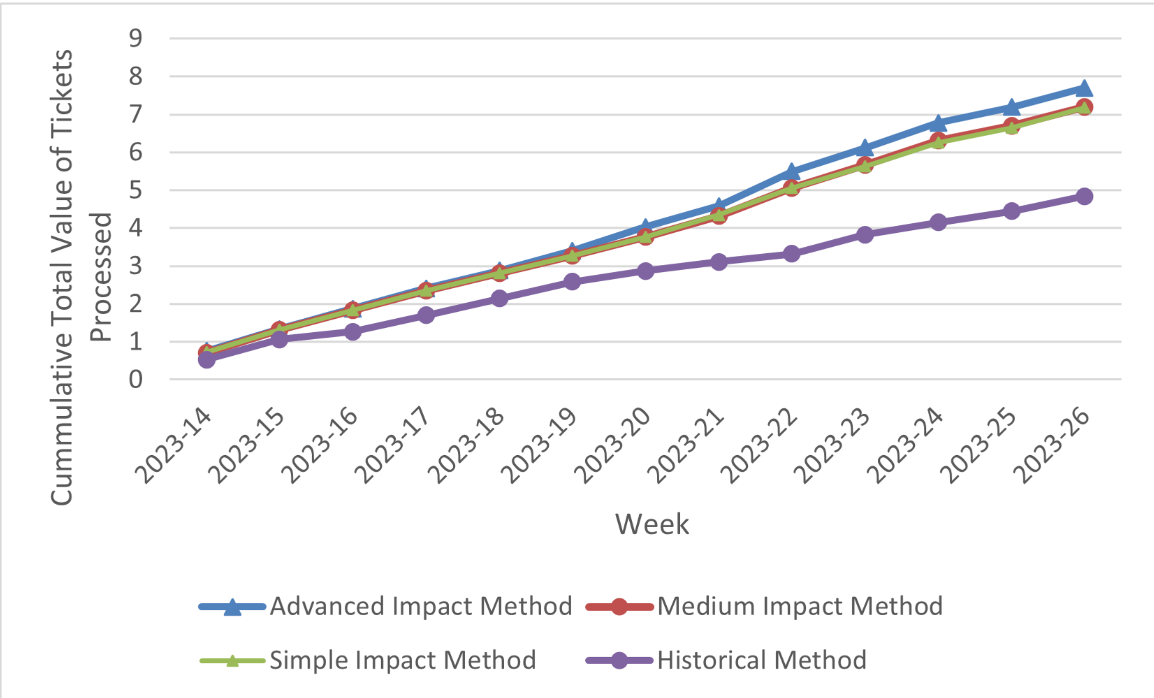

Figure 0.1: Historic compared to the Advance, Medium and Simple Impact Method with 10% Competence Engineer Capacity (4 hours per week)

Practical Contribution: The model serves as a guide for prioritising tickets, making it applicable to current backlogs, and supports the de-nesting process by identifying high-priority procedures, which involve large lists of interlinked procedures.

Preface

Dear reader,

You are about to read the master thesis titled "Data-driven Priority Setting for Improvements on Service Procedures and Sequences". This research is conducted at ASML, located in Veldhoven, the Netherlands, as the final assignment for my Master's in Industrial Engineering and Management at the University of Twente.

I am thankful for the help, guidance, and endless possibilities within ASML. I am proud to have taken on the challenge of moving to a new city and completing my studies at such an innovative, market-leading company. From the diverging phases to the converging stages, I have always felt intrinsically motivated to improve. Therefore, I would like to thank Marit Rijpert and Giel Passier, my two ASML supervisors, who kept me going throughout this journey.

I would also like to thank my colleagues within the CS EUV Service Engineering System team and department for allowing me to attend numerous meetings and present and refine my work. Writing a thesis can sometimes feel like being on an island, but colleagues were almost always available for a chat or lunch.

Special thanks go to Matthieu van der Heijden for his guidance and for always finding time for our regular meetings during my visits to Enschede or online. I would also like to thank my second supervisor, Ipek, for her valuable tips and critical feedback.

Lastly, I am grateful for the conversations I had with fellow interns at ASML and especially for the support of family and friends throughout this research.

But enough with the beautiful words — I hope you enjoy reading this thesis.

I look forward to continuing to improve!

Best regards,

Jimmy van Santen
Eindhoven, November 2024

Reader's Guide

This master thesis provides how the research within the ASML Customer Support Service Engineering department is performed. This reader's guide briefly introduces the chapters.

Chapter 1: Introduction
Serves as an introduction to the problem by providing the context of the problem with an explanation of global service activities and machine availability and loss—guiding the reader towards the CS interventions with the most improvement potential. For this intervention, the problem identification phase provides the problem cluster and core problem, ending with the availability of data and the research design.

Chapter 2: Context Analysis
After identifying the core problem, this chapter provides the current working method and performance metrics. It provides a stakeholder analysis and a process analysis on procedures, auto-comments, sequences, and de-nesting tasks—followed by a data collection and validation on how the data on the different Service Mix feedback types can be collected and used. It ends with the bridge to the literature review.

Chapter 3: Literature Review
Provides a literature study on the specific case where research is done on different work prioritisation models and a quantitative process analysis to better understand the problem—concluding how the literature can be used as a foundation for the following chapters.

Chapter 4: Methods for Measuring the Comment Impact
First, the two categories with multiple variables to consider for prioritisation are introduced: the prioritisation factors connected to procedure and sequence characteristics and the factors connected to the different Service Mix Feedback types with their priorities and comment types. Then, a survey is conducted to rank these factors, and based on the survey, the Analytical Hierarchy Process method is executed. A Simple, Medium, and Advanced impact model are constructed to measure the comment impact, in which the advanced impact model takes into account the factors found with the AHP method.

Chapter 5: Model and Results
The general model and the model per cluster provide the basis to use the method to measure comment impact from Chapter 4. With a developed method to measure the comment impact, it is possible to see how the new method behaves over time, but it is also possible to see the difference with the old method, all based on the developed score.

Chapter 6: Conclusions and Recommendations
This section provides the conclusion, recommendations, and limitations of the research.

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List of Abbreviations

AHP Analytical Hierarchy Process.

CARS Common Access & Recovery (or Repair States).
CS Customer Support.

D&E Design and Engineering.
DDF Deterministic Diagnostic Flow.
DOA Dead On Arrival.
DR Design-Related.
DUV Deep Ultra-Violet.

EUV Extreme Ultra-Violet.
EXE Extended EUV.

FCO Field Change Order.
FSE Field Service Engineer.
FTE Full Time Employee.

KM Knowledge Management.

LH Labour Hours.

MOID Manageable Object IDentifier.
MPSM Managerial Problem-Solving Method.
MTTD Mean Time To Diagnose.
MTTR Mean Time To Repair.

NDR Non-Design Related.
NPI New Product Introduction.
NXE New Generation TWINSCAN with EUV.

PGP Product Generation Process.
PM Preventive Maintenance.

ROI Return On Investment.

SAT Site Acceptance Test.
SD Scheduled Downtime.
SDS System Design Specification.
SLA Service Level Agreement.
SMD Supplier Maintenance Delay.
SMIX Service MIX.

TPMS TWINSCAN Parameter Monitoring System.

USD UnScheduled Downtime.

WIP Work In Progress.
WPD Wafers Per Day.

XLD eXtreme Long Down (>12h).

1 Introduction

This master's thesis is conducted within the Customer Support (CS) Extreme Ultra-Violet (EUV) Service Engineering department at ASML and Section 1.1 provides the company description. Section 1.2 provides background information on the context of the problem. Consequently, Section 1.3 provides the problem identification phase. Then Section 1.4 discusses the availability of data and 1.5 focuses on the research objectives and questions. Finally, 1.6 provides the problem-solving approach with the stakeholders, scope, and project timeline.

1.1 Introduction to ASML

ASML is a technology leader in the semiconductor industry, specialising in the designing and manufacturing of advanced lithography machines essential for chip production. Based in Veldhoven, the company's technology enables the creation of smaller, more efficient chips that form the basis of a wide range of modern electronics. These chips are printed on a wafer, a thin slice of semiconductor consisting of silicon. With a focus on EUV and Deep Ultra-Violet (DUV) technologies, ASML plays a critical role in advancing computing power and efficiency to meet the increasing demand for high-performance semiconductor components.

ASML has two machine types with EUV technology, which are the New Generation TWINSCAN with EUV (NXE) and the Extended EUV (EXE) machine. This thesis focuses on the machine availability of the NXE machines as depicted in Figure 1.1. ASML's NXE lithography systems are a revolutionary development in the semiconductor manufacturing sector. These systems were the first to print microchip features with an unprecedented 13 nanometer (nm) resolution thanks to ASML's groundbreaking 13.5 nm EUV light source. This kind of accuracy is not possible with conventional DUV lithography and is necessary for the manufacturing of advanced logic and memory chips. They are primarily utilised for printing the complex foundation layers of cutting-edge 7nm, 5nm and 3nm nodes. The NXE systems play a key role in advancing the transition from theoretical concepts to realistic, high-volume manufacturing solutions (ASML, n.d.-b).

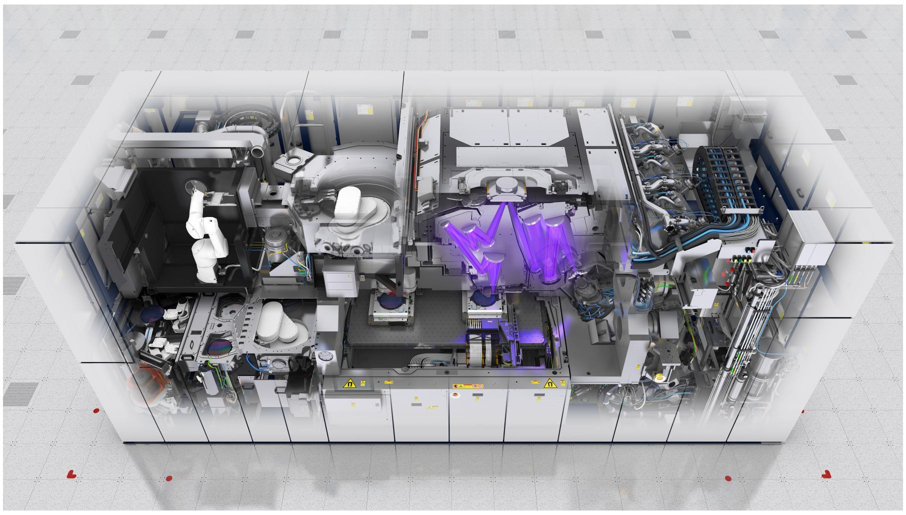


Figure 1.1: Overview NXE machine

This master thesis is conducted within the CS EUV Service Engineering department at ASML. This department enables CS EUV Field Operations to maintain, repair, and continuously improve ASML EUV systems at customer locations worldwide. CS EUV is accountable for the machine after installation at the customer's site and the Site Acceptance Test (SAT) is completed. This means that the operations are primarily active in the customer domain. However, due to the complexity of the machine and the focus of the CS department on serviceability, the involvement of CS EUV Service Engineering starts earlier in the Product Generation Process (PGP). This means the department is involved from the start of the design process for a new machine to incorporate the added value of CS in design, with a broader mission to make the job of field service engineers easier so they can serve customers efficiently and effectively (ASML, 2024e).

With the service activities on the installed base, the goal is to enable local teams to serve customers at Service Level Agreement (SLA) and cost. The customer service value depends on three fundamentals:

1. High machine availability and minimal long-term downs.
2. Lowest possible service cost per wafer.
3. Maximum good Wafers Per Day (WPD).

1.2 Context of the Problem

Before introducing the problem context, it is important to note that this section aims to explain my research by providing an overview of how ASML conducts its service activities in Section 1.2.1, measures machine availability in Section 1.2.2, identifies components of availability loss in Section 1.2.3, and assesses Customer Support (CS) interventions and their impact in Section 1.2.4. From this analysis, the problem is identified in Section 1.3, focusing on the CS intervention with the greatest impact on availability. The problem identification will specifically address this intervention.

1.2.1 Enabling the Global Service Activities

The NXE installed base continues to grow. At the introduction of EUV, it was easy for employees to remember the series numbers, locations or responsible colleagues for the specific machine. However, with the current fleet of machines stationed at customer locations growing more and more, those days are over. Nowadays, machine performance data is collected via various sources: worldwide, region, factory, machine, machine-module, and part-specific level, all the way down to specific parameters. CS EUV and specifically, the Service Engineering department collects all this performance data, and they use it as input in the decision process to implement their solutions. The Service Engineering department enables thousands of local operational support and field engineers. The increase in machine fleet and operational engineers raises the demand for more scalable, standardised methods. All these methods together drive the mission to enhance efficiency in the field.

Furthermore, the service entails an execution of Service MIX (SMIX) in the field consisting of 6S: Specifications, Service Tools, Sequences, Site Readiness, Skills & Knowledge, and Spare Parts. It describes everything that is needed to service a system in a customer factory (ASML, 2023c). These are, for example, the procedures and sequences available to execute the service action, the engineering skills in the field, the quality and availability of parts and tools, and finally (and most importantly), safety concerns. Figure 1.2 shows that the service activities have a certain complexity, duration, frequency, and failure mode that result in a certain activity impact.

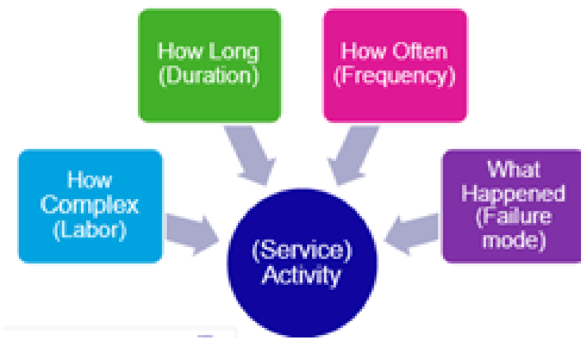


Figure 1.2: The Service Activity
Note. Figure from (ASML, 2023d)

Moreover, the following highlights the significance of machine availability: A customer loses production if a single machine is unable to produce wafers, and this downtime can cost them up to €72.000 per hour. This is why customers attach high value to reliable and continued support (ASML, 2024a). The ASML machine is essential in the chip-making process, and continuous production is needed for the customer to ensure a better Return On Investment (ROI). Furthermore, if ASML cannot live up to the SLAs regarding machine availability, this results in negative consequences for ASML. The goal is to improve this overall machine availability as much as possible. Section 1.2.2 elaborates on this goal and explains the machine availability measured with the SEMI E10 standard. The CS service products are purchased by customers through a SLA. SLAs describe a level of commitment from ASML towards customers on:

- Machine performance (e.g. uptime, eXtreme Long Down (>12h) (XLD), good WPD).

- Manpower support (e.g. 1st, 2nd line support).
- Part usage & delivery.
- Miscellaneous: Remote Diagnostics, Documentation, Self-Service Package, etc.
- Projects: Upgrades, Installs, Relocations.

1.2.2 SEMI E10 Availability

This thesis focuses on machine availability improvement within the limitations of the CS EUV Service Engineering department. The machine availability is the percentage of time the system can perform its intended function, and it is part of the machine's performance. Consequently, it is essential to understand how ASML measures their machine availability. This is done by using the SEMI E10 standard developed by the semiconductor industry itself. This is a methodology for tracking and evaluating the application of information from equipment regarding its operating condition. The SEMI E10 standard establishes a common language and methodology between equipment suppliers and customers (Pomorski, 2009).

Figure 1.3 shows the SEMI E10 state chart with the equipment states and aggregation of those states to understand how the availability is measured. Below a list of definitions of all the states (ASML, 2022b).

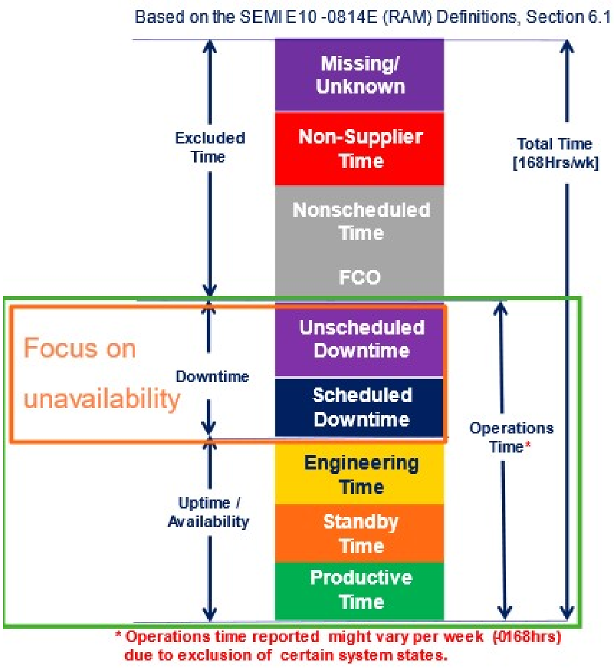


Figure 1.3: Breakdown of SEMI E10 standard
Note. Data from ASML (2022b)

- Missing/Unknown Time: Time that cannot be attributed to a specific system state due to missing data, unknown system state, or other reasons.
- Non-Supplier Time: The (un)scheduled state where an equipment system cannot perform its intended function, attributed to a customer-induced failure, action, or decision. These events can be scheduled (e.g. facility maintenance) or unscheduled (e.g. the time it takes to track a facility issue).
- Non Scheduled Time: The unplanned or unscheduled state where an equipment system cannot perform its intended function. This bucket contains commercial upgrades, installation, modification, or rebuilding.
- Field Change Order (FCO): Reporting FCO is taken as a separate bucket. From a design point of view, FCO is not part of Operations Time. FCOs are changes to reach agreed system specifications.
- UnScheduled Downtime (USD): The state where an equipment system cannot perform its intended function. It starts when the equipment system has experienced a failure event and lasts until it is restored to a condition where it performs its intended function (including "scheduled" repair or faulty part).

- Scheduled Downtime (SD): The state when the equipment is not available to perform its intended function due to scheduled or planned time events. This might consist of Preventive Maintenance (PM) actions.
- Engineering Time: The state when the equipment system is in a condition to perform its intended function, but is operated to conduct engineering experiments
- Standby Time: The state, other than the nonscheduled state, when the equipment system is in a condition to perform its intended function and consumable materials and facilities are available, but the equipment system is not operated.
- Productive Time: The state in which the equipment system is performing its intended function, where the intended function includes performing within the specified operating conditions for which the equipment system was built and configured.

The machine availability is calculated with the SEMI E10 standard. Why is it so important? To calculate the machine availability, the SEMI E10 standard prescribes that the machine availability:

$$\frac{Operations\ Time - Downtime}{Operations\ Time} * 100\% = \frac{Operations\ Time - (SD + USD)}{Operations\ Time} * 100\%$$

After an introduction on how ASML CS EUV enables the global service activities and introduction to how they are measuring their machine availability brings us to the components that result in availability loss in Section 1.2.3.

1.2.3 Availability Loss and Components

This Section provides the components and the actual number on availability loss.

As already stated in the previous section, the internal goal of ASML is to increase NXE machine availability. This goal is set based on the improvement ASML wants to make and based on design-related and non-design-related solutions that are going to be implemented in the field. All the ASML systems as well as the ASML NXE machines are designed on a certain availability level which is set in the System Design Specification (SDS). This SDS is the responsibility of the Design and Engineering (D&E) department. In this context, it is important to understand the impact of key variables that change overall availability. The availability loss is measured either in hours per system per year or in percentage of Operations Time. This can be, for example, an Unscheduled Extreme Long Down (USD XLD) or a Scheduled Extreme Long Down (SD XLD) with an availability loss in hours.

$$Availability\ Loss = Frequency * Repair\ Time\ (MTTR)$$

The availability loss depends on the duration and the frequency of the service activity. The frequency of both USD and SD are measured. For USDs, a specific diagnosis can be related to a failure mode that results in a corresponding service action. The time to diagnose this failure mode is the Mean Time To Diagnose (MTTD). The activity duration is of high importance to the customer as stated in Section 1.2; in other words, the machine is down and needs to be diagnosed and fixed as quickly as possible; due to the turnover that the customer cannot make during downtime. This is the Mean Time To Repair (MTTR): the average time to repair a machine from an inoperable state and represents the total duration of a service activity. Figure 1.4 shows a breakdown of the duration of a service activity. Including a legend for the accountability of optimal execution time and the delay for which either CS, D&E, or the customer is responsible. In these situations CS is responsible after the machine is installed at the customer location.
An elaboration on the breakdown of the MTTR:

- The Optimal Execution Time (A-time): diagnosing the failure MTTD, accessing the machine, repairing the machine and ultimately recovering the machine.
- The Supplier Maintenance Delay (SMD):
  - Downtime Waiting Engineer (DTE): waiting time for engineers to travel to the customer factory, either from the local offices or from central or suppliers for expert support.
  - Downtime Waiting Parts or Tools (DTP/T): waiting time for parts and or tools to arrive at the customer factory, either from the Local Warehouse (2 hrs) or the Global Warehouse (48 hrs).
- The Unplanned Delay in Execution Time (B-time) consists of (ASML, 2023c):

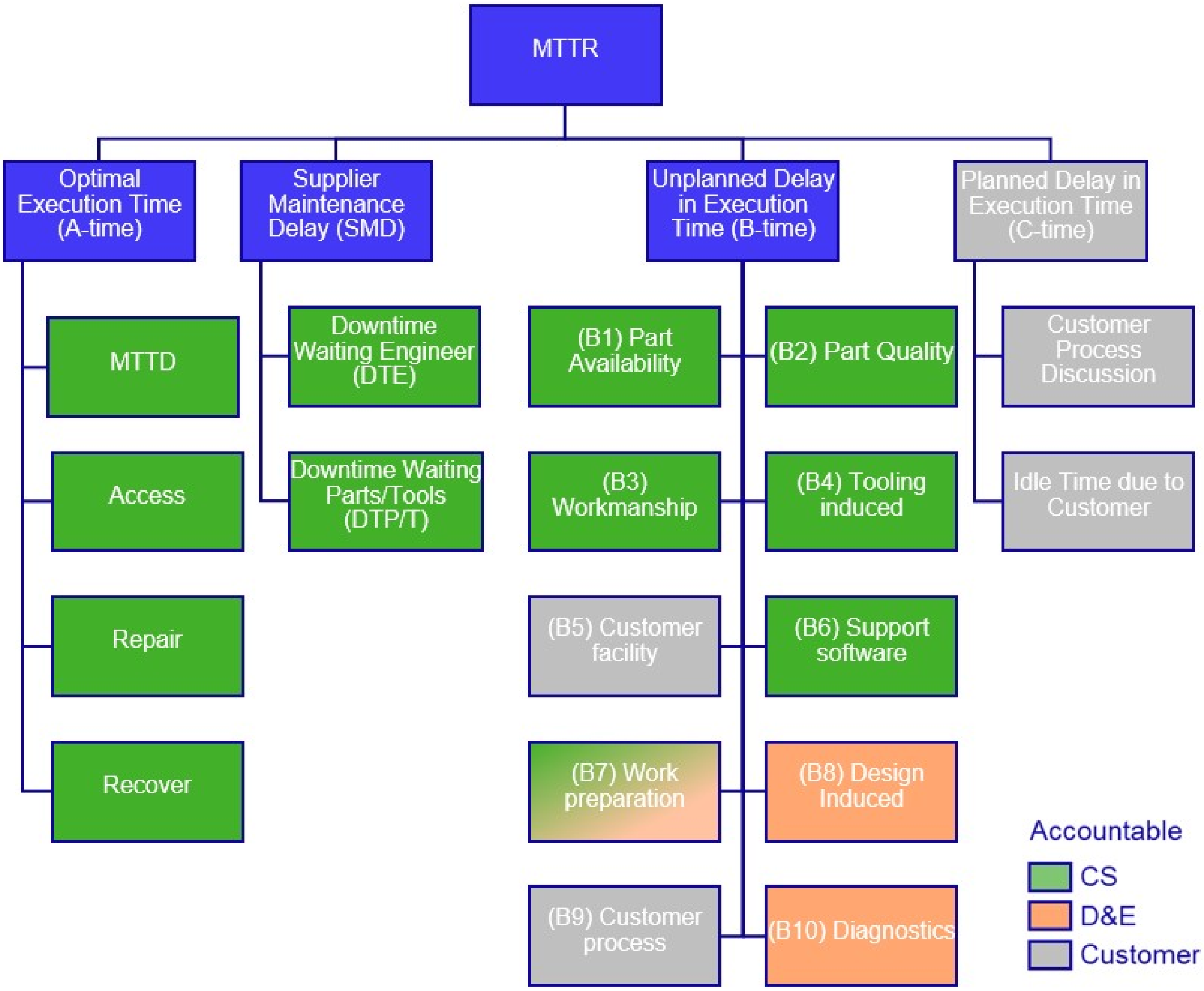


Figure 1.4: Breakdown of MTTR with Legend
Note. Figure from (ASML, 2024b)

- B1: Part Availability (not available or wrong part).: representing a spare part availability disturbance; work is delayed because the required materials have not been delivered on time according to DTP/T (SMD). Time beyond agreed Supplier Maintenance Delay (SMD) is B1.
- B2: Part Quality: delivered material (spare parts) are not functioning, not complete, or incorrect.
- B3: Workmanship: damage on the system or additional delay due to an engineer's action.
- B4: Tooling induced: delivered tools are not functioning (Dead On Arrival (DOA)), not complete or incorrect.
- B5: Customer Facility: time lost due to customer facilities or utilities.
- B6: Support software: any of the CS operational support tooling down or unavailable. This support tooling consists, for example, of a HoloLens to support engineers in the field during escalation or the equipment performance server located at the customer.
- B7: Work preparation:
  * B7-1 SMIX: time lost due to missing or incomplete procedures and or sequences.
  * B7-2 Local Work Preparation: time lost due to incomplete local work preparation.
- B8: Design induced: time lost due to design issue.
- B9: Customer process: time lost due to customer processes in the critical path during USDs.
- B10: Diagnostics: missing or incorrect diagnostics.

- The Planned Delay in Execution Time (C-time) consists of:
  - Customer Process Discussion.
  - Idle Time due to Customer.

The MTTR represents all the downtime components per machine. Due to opportunity-based maintenance, the critical or longest service activity represents the downtime on a machine, and other service activities are executed in the shadow of this critical activity. Opportunity-based maintenance strategies are designed to optimize maintenance activities by executing service actions in parallel, thus reducing machine downtime (Kuhnle, Jakubik, & Lanza, 2019). Downtime is the time it takes to diagnose the failure mode, access the module or part within the machine, time to repair and finally recover the system.

The components in figure 1.4 can be influenced by CS EUV either directly, or indirectly, by working together with D&E or with the customer. The centre of attention will be solely on the green squares because CS has a direct impact on these squares. However, SMD is not taken into account due to limited data available. That is why the next paragraph only elaborates on the actual unplanned delay in execution time (B-time).

The Actual B-time Components
Table 1.1 provides the actual breakdown of B-time components. This breakdown is based on one customer factory: factory A. This factory has multiple ASML NXE machines and represents the components of unplanned delay in execution time (B-time) for 13 weeks (ASML, 2023b). This table illustrates how much availability ASML loses per system due to an unplanned delay in execution time over 13 weeks. The table is ranked in descending order; thus, the component with the highest availability loss is ranked first, and the component with the lowest availability loss is ranked last.

Table 1.1: Actual B-time Components Factory A.

B-bucket	**AV Loss**
B8 - Design Induced	Critical
B2 - Part Quality	High
B10 - Diagnostics	High
B7 - Work preparation	High
B1 - Part Availability	Medium
B9 - Customer Process	Medium
B0 - Undefined	Low
B5 - Customer Facility	Low
B3 - Workmanship	Low
B4 - Tooling Induced	None
B6 - Support Software	None

Note. From (ASML, 2023b)

1.2.4 CS Interventions and Impact

This section provides the solution package of the CS EUV Service Engineering department and provides an overview of the executed interventions—ultimately resulting in the most important intervention where the problem identification will focus on in Section 1.3.

All these actions are focused on predicting, preventing, or reducing the impact of machine failures. As stated in Section 1.2.2 the impact of the CS EUV department on machine availability is related to part availability (B1), part quality (B2), workmanship (B3), tooling induced (B4), support software (B6), and work preparation (B7). In addition to the components mentioned above the interventions have an impact on Supplier Maintenance Delay (SMD) related to downtime due to an engineer, part, or tool—and there is an impact on the MTTD and the time to access, repair, and recover. The example in Table 1.1 indicates the impact of CS on machine availability.

The following are examples of CS EUV Service Engineering interventions, along with Table 1.2 that indicates which downtime components of the CS EUV Service Engineering have an impact.

1. Prediction: From UnScheduled Down (USD) to Scheduled Down (SD).
2. Prevention through Periodic Maintenance (PM).

3. Prevention through Knowledge Management (KM).
4. Prevention and reduce impact through the Service MIX (SMIX).
5. Reduce impact through Diagnostics.
6. Reduce impact of Downtime Waiting Part (DWP).

	Category					
	Prediction	Prevention	Prevention	Prevention & Reduce	Reduce	Reduce
	Solution					
Downtime Component	**USD to SD**	**PM**	**KM**	**SMIX**	**Diagnostics**	**DWP**
(B1) Part availability	X	X		X		X
(B2) Part Quality						
(B3) Workmanship	X	X	X	X	X	
(B4) Tooling induced						
(B6) Support Software						
(B7) Work preparation	X	X	X	X		
SMD: DTE	X	X				
SMD: DWP/T	X	X		X		X
MTTD	X	X	X	X	X	
Acces, Repair and Recover			X	X		

Table 1.2: Impact interventions on downtime components

1. **Prediction; From USD to SD**.
ASML uses parameter monitoring system dashboards. These dashboards monitor multi-machine parameters in the field. The Service Engineering department delivers new or updated current parameters to predict machine failure and ensure the machine remains within specifications, not exceeding acceptable limits. Consequently, this results in less USD and only SD maintenance or repairs. These activities are mainly planned and performed in the shadow of other PM activities. The benefit of having a SD is that you have time to prepare, and this impacts multiple downtime components. The downtime waiting for engineers, parts, tooling, and all the other work preparation can be done beforehand, all reducing the availability loss. Table 1.2 provides an overview of the intervention's impact on downtime components.

2. **Prevention; PM.**
Introducing or adjusting the current SDs and periodic maintenance to prevent part failures or, in other words, USDs. PM means that ASML can prepare their work and reduce the availability loss. Table 1.2 shows the impact of the intervention.

3. **Prevention; Knowledge Management (KM).**
Through training, skills and Best-Known Methods (BKM). KM drives site-to-site benchmarking, delivers knowledge transfers, and drives for new skill introduction. All this prevents workmanship issues, improves work preparation, and reduces time to diagnose, access, repair, and recover.

4. **Prevention and Reduce impact; SMIX**
Enables service engineers in the field and providing them with updated and correct procedures. Multiple procedures together represent a sequence, and a sequence represents a service action. The Service Engineering department creates new and updated procedures. Engineers in the field can comment on procedures and sequences to further improve the SMIX quality. To conclude, clear procedures and sequences prevent workmanship issues, make sure the service is well prepared, make sure that the correct part is there, and can even reduce the time to diagnose, access, repair, or recover.

5. **Reduce Impact; Diagnostics**
Creating new Deterministic Diagnostic Flow (DDF): a part of the Service MIX, which supports engineers in diagnosing machine failures effectively and efficiently. A DDF acts as a dynamic flowchart, in which an engineer is advised to follow a sequence of actions to discriminate the failure cause or mode involved. The flows are based on new hits seen in the field. Next to this, it is important to update existing DDFs by adding expert rules on new learning or issues. This all reduces the time to diagnose and for new hits. It reduces the unplanned delay in optimal execution time to zero and hence introduces the time to diagnose.

6. **Reduce Impact; Downtime Waiting for Part or Tool**
Secure or increase the Safety Stock Level (SSL) on critical parts and or tools and therefore, eliminate part and tool waiting times. Accordingly, this reduces the downtime due to material unavailability.

Table 1.3 refers to the overall impact of CS interventions. Processed comments are related to standard procedures, sequences, diagnostic procedures, and interlinked or "nested" procedures. The other Non-Design Related represent solutions as TWINSCAN Parameter Monitoring System (TPMS) dashboards, the creation of DDFs and other larger issues with a specific individual availability gain. The immediate impact is not directly measured, depends on multiple factors, and often does not result in a direct benefit. Consequently, the department makes generalized assumptions for all interventions, leading to limited accuracy in assessing their true impact. This is because a solution is customer-specific, depends on tool availability, or depends on engineering skills. However, CS EUV Service Engineering accomplishes the availability gain by covering more than 14000 comments yearly.

Table 1.3: Impact of CS interventions in 2023

CS Intervention	Solution	Numbers	Estimated Availability Gain
Service Mix	Procedure Comments	12946	High
Service Mix	Sequence Comments	418	Low
Service Mix	De-nesting	455	Low
Diagnostics	Diagnostics Comments	300	Medium
Other	Non-Design-Related	419	High
	Total	**14538**	

Note. from ASML (2024d)

The impact of a single intervention on machine availability is limited, but Table 1.3 shows that multiple interventions significantly increase overall availability when combined. The goal is to identify the intervention with the greatest potential for improvement. According to Table 1.3 and Service Engineering experts, the greatest improvement potential is in the Service MIX: Procedure Comments, Sequence Comments, and denesting tasks.

This is also the reason why this thesis focuses on the fourth CS EUV Service Engineering intervention: **Prevention and reducing impact through the Service MIX (SMIX)**. The goal is to optimise the Service MIX maintenance; within this maintenance or improvement, the Service Engineering department processes thousands of comments. They are processing these comments with a limited number of resources or engineers, and an increasing installed base could result in a higher workload.

1.3 Problem Identification

This section is conducted to find the core problem and uses the first phase of the Managerial Problem Solving Method from Heerkens and Winden (2017). This phase starts with providing the problem context in Section 1.2. This results in a list of problems and challenges provided in Section 1.3.1 and results in a problem cluster—the core problem.

1.3.1 Problem Cluster

This section constructs the problem cluster after conducting several semi-structured interviews with stakeholders. This results in a list of challenges and is the foundation of the problem cluster. This problem cluster identifies the core problem by tracking back to the cause of all problems. The CS EUV Service Engineering department has an aligned goal to increase machine availability. But to reach this goal, they need to overcome challenges, and it is important to understand that the impact of all interventions Design-Related (DR) or Non-Design Related (NDR) have their limitations. How can we reach the goal within the existing limitations of resources and interventions?

As mentioned in Section 1.2 , the CS EUV Service Engineering focusses on the SMIX quality. SMIX is part of the work preparation, a component within the unplanned delay in execution time (B-time). It is expected to have the largest improvement potential, and the Service Engineering department, with their interventions, has a direct impact on this part of the work preparation. Currently, CS EUV is working on their Service MIX based on the experience of competence engineers. With over 14.000 comments processed and a growing installed base, they prefer a data-driven situation that optimises the use of human and other resources.

As the problem context serves as a guide to narrowing the scope of the research, the focus of this thesis is on the maintenance of the SMIX – more specifically, the maintenance of procedures and sequences within the Service MIX. The problem context resulted in the following list of problems and results in Figure 1.5.

- The available data on procedure opens and sequence exports are not utilised.

- The tooling is unable to automatically log all service actions.
- There is no overview of the number and actual execution time of service activities performed in the field.
- Working on the SMIX maintenance is based on the gut feeling and experience of competence engineers.
- The NXE installed base will only get larger while the number of competence engineers working on the SMIX stays flat.
- The competence engineers' workload will increase.
- The Service Engineering department makes inefficient use of its resources.

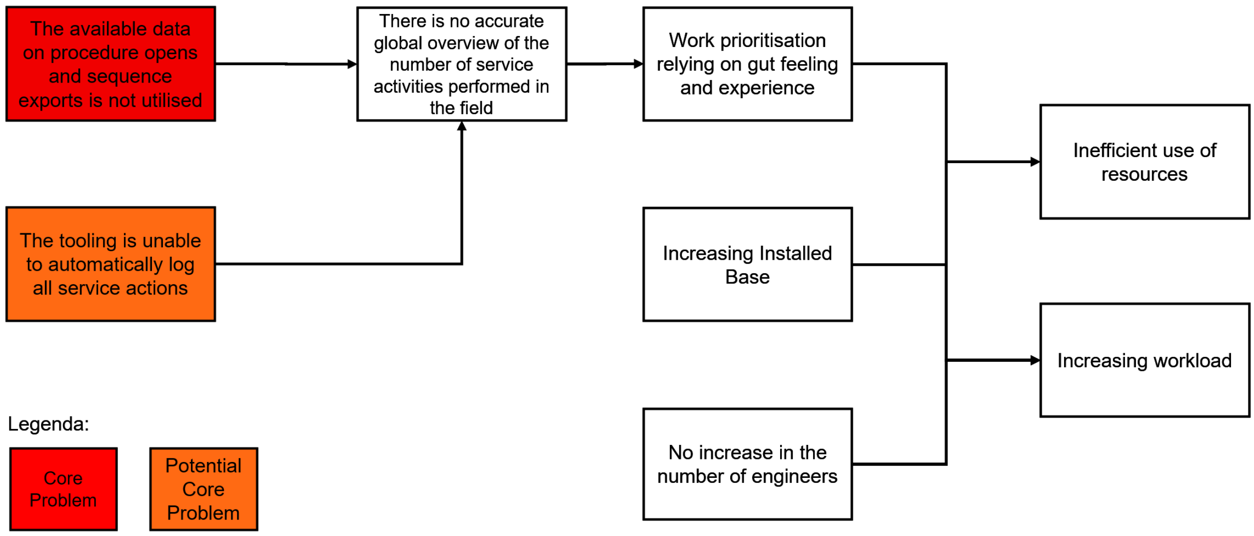


Figure 1.5: The Problem Cluster

1.3.2 Core Problem

This section defines and motivates the core problem. Figure 1.5 depicts the core problem in red; "The available data on procedure and sequence opens is not utilised". The core problem is the action problem that the research aims to solve (Heerkens & van Winden, 2017). This core problem is chosen because the other potential core problem in orange is too large to solve in the time frame of this research.

Norm: The prioritisation model for the Service MIX maintenance should update procedures and sequences based on data-driven insights. This model should take into account the number of service activities in the field and the actual execution time.

Reality: The current Service Mix maintenance prioritisation or method to update procedures and sequences is based on gut feeling and the experience of engineers.

Additionally, it is crucial to measure the discrepancy between the norm and reality. This can be achieved by comparing the current way of working with the new prioritisation approach. A score will be developed to quantify the comparison, highlighting the difference between the two methods. This score will demonstrate the benefit of the new prioritisation model by expressing the improvement in measurable terms, such as showing that the new method performs X percent better than the current approach.

1.4 Availability of Data

This section describes the availability of data, focusing on the essential Service MIX data available and its limitations.

- Procedure Details: with ProcedureID as Manageable Object IDentifier (MOID) or EPIC code, CS competence and metadata such as title, completion time, necessary persons, tools, and parts as Numeric Code (12NC).
- Procedure Opening Data: Frequency of opening procedure for a period of 11 months (April 2023 to February 2024).
- Sequence Opening Data: Frequency of opening sequences for 15 months (January 2023 to March 2024). Wherein a sequence is a sequence of procedures in order to execute a service action.
- Parts Data: Detailed records of parts used, focusing on usage frequency. With part description, main plant, machine, machine type, and customer.
- Comments Data: Documentation on the inflow and outflow of comments on procedures and sequences.

Data Limitations
The recorded opening times for both procedures and sequences do not guarantee that these were executed as a service action. These times simply log when an engineer, either in the field or the office, opened the procedure or sequence. Whether the opening was made by an engineer in the office or a field engineer is unclear. Therefore, validation is needed to ensure the logged openings accurately reflect field activity. However, the logging times serve as a representation of the service actions executed in the field.

1.5 Research Objectives and Questions

This section provides the research objectives and the research design, along with questions. The main research question is:

How can the procedure and sequence improvements be effectively enhanced within the CS EUV Service Engineering department?

To answer the research questions above, it is important to understand the current situation. Next to the current status, a deep dive into the literature is needed to create a functioning model and implementation plan.

1. What is the current status of the Service Mix and its maintenance?
   (a) Stakeholder analysis of the parties involved in the maintenance.
   (b) The future and current inflow and outflow of processing comments on procedures and sequences.
2. How can literature be used to find methods to improve Service Mix Maintenance?
   (a) A literature review focuses on work prioritisation models and tools that focus on work prioritisation with limited resources.
3. What methods can be used to measure the impact of comment in the service operation?
   (a) Making a Python prioritisation tool in cooperation with PowerBI and Python.
4. How to specify the improvement actions and measure the impact of the new way of working?
   (a) Comparison of the current with the new method, to get insight into the added value.

The goal is to make a prioritisation model and to improve the way of working to contribute to the enhancement of machine availability. The deliverables attached to this goal is a tested prototype in Python.

1.6 Research Design

This Section consists of Section 1.6.1 a stakeholder introduction, Section 1.6.2, the scope of the research and Section 1.6.3, the problem solving approach.

1.6.1 Stakeholders

First of all, the governance is provided by the CS Head of the EUV Service Engineering department together with the Head of the CS EUV Installed Base and Service Program. To understand the role of the stakeholders, it is important to address how Service Mix Maintenance influences their work. Within the CS EUV Service Engineering department, there is the Continuous Improvement department that proactively improves the SMIX quality. The benefit for them is that usage data creates insight into which Procedures or Sequences they need to work on.

Next to this department is the Competence Engineering department, which actively processes comments from engineers in the field. If they can do this more effectively, this will result in better resource usage.
Overall, this research involves these stakeholders with a broad perspective on how they are doing overall in terms of SMIX Maintenance.

1.6.2 Scope

The scope is from a strategic perspective because, in Veldhoven, the service operations are in central control. This centralized approach focuses on empowering local teams by providing the Service MIX, ensuring that the field service engineers can effectively execute service activities in the field, as described in Section 1.6.1.

In scope: The NXE installed spread all around the world. The impact of Service MIX on machine availability.

Out of scope: New product or machine introductions, which normally have more problem-solving capacity. The cost of service.

A consequence of the more strategic or centralized approach is that it is more difficult to measure the impact of Service MIX improvements on machine availability. Nonetheless, a small improvement applied to the entire fleet represents a greater impact.

1.6.3 Problem Solving Approach

This section provides the report structure by answering the research questions using the Managerial Problem-Solving Method (MPSM) methodology (Heerkens & van Winden, 2017). This method is applicable to various problems encountered in various situations in all areas of expertise in which the MPSM considers that the problem is embedded in the context of an organisation. It needs a fitting solution. The MPSM consists of the following phases:

1. Defining the problem
2. Formulating the approach
3. Analysing the problem
4. Formulating (alternative) solutions.
5. Choosing a solution
6. Implementing the solution
7. Evaluating the solution

Chapter 2 provides the current situation and describes how the Service Engineering department currently does Service Mix Maintenance by a process analysis. Next to the process analysis, semi-structured interviews will take place with the Continuous Improvement and Competence Engineering Teams. Consequently, the current situation is drafted in detail, with a deep dive into the current working method. All are part of analysing the problem and asking questions.

Chapter 3 provides the theoretical framework and the literature search to use the best work prioritisation methods and what to consider when building a prioritisation tool. Important for this Chapter is the preparation to find appropriate literature on various databases, such as Scopus. As well as relevant studies done at ASML or similar situations at different companies to determine the best methods found in the literature. The theoretical framework is part of analysing the problem.

Chapter 4 provides the methods for measuring the comment impact supported by the literature from Chapter 3 and the validation done with stakeholders is part of choosing a solution. Thus, using the literature to come up with methods to assess the impact of a comment for ASML. This Chapter is part of formulating (alternative) solutions and choosing the solutions.

Chapter 5 provides the model with the implementation of the plan when introducing this prioritisation method and compares it with the old way of working. It is part of the demonstration and evaluation. This requires a tool that automatically prioritizes procedures and sequences based on multiple weighting factors. This Chapter implements and evaluates the solution.

Chapter 6 provides the conclusions, recommendations, and limitations of the research.

2 Context Analysis

This section answers the first research question: What is the current status of the Service MIX and its maintenance? Section 2.1 starts with the current working method and performance metrics. Section 2.2 and Section 2.3 provide stakeholder and process analysis. The process analysis elaborates on the current maintenance of procedures and sequences. Finally, Section 2.5 provides the conclusion and bridge to the literature chapter.

2.1 Current Working Method and Performance Metrics

This section provides the metrics and current working method of the Service MIX Maintenance. It concludes with a comparison between the effort it takes to do this maintenance and the gain it provides for the ASML NXE Installed Base and so for ASML.

Currently, CS Competence Engineering processes all 14,000 sequences, procedures, and auto-comments a year. They are trying to solve all comments and issues on a first-come, first-served basis. Figure 2.1 represents the number of comments arriving at introducing a new machine type (NXE 3400B) in 2017. As with the introduction of other electronics, new machine types introduce more errors and challenges due to the complexity of engineering and design. (Elmaraghy, Elmaraghy, Tomiyama, & Monostori, 2012). Figure 2.1 shows that the number of comments increases after the SAT and that this increase ends after 2 years. Although this is just the introduction of 1 machine type, the logical assumption is that the effect will only be larger when introducing more machine types in a short time period and ASML will introduce multiple machine types in the coming 5 years. Being aware of this and the fact that the competence engineers' count within the service engineering department remains constant. With the introduction of multiple machine types and the number of competence engineers in the service engineering department remaining constant, engineers will face an increasing workload, resulting in a rise in WIP. This means that engineers need to be able to set priorities for their work on comments while currently, this is based on the experience and gut feeling of the engineers, and does not take into account the usage or relevance of procedures and sequences in the field.

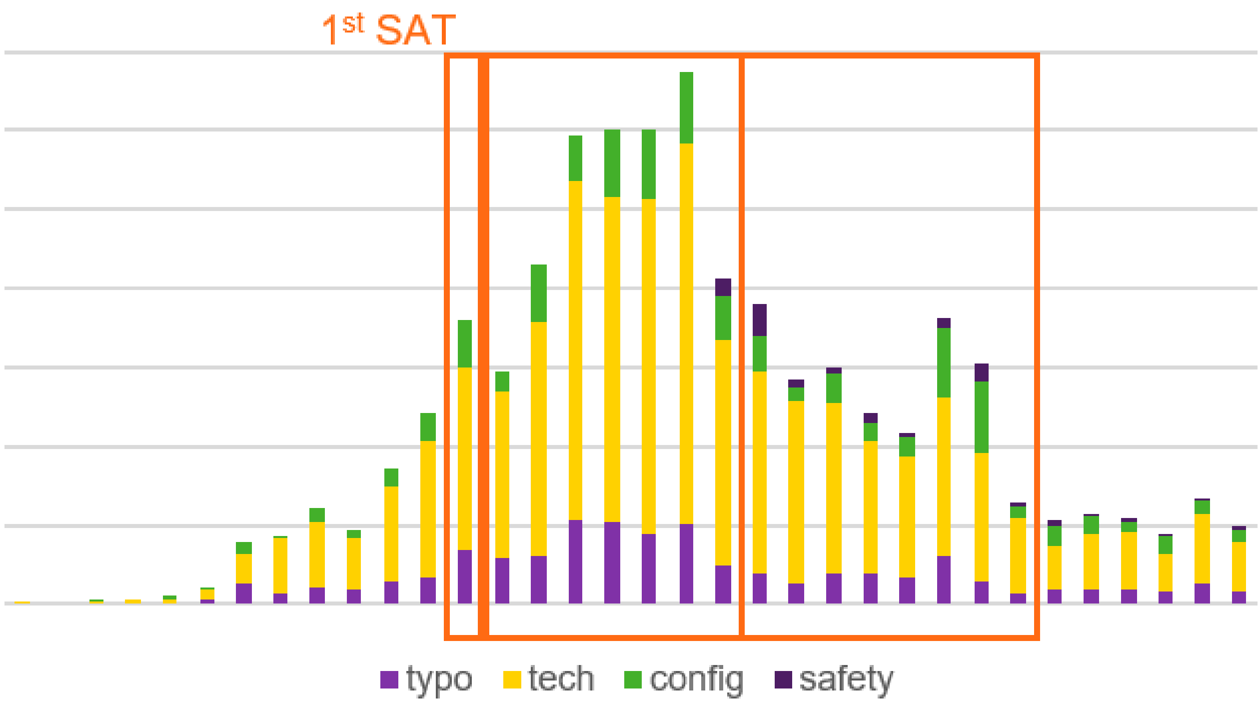


Figure 2.1: The number of comments for the NXE 3400B
Note. Data in Figure from (ASML, 2023a)

The number of comments processed results in a certain gain. Table 2.1 shows that for each of the solutions, ASML works with a business driver that can estimate the machine availability gain. Machine availability can be translated into monetary terms.

Table 2.1: Impact of CS interventions

CS Intervention	Solution	Numbers	Estimated Availability Gain	Effort per unit
Service MIX	Procedure Comments	6491	High	4 hours
Service MIX	Auto Comments	6455	Medium	0.25 hour
Service MIX	Sequence Comments	418	Medium	2 hours
Service MIX	De-nesting	455	Medium	4 hours
Total		**13819**		

Note. Data from ASML (2024d) and ASML (2024c)

Additionally, processing these comments takes time. For each solution component, ASML has a standard estimate of the number of hours it will take to process the comment (Effort per unit). Multiplying the effort in hours by the number of resolved comments gives the total number of hours spent by engineers on these comments. All these hours can be converted into the number of Full Time Employee (FTE)s working on these comments (Under the assumption that 1 FTE is equal to 1430 hrs). Dividing the total machine availability gain per system per year by the total FTE working on these solutions results in Figure 2.2. This figure shows the efficiency per FTE of the SMIX solution when using the standard norms for the gain and effort of the four different SMIX types. The graph shows that a sequence comment is the most efficient solution—and that a procedure comment is the least. However, a procedure comment is resolved more than ten times than a sequence comment. Although both the gain and effort norms are based on assumptions, they provide a strong basis for the business case for implementing these solutions.

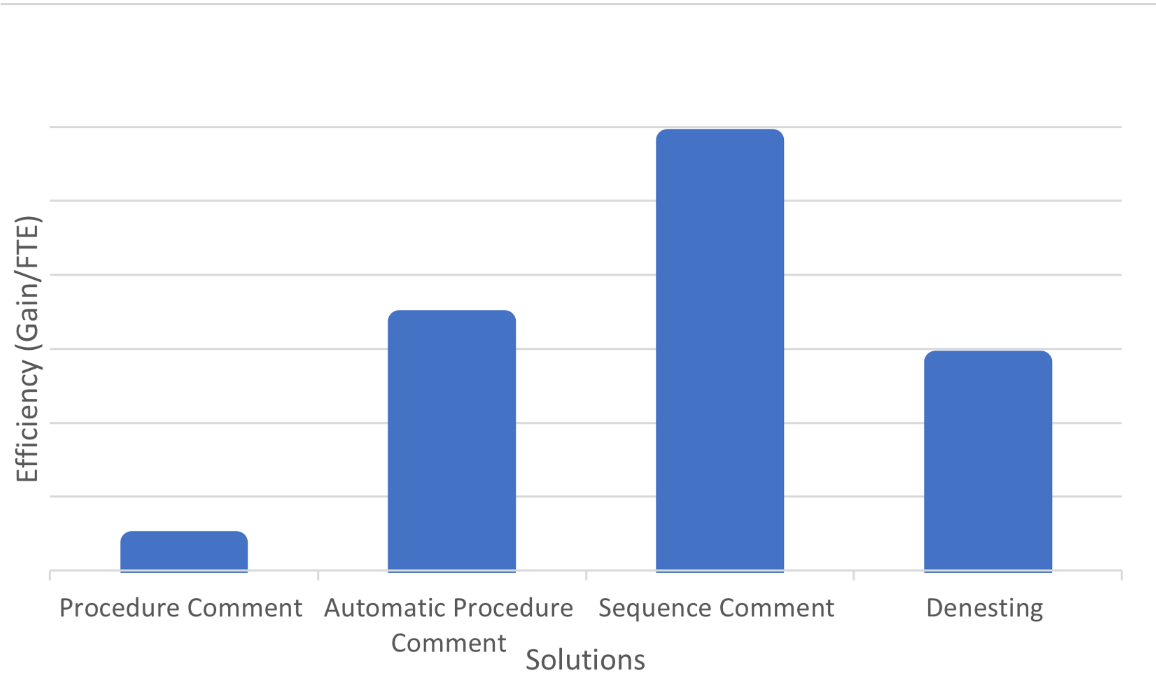


Figure 2.2: Efficiency of the SMIX solution
Note. Data based on Table 2.1

2.2 Stakeholder Analysis

To further explain the stakeholders within the Service MIX maintenance process, or more specifically, the maintenance of procedures and sequences, it is good to address the two involved departments within CS EUV Service Engineering: Continuous Improvement and Competence Engineering.

The Competence Engineering department is divided into 8 clusters, each representing a section of the machine: the Tin Supply, CO2 Laser, Body & Vessel, Optics & Collector, Metro & Software and Bottom Clamps & Defectivity. All are represented by a group lead. Next to the competence engineers, there are product leads who have the responsibility, for example, for the installed base and service product. The number of engineers in each CS cluster varies, ranging from 7 to 20; the Competence Engineering department represents about 80 engineers. They are responsible for the reactive improvement of the Service MIX. As all the work is cluster-specific. Comments from the field also arrive at the cluster level. This is possible because a procedure is related to a specific cluster. Next to the competence engineers, technical writers edit the procedures, and sequence engineers process the comments on sequences. The Continuous Improvement department is responsible for the active improvement of the Service MIX. They work as project leads to drive improvements as the 'denesting' of procedures. The competence engineers, authors, and sequence engineers execute these improvements.

2.3 Process Analysis

This section explains what processes are related to Service MIX Improvements. Starting with a detailed explanation of procedures and how field engineers can provide feedback on a procedure to improve the overall quality of the procedures. It is followed by an explanation of how procedures are part of a sequence with a further introduction of sequences. The section concludes with how ASML is currently doing their maintenance on their Service Mix.

2.3.1 Procedures

Procedures are crucial for service activities because they ensure consistency, quality, and safety, which are essential for maintaining reliable customer operations (Ungan, 2006). As the Standard for Factory and Field Procedures states: "Procedures are the documents that describe how to assemble, test and service ASML machines" (ASML, 2024g). Appendix A provides a procedure template. This shows that a procedure consists of a lot of metadata, such as the necessary persons involved in the action, the tools needed, and the parts used. In addition it shows in which product family, subsystem, software, machine type, or destination the procedure is in.

A procedure consists of 23 types: Assemble, Adjust, Performance Check, Diagnostics, Remove, Replace, Calibrate, Locking, Out of Control Action Plan (OCAP), Install, Packaging, Prepare, Checklist, Clean, Commercial Option, Customer Specific Request, Finalize, Glue, Library, Lubricate, Manual, Mount and Recovery sequence.

Procedure Comment process
The field service engineer's comments are very valuable. These comments on procedures are a direct feedback loop from the field. Users of procedures can submit a comment when they have found an issue in the procedure or procedure section. These comments can be created before, during, or after service activities, stating what is wrong and suggesting what can be improved. CS competence engineers validate a comment and valid comments will be translated into content updates. Invalid comments, instead, do not improve the procedure, and are rejected by the competence engineer. The submitter of the comment will receive feedback about the status and progress of the comment. For procedure comments, human safety comments always get priority. The rest is based in theory on a first-come, first-served system. In practice, this means that the competence engineer has some freedom to pick the comments he or she wants to work on.

Within ASML, there are four categories of procedure comments made by field engineers: typographical, configuration, technical and as already mentioned human safety. Human safety refers to errors in the safety information of a procedure (warning labels, safety header info, etc.) and are the most crucial ones, since safety comes first in ASML. According to their Code of Conduct, they put safety first and are committed to creating a safe place to work (ASML, 2020). Typographical refers to errors in spelling, writing, unclear sentences, malfunctioning links, etc. Configuration refers to incorrect profiling (machine type or software version). Finally, technical refers to errors in technical instruction and unclear structure of actions in the procedure. Configuration comments are related to the different machine configurations ASML has in the field. Once approved, all comment types pass the change control board, and except for typographical comments, they need no alignment at all. Comments are a change management process for documentation in the field. The owners of the procedures or sequences are the owners of a comment. Ownership is defined by profiling, which is based on machine type and subsystem. Comments are assigned to an owner within 3 working days, and officially, they need to be solved within 12 working days (ASML, n.d.-a).

In Appendix B there is a detailed overview of the business process model. Figure 2.3 provides the flowchart of the comment process.

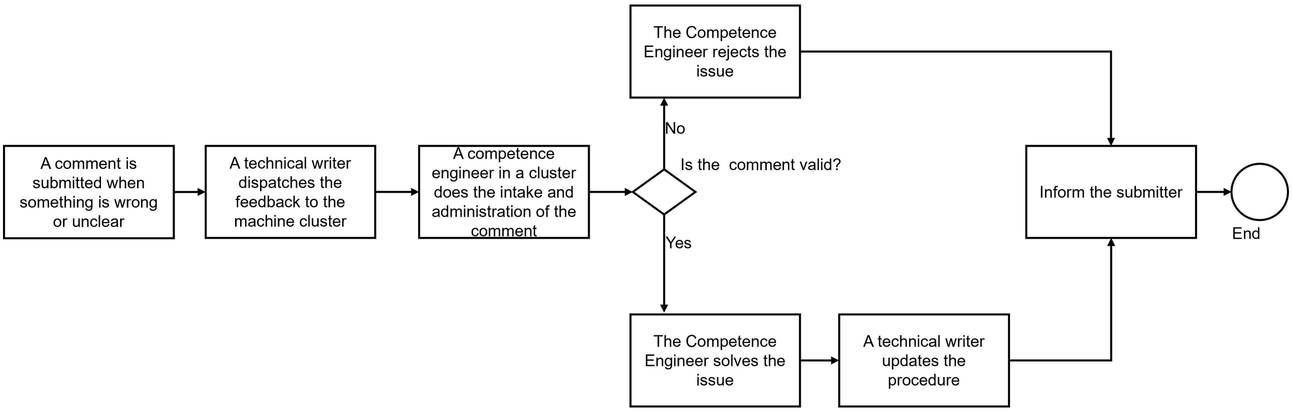


Figure 2.3: Flowchart of the Procedure Comment Process

Figure 2.4 provides an overview of the inflow and outflow of comments within the CS Service Engineering department. On average 400 comments arrive per month. The WIP represents the backlog of unprocessed comments. The backlog consists of around 750 unsolved comments. According to Little's formula (*Little's Law - Defined, Formula, Example, Origin*, n.d.):

$$WIP = Throughput * Cycle\ Time$$

This represents a lead time of 1.9 months. While comments need to be picked up by a competence engineer in 3 days, this is only the case in around 75% of the cases. The percentage that is closed in 12 days is around 60%.

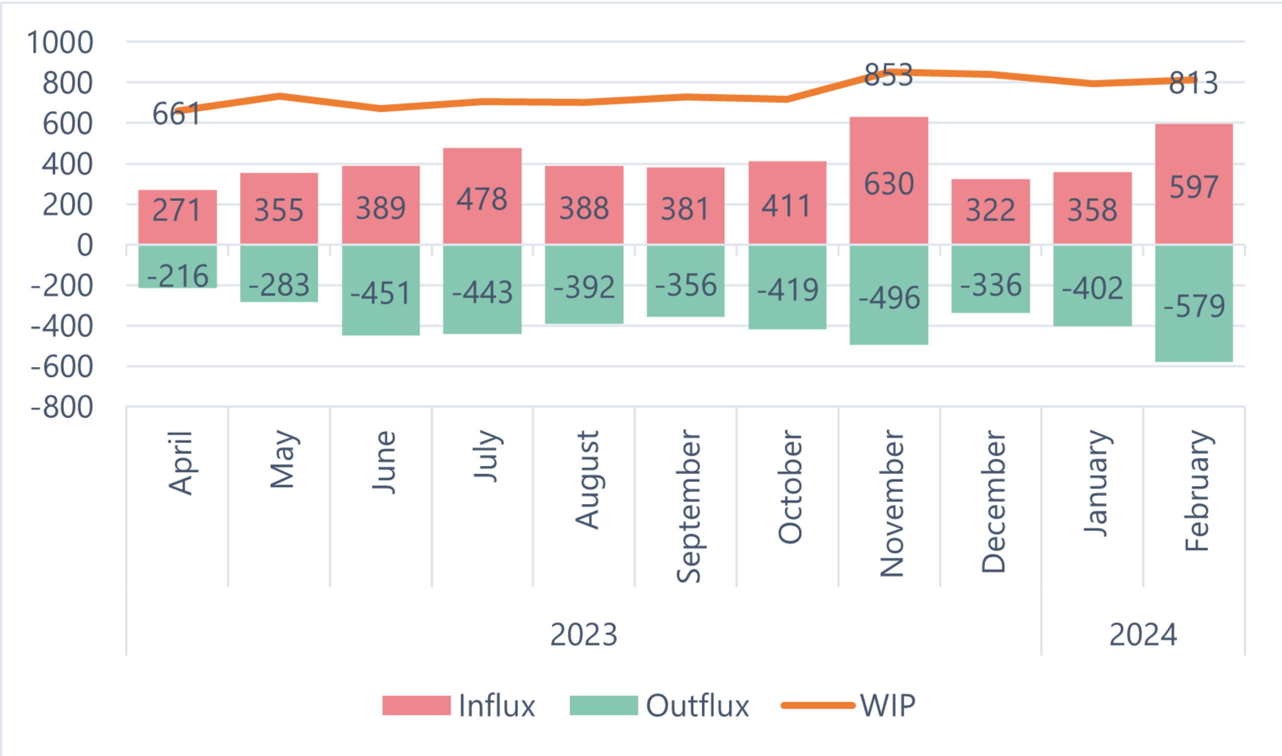


Figure 2.4: The WIP, in- and outflow of procedure comments over a period of 11 months

Figure 2.5 provides the number and percentage of the distribution of the different comment types over the total comments, in which it is clear that the technical comments in yellow are the most common and frequently submitted.

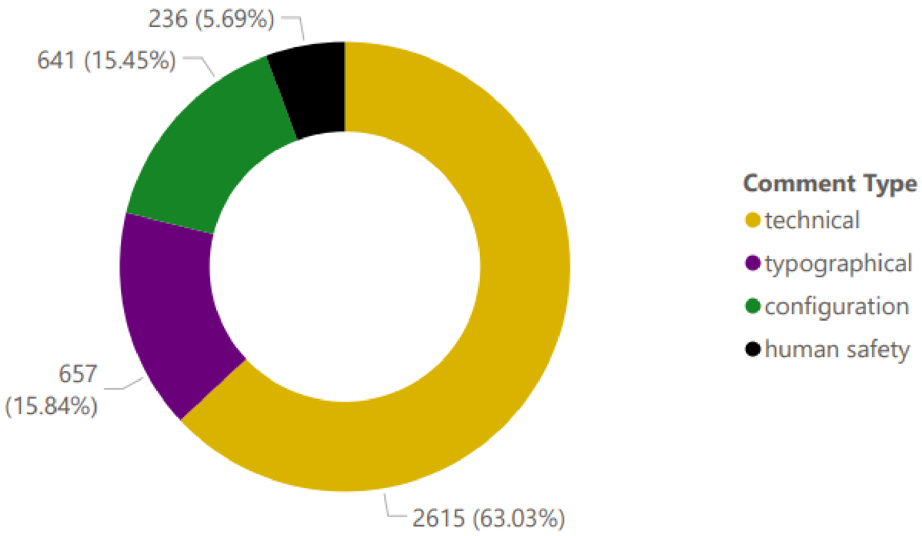


Figure 2.5: The distribution of the procedure comment types

Within these comment types, comments are either rejected or solved. Figure 2.6 shows the distribution of solved and rejected comments. In general, less than 30% of the comments are rejected. Human safety comments have a higher rejection rate. This could be the case because of ASML's focus on human safety. This means that the comment submitters know beforehand that the priority is on human safety, consequently this could by the reason why the reject rate is higher. The lowest rejection rate is for the comment type typographical; this could be the case because typographical comments are in essence simple, because there is just incorrect information within the procedure. While technical and configuration comments depend on the interpretation of the field service engineer and the interpretation of the competence engineer. The evaluation of right and wrong comments could be subjective.

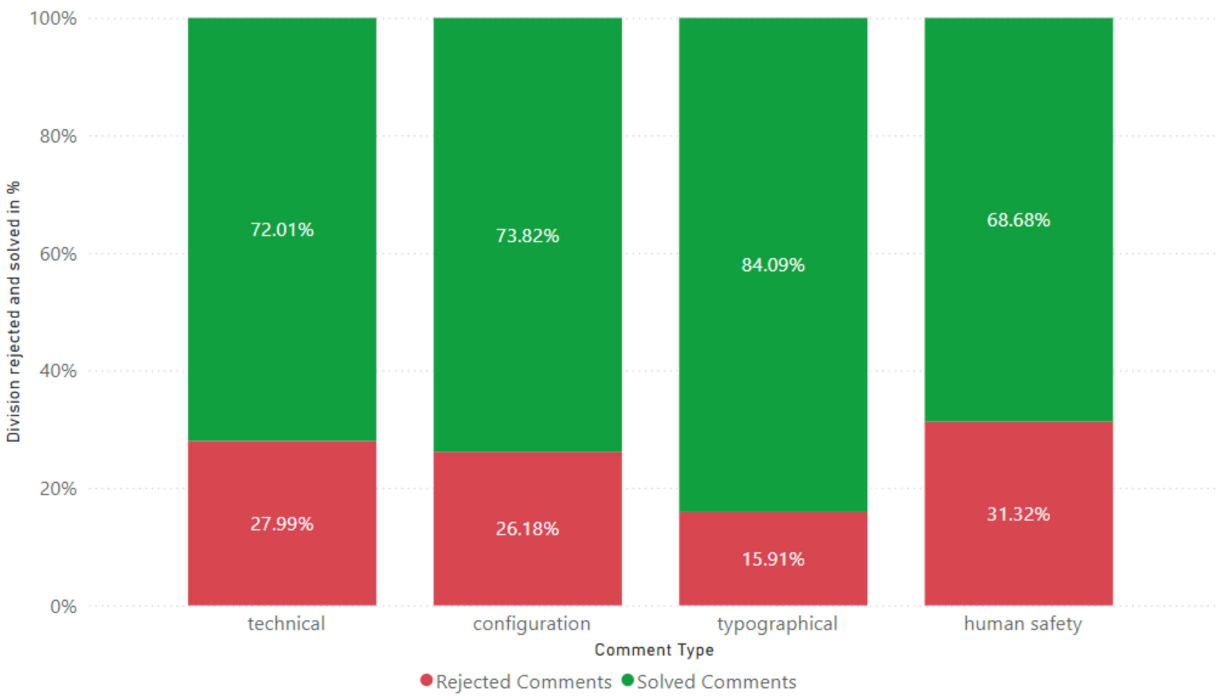


Figure 2.6: The division between rejected and solved comments

2.3.2 Auto-Comments

Next to procedure comments (which are interactive), there are automatically generated comments. Even though those comments are called auto-comments, an employee must still process them. A simple example of an auto-comment is when the service procedure contains a factory part (4022.644.xxxxx), which must always be changed to a service part (SERV.644.xxxxx). Service parts are stored locally near the customer factories, while factory parts are delivered from the central warehouse in Veldhoven. A 12NC code uniquely identifies parts.

Additional examples include procedure or section titles—or 12NCs in incorrect formats. Solutions for these examples are changing the title or replacing the 12NC. But also, for example, metadata which is empty or in the incorrect format, like the time to complete procedure field is empty or is not a number, the number of person's field is empty, or does not contain a number, (or have a replacement procedure with no parts). All these variants are indicated with a dashboard.

2.3.3 Sequences

Multiple procedures together form a sequence. Figure 2.7 shows an example of a sequence. The procedure provides the work instructions, and the sequence provides the order and dependencies of the work instructions or procedures. Within the field, service engineers use a sequence-based way of working to reduce risk, cost, and labor hours. To ensure this, the sequence team uses a tool that generates recovery sequences to bring the machine back to specification. Those sequences are called Common Access & Recovery (or Repair States) (CARS). The goal is to create simple, transparent, and modular procedures with a 'one procedure per process step' concept. Such a single activity procedure can then be reused in any sequence where that particular activity is required (ASML, n.d.-c).

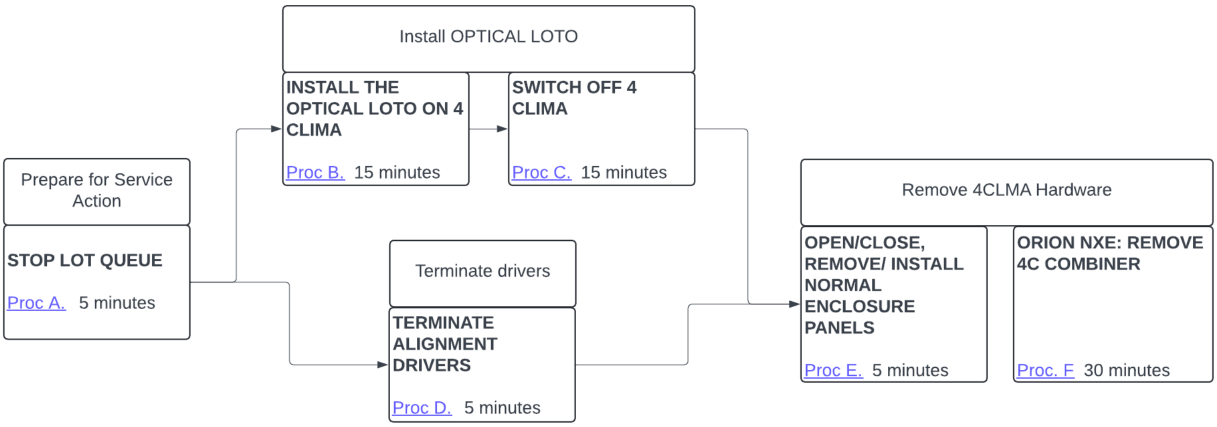


Figure 2.7: Example of a Sequence that consists of multiple procedures

One procedure per process step provides the following advantages:

- Flexible composition, adjustment, and maintenance of sequences.
- Re-usability of the building blocks.
- Support of controlled material flow as it is clear what parts, tools, and people are needed for each step.
- Navigation through the procedures because linking can be limited to an absolute minimum. Linking or so-called 'nesting' is a procedure that refers to another procedure (ASML, n.d.-c).

Sequence Comments Process

When there is an issue with a sequence, the user can provide feedback by submitting a comment. The sequence comments categories are typographical, configuration, and technical—In which it is not possible to make a human safety related comment as in the procedure comment process. Figure 2.8 provides an overview of these comment types for the period of April 2023 until February 2024. The figure shows that most of the comments are technical, which refers to an unclear structure of actions in the sequence. Only a small part of the comments are typographical (5.3%) and configurational (9.69%).

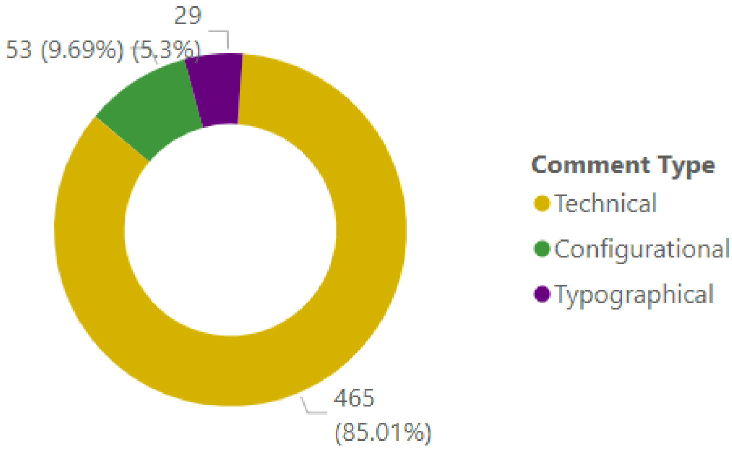


Figure 2.8: Overview Sequence Comment Types

For sequence comments specifically, it is possible for the submitter of the comment to choose the criticality of the comment, either critical, high, medium, or low. Figure 2.9 shows that an estimate of 50 percent is a comment with a low priority, 25 percent is a comment with a medium priority, 20 percent is a comment with a high priority and, finally, only 2 percent with a critical priority. Sequence engineers process these comments. When the root cause is found, the issue is solved (ASML, n.d.-c). 30 percent of comments are rejected, which is the same as for the procedure comment.

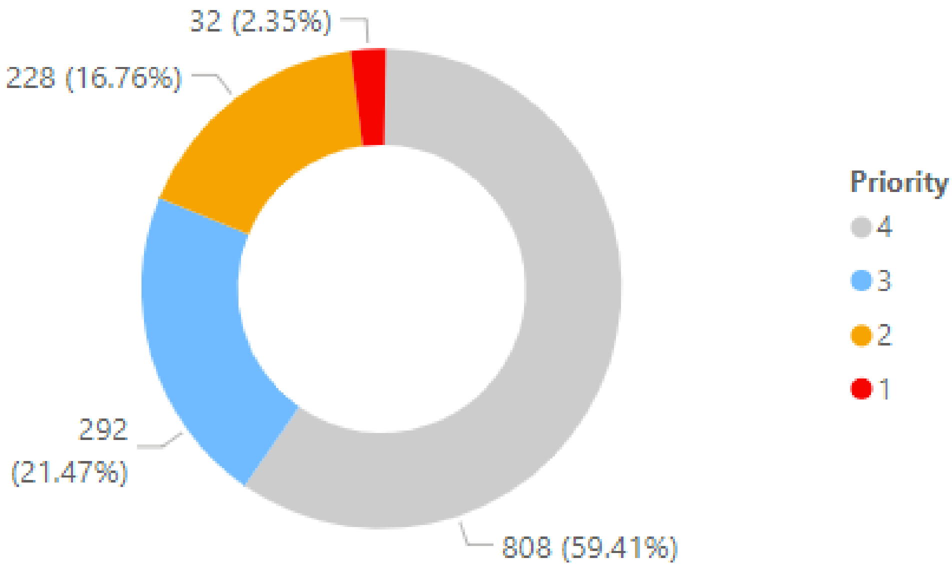


Figure 2.9: Overview Sequence Comment Priorities

2.3.4 De-nesting

De-nesting the procedure is removing all links to other procedures: breaking down procedures into smaller steps, and creating sequences and implementing them within the sequence application. This will reduce the hours in preparation and execution of service actions (ASML, 2022a).

2.4 Data collection and validation

This section addresses how it is possible to make use of unused sequence export data, procedure opening data, and spare parts usage. In addition, it shows how this data can be connected to sequence, procedure, auto-comments or de-nesting tasks. It provides a data model in Section 2.4.1 and data insights in the available data in Section 2.4.2.

2.4.1 Data model

Figure 2.10 makes it possible to combine multiple data sources. The sequence comments, procedure comments, auto-comments, and de-nesting tasks can be combined with the number of sequence exports, procedure opens, parts usage, and procedure metadata through the MOID, The EpicCode, the 12NC. The parts usage data, sequence export data and procedure open data used is over a period of 11 months.

A detailed collection of all the filters used can be found in Appendix C. For most of the data tables, the following filters are used: CS, EUV, NXE Twinscan, NXE Twinscan Source, and NXE Twinscan Driverlaser. The data filter is in a range from April 2023 to February 2024.

For the SequenceExportData table in particular the Veldhoven location is excluded, this to prevent data from being contaminated by sequence engineers in CS central office. Unfortunately this is not possible for the procedure data.

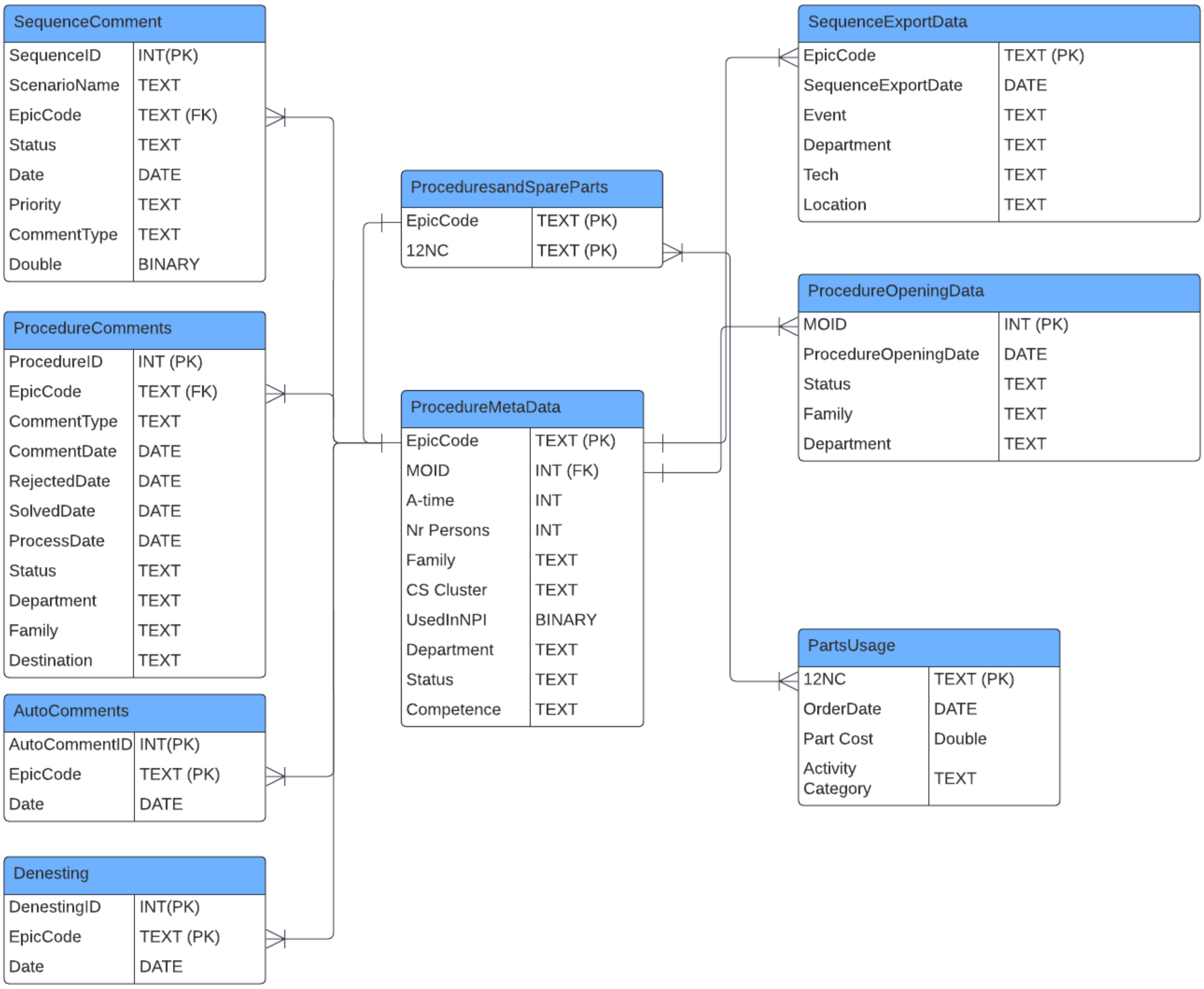


Figure 2.10: Data model

2.4.2 Data Summary

Parts usage, sequence exports, and procedure opens per procedure in 11 months. Figure 2.11 provides an overview of on average per procedure what is the part usage, procedure opens, and sequence exports. This means that, per EpicCode, it is possible to determine the parts usage, procedure opens and sequence exports that have occurred in a certain period.

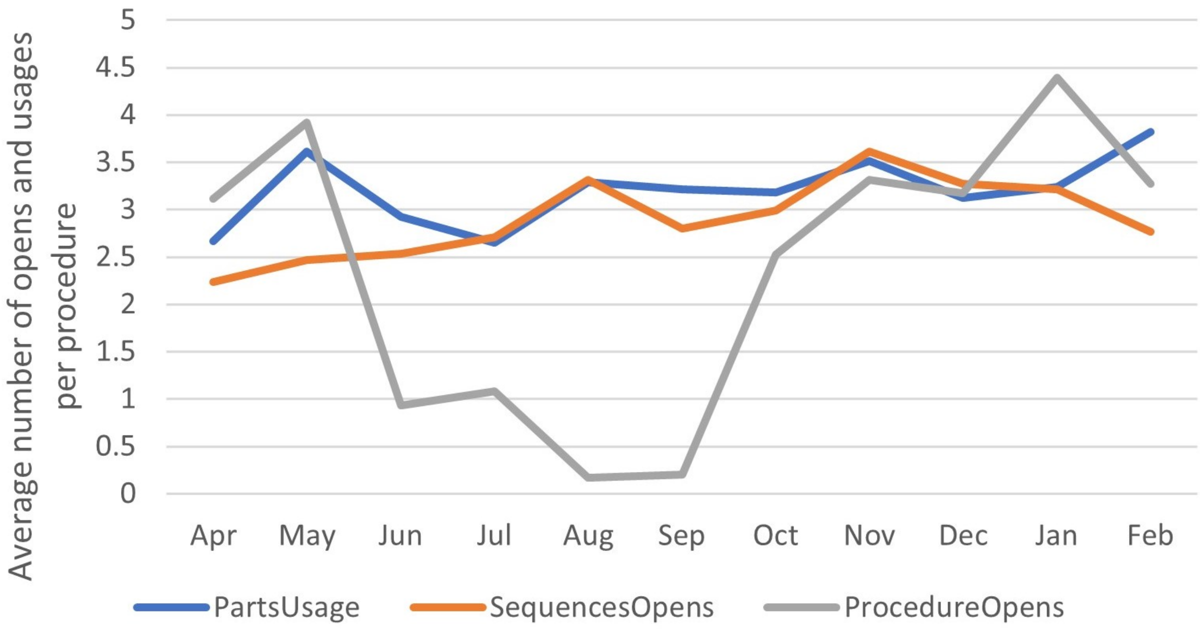


Figure 2.11: Average Parts Usage, Procedure Opens and Sequence Opens per Procedure

2.5 Conclusion

As ASML introduces new machine types or (New Product Introduction (NPI)): the inflow of comments from field service engineers increases due to opportunities for improvement in procedures and sequences. However, with no corresponding increase in competence engineers, this calls for a more efficient use of resources. Using procedure opens and sequence exports, a data-driven prioritisation method offers a solution by ensuring that the most important tasks are addressed at the right time, rather than relying only on gut-feeling.

This approach allows engineers to work more efficiently by focusing on high-impact tasks, although it will not reduce their overall workload. Instead, it ensures they are working more effectively addressing the most critical issues, such as those already done with human safety comments, but now, for example, with more frequently used procedures. While some lower-priority comments may remain in the backlog, this trade-off ensures that resources are directed towards tasks that offer the greatest value.

However, a literature study is needed to find the best prioritisation method. Here, unused metrics such as sequence exports, procedure opens and procedure length, and if a procedure is also used in a new product or machine, could be all metrics to prioritise. Furthermore, the data on procedure opens and sequence exports needs to be analysed. The study of this data is required to assess the validity of the priority-setting method. This data, together with the work prioritisation method, will be used to improve the service mix maintenance in a data-driven way.

3 Literature Review

This chapter answers the following research question: How can literature be used to find methods to improve Service Mix Maintenance? This literature review explores existing work prioritisation methods in Section 3.1 to identify those best suited for improving Service MIX Maintenance. It uses quantitative process analysis in Section 3.2 to analyse system performance. Finally, it fills the gap between theoretical models and practical applications in Section 3.3.

3.1 Overview of Work Prioritisation Models

Chapter 2 demonstrates the need for a data-driven work prioritisation model. A variety of methods exist for work prioritisation, and this section will introduce several approaches.

When examining how organisations choose which projects or tasks to execute or prioritise, there is a consistent desire for clear, objective, and mathematical criteria (Haas & Meixner, 2005). However, decision-making is inherently a cognitive and mental process, shaped by the selection of criteria—both tangible and intangible—that are arbitrarily chosen by decision-makers (T. Saaty, 2010). When confronted with tasks of differing levels of urgency and importance, how does one determine which tasks to prioritise? Zhu (2018) highlights that people often prioritise less important tasks over important ones, especially when the less important tasks have time constraints.

Prioritising projects or tasks is essentially an ordering scheme based on a benefit-cost relationship. Tasks with higher benefits relative to their costs are assigned higher priority. Each activity or task receives a priority score, which is used to create an ordered priority list (Vargas, 2010).

In data-driven prioritisation, the most critical tasks naturally receive the highest scores. Requirement prioritisation, in particular, involves key activities aimed at ranking tasks or requirements. One common approach is to assign a rank to each requirement based on a specific criterion, while another approach involves ranking requirements by comparing pairs of requirements based on preference.

There are several prioritisation models, including the Weighted Scoring Model, Weighted Product Model, Eisenhower Matrix, MoSCow Method, Cost of Delay and Pareto Analysis. Each model offers a unique approach to evaluating and prioritising tasks based on different criteria. For example, the Weighted Scoring Model assigns numerical values to various criteria (Yang, 2014), allowing tasks to be quantitatively compared in terms of relative importance. This model is particularly useful in complex decision-making environments where multiple factors must be considered (Triantaphyllou & Baig, 2005).

Another commonly used model is the Eisenhower Matrix, which categorizes tasks based on their urgency and importance. Created by Dwight D. Eisenhower, this method is particularly useful for personal productivity, helping individuals focus on tasks that are both urgent and important while delegating or eliminating less critical tasks (Ngandam Mfondoum, Tchindjang, Mefire Mfondoum, & Makouet, 2019).

Similarly, the Moscow Method (Must have, Should have, Could have, Won't have) is widely used in project management, particularly in agile teams. This method helps categorize work items by priority, ensuring that the most essential features or tasks are addressed first (Shafi, n.d.). Finally, Pareto Analysis, based on the 80/20 rule, suggests that 80% of the results come from 20% of effort. This analysis emphasizes focusing on tasks that yield the greatest impact.

The Analytical Hierarchy Process (AHP)

While several prioritisation models provide useful frameworks, the complexity of managing multiple factors in Service MIX Maintenance requires a more sophisticated approach. The AHP method allows for comparing both qualitative and quantitative criteria (Haas & Meixner, 2005), making it highly suitable for addressing the multi-dimensional nature of task prioritisation in this context.

Among the most widely studied techniques for requirement prioritisation is the AHP (R. Saaty, 1987). Known as a pair-wise comparison method, AHP is one of the key mathematical models currently supporting decision theory (Vargas, 2010). It is extensively used in multi-criteria decision-making, resource allocation, planning, and conflict resolution. The strength of AHP lies in its ability to consider multiple factors simultaneously, while accounting for the relative importance of these factors. This helps in making decisions by systematically weighing each criterion.

The process can be visualized as a hierarchy structure representing the decision problem. The elements in the hierarchy are grouped into a cluster based on homogeneity, with each level containing one or more homogeneous clusters. By evaluating requirements in pairs for their relative importance, a pairwise comparison matrix is generated. This matrix allows the decision-maker to determine which requirement should be prioritised. The basic concept is to calculate the priorities of requirements by comparing all unique pairs of requirements to estimate their relative importance.

In practical terms, users must decide which requirement is more important and to what extent, using a scale from 1 to 9. A value of 1 indicates that two requirements are equally important, while higher values represent increasing levels of importance. The diagonal elements of the matrix always contain a value of 1, as each requirement is equally important compared to itself. The steps involved in using the AHP method are as follows:

1. Create a requirements-to-requirements matrix and list the rows and columns within the matrix.
2. For each unique pair of requirements (e.g. requirements 1 and 2), insert their relative importance in the corresponding matrix cell. The reciprocal value is automatically inserted into the transposed position (e.g. if cell 1-2 = 8 then cell 2-1 = 1/8)
3. Finally, to obtain the relative priority of each requirement, calculate the eigenvalues of the resulting comparison matrix. This provides the relative priorities of the requirements. AHP also checks the consistency of the comparisons by calculating the consistency ratio. This requires $nx(n-1)/2$ comparisons, acknowledging that pairwise comparisons produce redundancy.

The AHP method uses the following scale for pairwise comparisons:

- 1: Equal importance
- 3: Moderate importance of one over another
- 5: Strong importance
- 7: Very strong importance
- 9: Extreme importance

The comparison clusters include the factors or criteria being evaluated. To ensure consistency, AHP calculates a consistency ratio, which helps check the reliability of the pairwise comparisons.

A critical aspect of the AHP method is ensuring consistency in the pairwise comparisons. AHP evaluates the consistency of the decision-maker's judgements by calculating the Consistency Index (CI) and the Consistency Ratio (CR).

The Consistency Index (CI) is calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.1}$$

Where:

- λ_{max} is the maximum eigenvalue of the pairwise comparison matrix.
- n is the number of elements being compared

The Consistency Ratio (CR) is then computed to assess the reliability of the comparisons:

$$CR = \frac{CI}{RI} \tag{3.2}$$

Where:

- CI is the Consistency Index.
- RI is the Random Consistency Index, which is a standard index based on the size of the matrix (i.e. the number of comparisons).

Table 3.1: Example of the AHP method

Requirements	R-1	R-2	R-3	R-4	AHP weight
R-1	1	3	7	5	0.558
R-2	1/3	1	5	3	0.263
R-3	1/7	1/5	1	1/3	0.057
R-4	1/5	1/3	1	1	0.122

Note. Table created using data from Vargas (2010)

A CR value below 0.10 indicates that the comparisons are consistent and acceptable. If the CR exceeds this threshold, it suggests that the comparisons are inconsistent and should be revised. This step is crucial because pairwise comparisons can introduce redundancy and potential bias, and the consistency check helps to mitigate these issues (R. Saaty, 1987).

The ranking of priorities from the pairwise matrix is computed by calculating the eigenvector. A simplified method to obtain this ranking involves the following steps:

1. Raise the pairwise comparison matrix to powers that are successively squared at each step.
2. Calculate the row sums and normalize them.
3. Repeat the process until the difference between sums from two consecutive calculations is smaller than a predefined threshold.

This process yields the relative ranking of the criteria. The resulting eigenvector represents the weights assigned to each criterion, providing a clear guide for decision-making. Through this method, AHP effectively prioritises tickets by comparing and ranking their relative importance based on the defined factors.

While simpler models like the Eisenhower Matrix are effective for individual task management, their simplicity may not suit the complex, multi-factor prioritisation required for Service Mix Maintenance (Ngandam Mfondoum et al., 2019). To address this complexity, AHP provides a more detailed approach through pairwise comparisons, making it a better fit for this application, as outlined in Winston's Chapter 13.7 on decision-making under uncertainty (Winston & Goldberg, 2004). This chapter emphasizes the value of structured decision-making tools like AHP when managing uncertainty and conflicting criteria in complex environments.

3.2 Quantitative Process Analysis

Quantitative process analysis is a valuable tool for gaining insights into a system's performance (Dumas, La Rosa, Mendling, & Reijers, 2018). One key method, flow analysis, uses the cycle time of a task or process. This concept is closely related to the comment process discussed in Chapter 2, where an individual submits a comment and waits for a response. This cycle time can be divided into two components: waiting time and processing time, as described by Dumas et al. (2018).

Waiting time refers to the portion of the cycle time when no active work is being done to advance the process, while processing time refers to the time employees spend on the actual task, such as when a competence engineer works on solving the comment. Overall, the total cycle time can be calculated by using Little's Law:

$$WIP = \lambda \times CT$$

The cycle time (CT) is directly related to the arrival rate (λ) and the Work-In-Process (WIP) (*Little's Law - Defined, Formula, Example, Origin*, n.d.). In this context, the arrival rate refers to the average number of new comments or tickets (instances of the process) generated per time unit. This included the arrival of the different Service MIX Feedback types: procedure comments, sequence comments, auto-comment and de-nesting work. The WIP refers to the average number of instances (tickets or comments) that are in progress but not yet completed, representing the backlog of unsolved tickets or comments.

Little's Law further explains that WIP increases if either the cycle time increases or the arrival rate increases. This is particularly relevant in Service MIX maintenance, where the number of comments grows due to the introduction of multiple NPIs. In other words, if the process slows down (i.e., cycle time increases), the number of active tasks (comments or tickets) in progress will rise.

If the arrival rate increases and the goal is to maintain current WIP levels, the cycle time must decrease. In the context of solving comments, this means the process needs to be made faster.

Little's law holds for any stable process. A stable process is one in which the number of active tasks does not grow indefinitely – meaning that the backlog of work is not increasing out of control.

Capacity and Bottlenecks
The application of Little's Law relies on the assumption that the process is stable. To verify this assumption, it is essential to consider the theoretical capacity of the process and the resource utilization of the resources involved.

The theoretical capacity of a process is the maximum number of tasks (instances) that can be completed per time unit, given the available resources. The process reaches its theoretical capacity when certain resources are fully utilized with no idle time. Once this limit is reached, the resources at full capacity cannot handle more work within the same time frame. This point represents the process's bottleneck; the point where further increases in arrival rate would result in increasing WIP. Winston (2004) highlights the role of bottlenecks in limiting the system capacity, suggesting that efficient resource allocation can significantly reduce cycle time.

Limitations of flow analysis
While flow analysis is useful, estimating the average cycle time for each task can be challenging. However, cycle times can often be estimated through interviews or by analyzing data log from information systems. Additionally, resource contention arises when there is more work than available resources to handle, which can significantly impact the cycle time (Winston & Goldberg, 2004).

Arrival Rate and Capacity
The arrival rate (λ) refers to the mean arrival number of tasks arriving per time unit. Meanwhile, capacity per resource (μ) refers to the theoretical number of tasks that a resource (e.g. competence engineer) can handle per time unit. Similar to the arrival of comments and the capacity of competence engineers to solve them (Dumas et al., 2018).

Conclusion
Quantitative process analysis provides valuable insights into the flow and efficiency of the Service MIX maintenance process, particularly through the use of Little's Law to analyse cycle time and backlog. This analysis highlights the relationship between arrival rate, work-in-process (WIP), and the theoretical capacity of resources, such as competence engineers. While flow analysis and capacity assessment offer a strong foundation for understanding the system's performance, a key challenge remains: How to effectively prioritise comments?

Although we can estimate the arrival rates and solve capacity, there is no clear method introduced to evaluate the impact of individual comments on the system. Without a clear understanding of how to measure this impact, it is difficult to prioritise comments and optimize the overall process. Identifying or developing a method to assess the relative importance of comments is critical for the next step in building an effective prioritisation model.

3.3 Knapsack Problem

In many practical scenarios, optimization problems can be formulated as Integer Programs (IPs). A common class of IPs is the 0-1 integer problem, where variables are restricted to binary values (0 or 1). This is particularly relevant when decisions involve choosing whether or not to include certain items. One such example is the knapsack problem, a classical IP with a single constraint where each item can either be included or excluded. It can be written as:

$$
\begin{aligned}
&\max\ z = c_1x_1 + c_2x_2 + \cdots + c_nx_n \\
&\text{s.t.} \\
&\quad a_1x_1 + a_2x_2 + \cdots + a_nx_n \leq b \\
&\quad x_i \in \{0,1\},\ i = 1, 2, \ldots, n
\end{aligned}
\tag{3.3}
$$

This problem structure reflects the challenges faced in ticket prioritisation for Service MIX Feedback, where the capacity (engineer hours) is limited, and each ticket must be evaluated based on its contribution to overall system performance. The knapsack problem's capacity constraint ensures that only the highest-priority tickets are addressed within the available resources.

In this formulation, c_i represents the benefit derived from solving ticket i, a_i is the amount of the available resource (such as time or capacity) consumed by ticket i, and b is the total resource capacity (in this case, the total hours engineers have available). Each ticket can either be solved ($x_i = 1$) or not solved ($x_i = 0$) in the current period. The goal is to maximise the total benefit while staying within the given capacity (Winston & Goldberg, 2004).

The knapsack problem's structure aligns with the problem of prioritising and solving Service Mix Feedback tickets in the model. Here, the total working hours of engineers per period serve as the capacity, and the tickets are assigned values based on the score developed in Chapter 4. The model selects the most valuable tickets for resolution within the given period, constrained by the available solving capacity. Tickets that cannot be solved due to capacity limitations are deferred to the next period.

As outlined by Winston (2004), the knapsack problem offers a valuable framework for resource allocation problems, where the goal is to choose the optimal set of tasks under limited resources, ensuring that the highest-value tasks are prioritised under limited capacity. Applying this to the model allows for an efficient allocation of engineer time, ensuring that the highest-value tickets are resolved first, while tickets that cannot be addressed due to capacity constraints are carried over to future periods. The set of tickets for a new period is formed by combining the tickets carried over from the previous backlog with the new incoming tickets for the current period, often called as a multi-period knapsack problem.

This application of the knapsack problem shows how literature on IP problems can inform and improve the ticket prioritisation process. Specifically, by solving the model iteratively for each period, the most critical tickets are handled first, ensuring optimal resource utilisation while managing the backlog for future periods.

3.4 Conclusion

This literature review explores various methods derived from the literature to improve Service MIX Maintenance. By applying structured decision-making frameworks, such as the AHP method and the knapsack problem, the review identifies key approaches to enhance task prioritisation and resource allocation within this context. In Chapter 4, the AHP method is employed to prioritise tasks based on multiple factors, reflecting a benefit-cost relationship that ensures higher priority is given to tasks with the greatest relative value.

Further, the knapsack problem, as discussed in the literature, provides a robust model for optimizing the allocation of limited resources—in this case, the working hours of engineers. This model is explored in Chapter 5, where it is combined with quantitative process analysis to evaluate the model's performance and ensure efficient management of the backlog.

Despite these advances, the review highlights a significant challenge: accurately measuring the impact of comments remains complex and unresolved. However, the AHP method offers a viable approach to address this challenge. The literature provides valuable frameworks for prioritisation and resource optimization, yet further research is needed to develop precise methods for assessing comment impact, which is crucial for fully optimizing Service MIX Maintenance.

4 Methods for Measuring Comment Impact

In Chapter 2 and Chapter 3, we established the need for a systematic approach to prioritising work due to the increasing influx of comments and the need to use available resources efficiently. This chapter addresses the following research question: What methods can be used to measure the impact of comments in service operations? It starts with the factors to consider when measuring the effect of comments in Section 4.1 and assessing their importance in Section 4.2. Finally, it presents three methods for assessing the impact of procedure, sequence, automatic, and de-nesting comments in Section 4.3, ultimately leading to a conclusion in Section 4.5 and the basis for data-driven prioritisation model in Chapter 5.

4.1 Variables to Consider for Prioritisation

Several key factors influence the work prioritisation model for Service MIX maintenance. These include Service MIX feedback types and prioritisation factors based on procedure or sequence characteristics. To ensure these factors are comparable, the AHP method, detailed in Chapter 3, is used to weigh and rank them effectively.

4.1.1 Service Mix Feedback Type

Various types of comments exist within the Service MIX, including procedure comments, sequence comments, auto-generated comments and de-nesting work. Each type varies in complexity and impact. For example, solving a sequence comment may be more labour-intensive than addressing an auto-comment. This results in a different weight for different types of Service MIX.

Within the sequence and procedure comments, there are different comment types and priorities, all influencing the importance of a comment. The weight of the SMIX feedback type is determined by its comment type and priority. Detailed information is provided in Section 2.3 below in a short explanation of comment type and priority.

- **Comment Type:** For procedure comments, the categories are human safety, technical, configuration, or typographical. Human safety comments are always given priority. For sequence comments, only technical, configuration, or typographical comments are relevant, as human safety is not an applicable factor. For auto-comments and de-nesting work, no comment type is considered. The comment type has an impact on the significance or weight of a comment.
- **Priority:** For the sequence comments, the submitter can indicate the priority level (low, medium, high, or critical). This self-assigned priority helps to filter out urgent issues. However, the guidance given to the submitter is limited, so the priority may be superfluous. However, for procedure, auto-comment and, de-nesting work, the submitter cannot specify a priority.

With different SMIX feedback types, comment types, and priorities come different costs and benefits. The following provides details the cost of solving with norms used for administrative purposes and the standard benefits used for the different SMIX feedback types. Finally, Table 4.1 provides an overview of all the SMIX feedback types, comment types, priorities, costs, and benefits.

- **Cost of Solving:** The resource cost for resolving procedures, sequences, auto-comments, or de-nesting tasks. These costs are based on the claim allocation template (ASML, 2024c); this template provides the cost in Labour Hours (LH) per solved comment and is used for administrative purposes. For procedure comments, the cost is 3 hours for a competence engineer and 1 hour for a technical author to update the procedure. So, in total, 4 hours to solve a procedure comment. For sequence comments, this takes 2 hours. For auto-comments, it takes 15 minutes. For de-nesting procedures, it takes 4 hours. Table 4.1 provides an overview of all norm costs in hours.
- **Benefit of Solving:** The potential gain from addressing each type of work. These gains are based on the standard used for NDR related solutions (ASML, 2024f). For procedure comments, the standard gain in LH per system, per year is low. This is the gain in LH for a Field Service Engineer (FSE) working on the machine. For sequence comments, this depends on its priority, which varies from significant LH/sys/yr for critical sequence comments to moderate for low sequence comments. For denesting, this is moderate. Ultimately, for auto-comments, this is minimal. Table 4.1 provides an overview of all benefits.

Table 4.1 shows the cost (in Labour Hours - LH) and benefit (in LH/system/year) factors based on the ASML CS EUV norms (ASML, 2024f) (ASML, 2024c). Chapter 2 already referred to the different priorities and comment types.

Table 4.1: The Cost and Benefit Factors based on the norm of the different SMIX feedback types.

SMIX Feedback Type	Comment Type	Priority	Cost (LH)	Benefit
Procedure Comment	human safety	N.A.	4	Low
	technical			
	configuration			
	typographical			
Sequence Comment	typographical	1 - Critical	2	Significant
	technical			
	configuration			
	typographical	2 - High	2	High
	technical			
	configuration			
	typographical	3 - Medium	2	Moderate
	technical			
	configuration			
	typographical	4 - Low	2	Moderate
	technical			
	configuration			
De-nesting	N.A.	N.A.	4	Moderate
Auto-Comment	N.A.	N.A.	0.25	Minimal

In conclusion, we have identified four distinct Service MIX Feedback types: procedure, sequence, auto-comments and de-nesting work, along with their associated comment types, priorities, costs, and benefits. In total there are 4 different comment types for procedure comments, 12 different types for sequence comments with comment type and priority, 1 for de-nesting and 1 for auto-comments, giving a total of 18 different types. Section 4.1.2 section will focus on identifying the prioritisation factors based on sequence or procedure characteristics. Together with these factors, they will form the foundation of the prioritisation model.

4.1.2 Prioritisation Factors Based on Sequence or Procedure characteristics

The following seven prioritisation factors are based on the characteristics of sequences and procedures. These include the frequency with which procedures or sequences are executed, the time required to complete them, whether they are also used in a NPI, the type of procedure or sequence, the number of comments per procedure or sequence, and the details of those comments. Below is a detailed explanation of each prioritisation factor, starting with frequency:

- **Frequency**: Indicates how often the procedure or sequence is used on average per week. This frequency is based on the following three factors:
  - **Procedure opens**: The average number of procedure opens per week performed by either a field engineer or a competence engineer. This data can be updated on a weekly or monthly basis to show trends. However, it is important to note that the opening of a procedure does not necessarily mean that it has been completed. This data is available for 11 months (from April 2023 to February 2024) and is represented by a float number.
  - **Sequence Exports**: Similar to procedure opens, this metric tracks how often a sequence is exported on average per week and can also be updated periodically to follow trends. Sequences are mostly exported to prepare one or multiple service actions in the field. As the procedure opens, sequence exports do not confirm execution. This data is available for 11 months (From April 2023 until February 2024) and is represented by a float number.
  - **Parts Usage**: Although procedure opens and sequence exports do not guarantee execution, they are, like parts usage, an indirect indicator that a procedure or sequence has probably been followed and executed. The link between part usage is possible because 12NC numbers are part of a procedure. This data is available for 11 months (from April 2023 until February 2024) and is represented by a float number.
- **Execution Time** The longer the execution time for a procedure or sequence, the greater its impact on resources and operations. Procedures or sequences with higher execution times can be prioritised to reduce downtime. The A-time is part of a procedure and represents the optimal execution time (in hours). In most cases, the execution time is not the optimal one, for a hardware service action the delay in execution

time (B-time) is equal to 0.4∗ A-time and for recovery service actions it is 0.8∗ A-time. The reason why the delay in execution time is higher for recovery service actions is that the recovery service action checks whether a hardware service action has been executed correctly or whether an important part has been missed or replaced incorrectly. Recovery and hardware service actions executed together result in a B-time of 0.6 * A-time. Finally, the execution time is 1.6 * A-time. This variable is represented by a float number.

- **Also Used in NPI (New Product Introduction):** A binary variable when procedures are used for both the installed base and new machine types. Errors in these procedures can have a significant impact on the NPI implementations. Prioritising comments for these procedures is essential to prevent continuous problems in NPIs. The binary value is true (1) if the procedure is also used in NPI, and false (0) if the procedure is not used in NPI.
- **Procedure or Sequence Type:** As discussed in Chapter 2, procedures are different: some are part replacements, others are performance checks. The type of procedure could influence its priority and may affect the impact of a comment.
- **Number of Field Service Engineers Involved:** Procedures or sequences that require more Field Service Engineers to perform have a higher potential impact, making them more critical for prioritisation. This variable is represented by an integer number.
- **Comments per Procedure or Sequence:** The number of comments per procedure or sequence indicates how often the procedure or sequence is used or says something about the quality of the procedure or sequence itself.
- **The Comment Details**: The specific content of each comment can provide deeper insights. However, analyzing this content requires text analysis tools, which remain outside the scope of this study.

So far, we have identified seven key prioritisation factors and the different Service MIX feedback types. Understanding the relative importance of both these factors and feedback types is crucial for effectively incorporating them into the prioritisation model. Section 4.2 addresses this issue by exploring methods to measure and assess the importance of each element.

4.2 Determining the Importance of the SMIX Feedback Types and the Prioritisation Factors by using the AHP Method

This section outlines the relative importance of the Service MIX feedback types and prioritisation factors. Section 4.2.1 begins by discussing the survey and concludes with the application of the AHP method in 4.2.2, which quantifies the importance of each factor. Through this process, a solid foundation for the prioritisation model is established.

4.2.1 The Survey for Prioritisation Factors and SMIX Feedback Types

As discussed in Section 4.1.1, the benefits (in LH/System/Year) of Service MIX feedback types are categorized by SMIX feedback type, not by comment type or priority. Similarly, while all prioritisation factors based on procedure or sequence characteristics have different values, their relative importance is unknown.

To ensure accurate weighting of the different SMIX feedback types and prioritisation factors in the model, we combine predefined norms with rankings collected from a survey. Although the survey was conducted as an alternative to the full AHP method found in Section 3.1, because this method was too time-consuming, the AHP method is still used to process the survey results. Competence and Sequence Engineers and Project and Group Leads were asked to rank the importance of each SMIX Feedback type or prioritisation factor. This allows us to maintain a structured decision-making process while simplifying the data collection.

The survey consists of two questions and can be found in Appendix D. After a brief explanation of the Service MIX feedback types and prioritisation factors, respondents were asked to rank both the prioritisation factors and the Service MIX feedback types in order of importance, from highest to lowest.

The survey enables the participants to rank the SMIX feedback types by importance. The sequence comment priority was excluded to make the survey more manageable, as priority levels (low, medium, high, critical) are already predefined. This reduction simplified the task for participants while still capturing the critical distinctions between feedback types.

Instead of the 18 factors outlined in Section 4.1.1, we now consider 9 factors: 3 types of sequence comments (typographical, technical, and configuration), 4 types of procedure comments (typographical, technical, configuration, and human safety), along with de-nesting and auto-comments.

For the prioritisation factors based on procedure and sequence characteristics found in Section 4.1.2 : **frequency, execution time, used in NPI, procedure or sequence type, number of field service engineers involved, comments per procedure or sequence,** and **comment details**. There are no established norms. To address this, a survey was conducted with a selected group of participants to gather insights and establish a ranking for these factors.

In this survey, participants were asked to rank the seven prioritisation factors. For the "frequency" factor in particular, the ranking was based on the number of executions per week. While the technical definition involves sequence exports, procedure opens, and parts usage, it was referred to simply as "frequency" to make the concept easier for participants to understand.

Figure 4.1 presents the results for the SMIX feedback type survey, completed by 15 employees (N=15), including 8 Competence and Sequence Engineers and 7 Group and Project Leads. These results provide the relative importance of the factors, enabling the application of the AHP method in alignment with the established norms.

All respondents ranked human safety issues as the top priority, which aligns with internal policy, as human safety should always be the primary focus. Figure 4.1 shows the average ranking in which the lowest number has the highest ranking; the higher the graph the lower the ranking. Human Safety was followed by technical procedure comments in second place, technical sequence comments in third, configuration procedure comments in fourth, configuration sequence comments in fifth, de-nesting in sixth, auto-comments in seventh, typographical sequence comments in eighth, and typographical procedure comments in last place.

In the average ranking, technical procedure comments are closely aligned with technical sequence comments, as are configuration procedure comments with configuration sequence comments, and typographical sequence comments with typographical procedure comments. This ranking does not fully correspond with the norms in Table 4.1, where sequence comments have the highest benefits, followed by de-nesting work in second place and procedure comments in third, with auto-comments ranked last. This difference highlights the importance of comment type, where technical comments are regarded as more important than configuration, and configuration is more important than typographical. The outcome of this survey shows that the norms are outdated and that the norms do not match the perceived reality. It would be valuable to revise the norms for all the Service Mix Feedback Types.

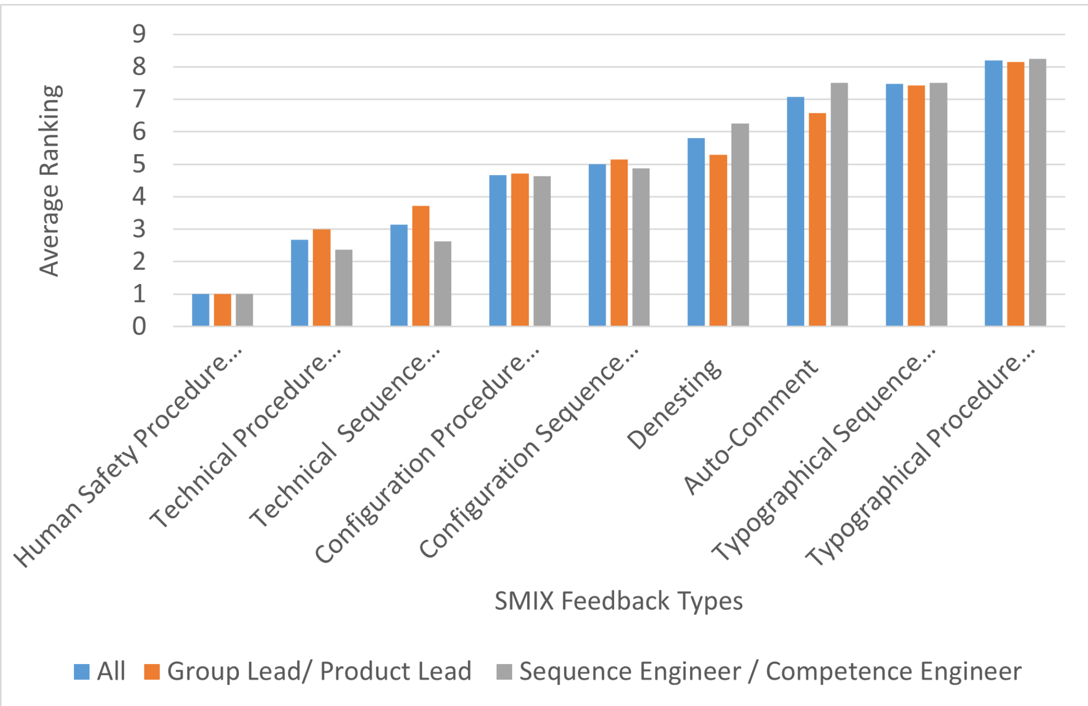


Figure 4.1: Average Ranking Results SMIX Feedback Types.

Figure 4.2 shows the ranking of the prioritisation factors, based on responses from 14 employees (N=14), including 7 Competence and Sequence Engineers and 7 Group and Project Leads, who may have different perspectives. The 15th employee completed the first part of the survey but did not provide answers for the second part. This could be due to several reasons, and as a result, we have chosen not to consider the blank response in the analysis of the second question. The orange graph represents the results from the Group and Project Leads, who ranked frequency first, but with the other six factors having very close average rankings. For the competence and sequence engineers, the comment details are more important. In contrast, the overall ranking is clearer: frequency was ranked first, followed by comment details in second, comments per procedure or sequence in third, procedure or sequence type in fourth, used in NPI in fifth, procedure or sequence execution time in sixth, and number of Field Service Engineers involved in seventh.

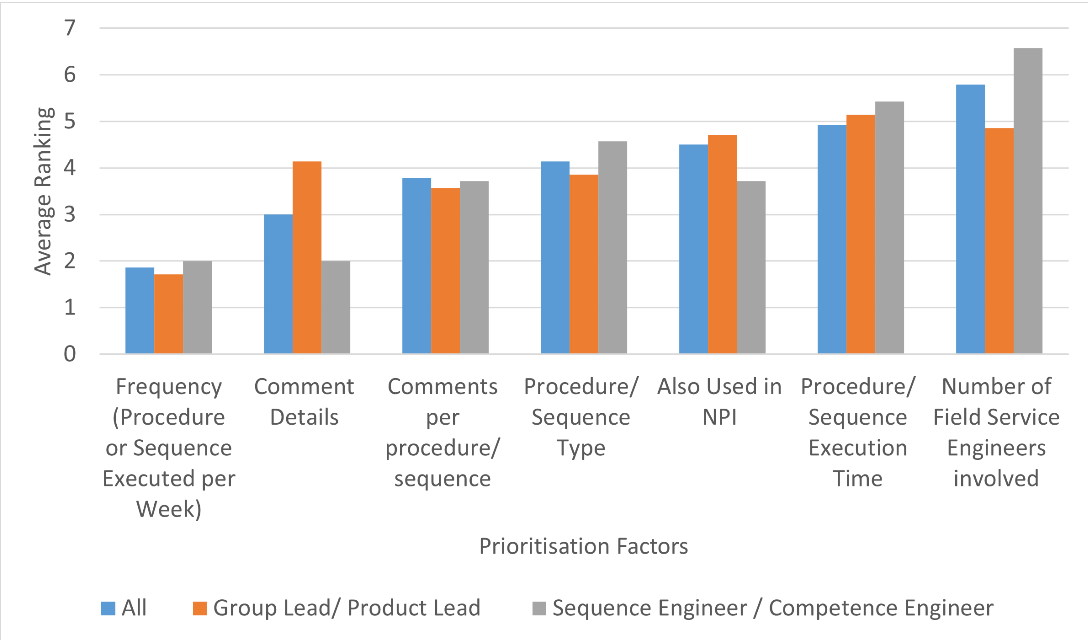


Figure 4.2: Average Ranking Results Prioritisation Factors.

4.2.2 The AHP method

This Section converts the survey results into an AHP matrix. First, the rankings of prioritisation factors are translated into pairwise comparisons to calculate AHP weights. Next, the Service MIX feedback types were ranked in a similar way, resulting in AHP weights for both the prioritisation factors and the feedback types.

The Prioritisation Factors based on Procedure or Sequence Characteristics

The AHP method was applied based on the survey results to derive the relative importance of factors for use in the prioritisation model. However, two factors—comment details and procedure or sequence types—were excluded due to the unavailability of sufficient data. Although their significance is recognised, these factors fall outside the scope of this study. As a result, the model focuses on the remaining five factors, which are ranked according to the survey findings.

The frequency (procedure or sequence executed per week), comments per procedure or sequence, procedure or sequence is also used in NPI, procedure or sequence execution time, and number of field service engineers involved in the service action.

The average ranking of these prioritisation factors is provided in Table 4.2. These rankings are as follows: Frequency (1.86), Comments per procedure or sequence (3.79), Also Used in NPI (4.5), Execution Time (4.93), and Engineers involved (5.79). To translate the ranking results into an AHP matrix, a systematic approach was employed by aligning the average ranking differences with the established AHP scale (1, 3, 5, 7, 9).

Table 4.2: The Average Ranking and Difference converted to the AHP scale

Ranking	**Factor**	**Average Ranking**
1	Frequency	1.86
2	Comments	3.79
3	NPI	4.5
4	Execution Time	4.93
5	Engineers	5.79

Difference in ranking (d)	**AHP scale**
$d \leq 0.5$	1
0.5 < d <= 1.5	3
1.5 < d <= 2.5	5
2.5 < d <= 3.5	7
d >3.5	9

Table 4.3 provides the absolute ranking difference between the different factors. Thus, for each pair, the difference in average ranking is calculated and the corresponding AHP value is assigned (e.g. the difference between "Frequency" and "Comments" is 1.93 which is between 1.5 and 2.5, it is assigned a 5, strong importance).

Table 4.3: Absolute difference between average ranking

Factor	Frequency	Comments	NPI	Execution Time	Engineers
Frequency	0	1.93	2.64	3.07	3.93
Comments		0	0.71	1.14	2
NPI			0	0.43	1.29
Execution Time				0	0.86
Engineers					0

The reciprocal values will be used for the reverse comparisons (e.g. if "Frequency" is strongly more important than "Comment" with a 5, then "Comment" compared to Frequency would be 1/5. Table 4.4 uses this approach and provides the matrix. The AHP weights are as follows: Frequency (0.584), Comments per procedure or sequence (0.199), Also Used in NPI (0.089), Execution Time (0.089), and Engineers involved (0.040). Due to rounding, the sum of the five factors slightly exceeds one.

Table 4.4: Prioritisation Factors AHP Pairwise Comparison

Factor	Frequency	Comments	NPI	Execution Time	Engineers	**AHP Weight**
Frequency	1	5	7	7	9	**0.584**
Comments	1/5	1	3	3	5	**0.199**
NPI	1/7	1/3	1	1	3	**0.089**
Execution Time	1/7	1/3	1	1	3	**0.089**
Engineers	1/9	1/5	1/3	1/3	1	**0.040**

Calculating the Consistency Ratio
To evaluate the consistency of the pairwise comparisons in the Analytical Hierarchy Process (AHP), the Consistency Ratio (CR) is computed using the Consistency Index (CI) and the Random Index (RI). The following calculations demonstrate the process.

Given:

- $\lambda_{\max} = 5.3262$
- $n = 5$
- $RI = 1.12$

Step 1: Calculate the Consistency Index (CI)
The Consistency Index is calculated using the formula:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4.1}$$

Substituting the given values:

$$CI = \frac{5.3262 - 5}{5 - 1} = \frac{0.3262}{4} = 0.08155 \tag{4.2}$$

Step 2: Calculate the Consistency Ratio (CR)
The Consistency Ratio is calculated using the formula:

$$CR = \frac{CI}{RI} \tag{4.3}$$

Substituting the values:

$$CR = \frac{0.08155}{1.12} = 0.0727 \tag{4.4}$$

Step 3: Evaluate Consistency
The calculated $CR = 0.0727$ is below the commonly accepted threshold of 0.10, indicating that the pairwise comparisons are consistent and acceptable, adhering to the consistency standards outlined in the literature (R. Saaty, 1987).

The Service MIX Feedback Types

Appendix F presents the factors for the various SMIX feedback types. Human Safety Procedure comments are always prioritised, and, for this reason, they are excluded from the /glsAHP method. The AHP is used to establish the factors for the overall prioritisation method, excluding factors that are given absolute priority, such as Human Safety Procedure comments. After excluding the Human Safety Procedure comment the survey consists of eight Service MIX Feedback types. As mentioned in Section 4.2.1 the sequence comment priority was excluded to make the survey more manageable, as priority levels (critical, high, medium, low) are already predefined. However, for the prioritisation model, these priorities should be included.

For the Service MIX feedback types, the average ranking according to the survey is:

1. Technical Procedure Comment = 2.17
2. Technical Sequence Comment = 3.13
3. Configuration Procedure Comment = 4.67
4. Configuration Sequence Comment = 5
5. De-nesting = 5.8
6. Auto Comment = 7.07
7. Typographical Sequence Comment = 7.47
8. Typographical Procedure Comment = 8.2

To incorporate the different priorities for the sequence comments (critical, high, medium, low), we used the difference between successive factors in the ranking of the Service MIX Feedback types. For instance, the Technical Sequence Comment (3.13) the Configuration Procedure Comment (4.67) have a difference of $4.67 - 3.13 = 1.54$. By dividing this base difference by four, we obtained an increment value of 0.385, which is applied to distinguish between the different priority levels for sequence comments.

- Technical Sequence Comment Critical - 1 = 3.13 (used the base Technical Sequence Comment Score)
- Technical Sequence Comment High - 2 = 3.13 + 0.385 = 3.515
- Technical Sequence Comment Medium - 3 = 3.515 + 0.385 = 3.9
- Technical Sequence Comment Low - 4 = 3.9 + 0.385 = 4.285

Table 4.5 also presents this approach for the two other sequence comment types, namely Configuration Sequence Comment and Typographical Sequence Comment.

Table 4.5: Average Ranking and AHP Weights for Service MIX Feedback Types

Ranking	Factor	Average Ranking	AHP Weight
1	Techical Proc. Comment	2.17	0.2021
2	Technical Seq. Comment - 1 Critical	3.13	0.1325
3	Technical Seq. Comment - 2 High	3.52	0.1135
4	Technical Seq. Comment - 3 Medium	3.9	0.0933
5	Technical Seq. Comment - 4 Low	4.29	0.0787
6	Config. Proc. Comment	4.67	0.0648
7	Config. Seq. Comment - 1 Critical	5	0.053
8	Config. Seq. Comment - 2 High	5.2	0.0486
9	Config. Seq. Comment - 3 Medium	5.4	0.0453
10	Config. Seq. Comment - 4 Low	5.6	0.0425
11	Denesting	5.8	0.0385
12	Auto-Comment	7.07	0.0186
13	Typo Seq. Comment - 1 Critical	7.47	0.0157
14	Typo Seq. Comment - 2 High	7.65	0.0142
15	Typo Seq. Comment - 3 Medium	7.84	0.0133
16	Typo Seq. Comment - 4 Low	8.02	0.0129
17	Typo Proc. Comment	8.2	0.0123

As was done for the prioritisation factors based on procedure and sequence characteristics, the method for the Service MIX Feedback types is the same. This is due to the fact that the method includes 17 factors; both the difference table and the AHP matrix can be found in Appendix F. The last column of the table 4.5 contains the AHP weight for the Service MIX Types. The calculation of the Consistency Index can be found in Appendix G.

Table 4.6: Conversion of SMIX Feedback Survey into AHP

Difference in ranking (d)	**AHP scale**	
$d \leq 0.67$	1	Equal Importance
$0.67 < d \leq 1.34$	2	
$1.34 < d \leq 2.01$	3	Moderately more important
$2.01 < d \leq 2.68$	4	
$2.68 < d \leq 3.35$	5	Strongly more important
$3.35 < d \leq 4.02$	6	
$4.02 < d \leq 4.69$	7	Very strongly more important
$4.69 < d \leq 5.36$	8	
$d > 5.36$	9	Extremely more important

4.3 The Concept of prioritisation

The main idea behind prioritisation is to optimize the use of limited resources by focusing on the most impactful tasks. The key to effective prioritisation lies in measuring the impact of comments. This can be approached in several ways, ranging from a basic model based on frequency in Section 4.3.1 to more advanced methods that incorporate multiple variables in Section 4.3.2 and 4.3.3. This section will introduce a relatively simple, medium and advanced impact factor.

4.3.1 Simple Impact Model: Frequency-Only Approach

This model considers the different Service MIX feedback types, but focuses only on the frequency as a prioritisation factor based on procedure and sequence characteristics. The simplest model ranks comments based solely on the frequency on which a procedure, sequence or part is opened or used. While this approach offers a straightforward ranking, it has its limitations, as procedure opens and sequence exports do not necessarily mean they are executed. Combining multiple data sources (e.g. sequence exports, procedure opens, and parts usage) may offer a more nuanced understanding of frequency. Furthermore, it serves as the only worldwide indication on how often service activities are executed.

Although this model does not take into account many factors, it is still relevant to combine multiple data sources: procedure opens, sequence exports and parts usage.

As a result of procedures that are linked to sequence exports and procedures that are linked to multiple parts, it is possible to make a combination table. Because multiple parts are linked to one procedure, we chose the most expensive part as the part for which we take into account the parts usage. Then it is possible to create a list of all the procedures with their parts usage, sequence exports, and procedure opens. Table 4.7 provides this information with the Epic Codes of ten procedures. The table is sorted in descending order, from the highest to the lowest score. The score consists of the following formula

$$\text{Score} = \frac{\text{Sequence Exports} + \text{Procedure Opens} + \text{Parts Usage (if Parts Usage} > \text{€1000)}}{n}$$

Where:

- n is the number of components included
  - n = 3 if Sequence Exports, Procedure Opens and Parts Usage (if Part > €1000) are all present.
  - n = 2 if only two of the components are present.
  - n = 1 if only one component is present.

The score is calculated by averaging the values of Sequence Exports, Procedure Opens, and Parts Usage (if the part cost exceeds €1000). If all three components are present the score is divided by 3. If only two components are included, the score is divided by 2, and if only one component is present, the score equals the value of that component.

This method can be applied, for instance, in the context of de-nesting, where many procedures are nested or interlinked and a large list is provided. Determining where to begin can be challenging. However, a simple approach of ranking procedures within the list based on frequency can significantly ease the engineer's tasks. By relying on data rather than intuition, the process becomes more objective and structured. Nevertheless, it remains important to consider expert judgement and validate the data through cross-checking the accuracy.

4.3.2 Medium Impact Model: Frequency and Execution Time

This model considers the different Service MIX feedback types and builds further on the simple frequency model by also considering the duration of service actions. Long procedures have a larger impact on operations, while frequent but shorter procedures can still represent a significant workload. This model balances both dimensions for a more accurate prioritisation. To explain this medium impact model Table 4.8 shows the same procedures with the A-time included.

For simplicity, the delay in execution time (B-time) is equal to 0.6 times the A-time. Consequently, the total execution time is equal to 1.6 times the A-time. Therefore, the score is calculated using the formula used in Section 4.3.1, now multiplied by 1.6 times the A-time. The formula is as follows:

$$\text{Score} = \frac{\text{Sequence Exports} + \text{Procedure Opens} + \text{Parts Usage (if Parts Usage} > \text{€1000)}}{n} * 1.6 * \text{A-time}$$

Table 4.7: 10 Procedures with the Simple Impact Model

Procedure	Score	Part Usage	Sequence	Procedure	Part Cost	Sub System
A	**2.55**	0.00	0.00	2.55	≥€1000	ImageSensor
B	**2.53**	0.00	0.00	2.53	<€1000	ReticleStage
C	**2.51**	0.04	0.00	2.51	<€1000	Projection
D	**2.44**	0.21	0.00	2.44	<€1000	VacuumSystem
E	**1.27**	0.42	0.00	2.13	≥€1000	VacuumSystem
F	**1.11**	0.27	0.23	1.98	<€1000	WaferStage
G	**1.03**	0.00	0.40	1.66	≥€1000	WaferStage
H	**0.86**	0.00	0.80	0.93	≥€1000	WaferHandling
I	**0.69**	0.06	0.51	1.49	≥€1000	DropletGeneration
J	**0.57**	0.04	0.82	0.84	≥€1000	FlowAndTemp.

Where:

- n represents the number of components included (either 1,2, or 3).
- *A-time* is the optimal execution time assigned to a procedure while B-time is a constant factor.

The table is sorted in descending order, from the highest to the lowest score. By comparing Table 4.7 with Table 4.8, it becomes evident that the inclusion of the A-time factor changes the order of procedures. This change highlights the influence of the execution time on the ranking process, demonstrating that procedures with longer execution times are prioritised differently than when time was not considered.

It is important to note that the sequence exports, procedure opens, and parts usage are live metrics that continuously change over time as new data becomes available, whereas A-time is a standardized value assigned to a procedure. Although the A-time can be updated if the procedure is modified, these changes do not occur in real-time.

Incorporating execution time into the prioritisation process ensures that decisions are not solely based on frequency as in Section 4.3.1, but also account for the time required for each procedure.

Table 4.8: 10 Procedures with the Medium Impact Model

Proc.	Score	Part Usage	Sequence	Procedure	A-time(hrs)	Part Cost	Sub System
A	**8.23**	0.00	0.00	2.55	2.02	≥€1000	ImageSensor
B	**8.08**	0.00	0.00	2.53	2.00	<€1000	ReticleStage
C	**7.94**	0.04	0.00	2.51	1.98	<€1000	Projection
D	**7.54**	0.21	0.00	2.44	1.93	<€1000	VacuumSystem
E	**3.42**	0.42	0.00	2.13	1.68	≥€1000	VacuumSystem
F	**2.78**	0.27	0.23	1.98	1.57	<€1000	WaferStage
G	**2.18**	0.00	0.40	1.66	1.32	≥€1000	WaferStage
I	**1.30**	0.06	0.51	1.49	1.18	≥€1000	DropletGen.
H	**1.01**	0.00	0.80	0.93	0.73	≥€1000	WaferHandling
J	**0.61**	0.04	0.82	0.84	0.67	≥€1000	FlowAndTemp.

4.3.3 Advanced Impact Model: Comprehensive Approach

Based on 4.1.2 it is possible to use the factors for prioritisation and consider the prioritisation factors and the SMIX feedback types. The formula 4.6 shows an overview of these factors, with on the left-hand side the prioritisation factors taking into account the procedure and sequence characteristics and on the right side the SMIX feedback types.

As mentioned in Section 4.1.2 the comment details and the procedure or sequence type are not taken into account, the data set available does not support prioritisation based on these two factors. This means that only five factors are used based on the Frequency, Execution Time, Also Used in NPI, Field Service Engineers and the Number of Comments.

Table 4.9: Ten procedures with the Advanced Impact Model

Procedure	**Frequency**	**Comments**	**Engineers**	**Used in NPI**	**Execution Time (hrs)**
A	2.55	3	2	0	3.23
B	2.53	3	1	1	3.20
C	2.51	0	2	0	3.17
D	2.44	0	2	0	3.09
E	1.27	4	1	1	2.69
F	1.11	0	2	0	2.51
G	1.03	3	1	0	2.11
H	0.86	2	2	1	1.17
I	0.69	0	1	0	1.89
J	0.57	0	1	0	1.07

Table 4.9 shows that the advanced impact model considers 5 factors with all different values.

However, multiplying numerical values with categorical values can lead to ambiguity in the resulting objective value. The AHP method, as explored in Chapter 3, allows for the comparison of both numerical and categorical values. To effectively compare these different types of data, the AHP method is combined with normalization techniques. This ensures that all scores are standardized to a range between 0 and 1.
The normalized score is calculated using Min-Max normalization, where the minimum value of each variable is transformed to zero, the maximum value is transformed to one, and all other values are scaled as decimals between 0 and 1. The formula is as follows:

$$\frac{\text{value} - \text{min}}{\text{max} - \text{min}} \tag{4.5}$$

Table 4.10 provides the maximum and minimum values used in the normalization process, and Table 4.11 presents the resulting normalized factors.

Table 4.10: The Maximum and Minimum Factors used for Normalization

Factor	**Frequency**	**Comments**	**Engineers**	**Used In Npi**	**Execution Time**
Maximum	10	30	6	1	20
Minimum	0	0	0	0	0

Table 4.11 presents all the normalized factors, with the exception of the UsedInNPI factor, as this factor is binary and takes values of either 0 or 1.

Table 4.11: The Normalized Factors

Proc.	**Norm. Freq.**	**Norm. Comments**	**Norm Engineers**	**UsedinNPI**	**Norm Execution Time**
A	0.149	0.0199	0.0133	0	0.288
B	0.148	0.0199	0.0067	1	0.285
C	0.146	0.0000	0.0133	0	0.282
D	0.143	0.0000	0.0133	0	0.275
E	0.074	0.0265	0.0067	1	0.239
F	0.065	0.0000	0.0133	0	0.224
G	0.060	0.0199	0.0067	0	0.188
H	0.050	0.0133	0.0133	1	0.104
I	0.040	0.0000	0.0067	0	0.168
J	0.033	0.0000	0.0067	0	0.095

The normalised factors are multiplied by the AHP weights from table 4.12 for the prioritisation factors. Using the following prioritisation formula with the normalised factors:

$$(0.584\,\text{Frequency} + 0.089\,\text{Execution Time} + 0.089\,\text{Used in NPI} + 0.04\,\text{Field Service Engineers} + 0.199\,\text{Comments}) \\ *\text{SMIX Feedback Type} \tag{4.6}$$

In this way the scores are built up based on the survey conducted, and the AHP method.

Table 4.12: The AHP Weights

Factor	Frequency	Comments	Engineers	Used in NPI	Execution Time	Total
AHP Factor	0.584	0.199	0.04	0.089	0.089	**1**

Ultimately, the different factors are summed to represent the total score for the impact based on sequence and procedure characteristics, as shown in Table 4.13.

Table 4.13: The Advanced Impact Model

Procedure	Total Score	Frequency	Comments	Engineers	UsedinNPI	Execution Time
B	**0.204**	0.087	0.004	0.001	0.000	0.025
E	**0.159**	0.086	0.004	0.000	0.089	0.025
H	**0.131**	0.086	0.004	0.000	0.089	0.025
A	**0.117**	0.083	0.000	0.001	0.000	0.024
C	**0.111**	0.043	0.005	0.000	0.089	0.021
D	**0.108**	0.038	0.000	0.001	0.000	0.020
F	**0.058**	0.035	0.004	0.000	0.000	0.017
G	**0.056**	0.029	0.003	0.001	0.089	0.009
I	**0.039**	0.019	0.000	0.000	0.000	0.008
J	**0.028**	0.019	0.000	0.000	0.000	0.008

4.4 Comparison Between the Three Methods

Table 4.14 presents the rankings derived from the three methods, with the ranking order based on the advanced score. The table illustrates that there is minimal difference between the rankings produced by the medium and simple score methods.

When focusing on Procedure H, which ranks third in the Advanced Score ranking but falls to ninth and eighth in the Medium and Simple Score rankings, the variation in its position can be attributed to differences in the scoring criteria. Procedure H scores are relatively low on factors such as frequency and execution time, which is emphasised in the Simple and Medium methods. However, it achieves higher scores in factors such as the number of comments, the number of engineers involved, and its utilisation in NPI. The Advanced Impact method incorporates these additional factors, resulting in a higher overall ranking for Procedure H.

It is important to note that this ranking is solely based on prioritisation factors related to procedure and sequence characteristics. The Service MIX Feedback types have not been considered in this ranking.

Table 4.14: Rankings of Procedures by Advanced, Medium, and Simple Scores

Procedure	Advanced Score Ranking	Medium Score Ranking	Simple Score Ranking
B	1	2	2
E	2	5	5
H	3	9	8
A	4	1	1
C	5	3	3
D	6	4	4
F	7	6	6
G	8	7	7
I	9	8	9
J	10	10	10

4.5 Conclusion

To conclude, the Advanced Impact Model emerges as the most suitable method for measuring the impact of a comment on service operations. After collecting data and conducting the survey based on multiple criteria, the Advanced Impact Model provides a structured approach that incorporates the AHP method and integrates several normalised factors to achieve the desired prioritisation outcomes. This chapter serves as the foundation for Chapter 5, where the prioritisation method will be further developed. Additionally, in Chapter 5, the results of the three different methods will be compared to evaluate their effectiveness in real-world scenarios.

5 Model and Results

This chapter introduces the model and the results. Section 5.1 briefly introduces the model. Section 5.2 provides the general prioritisation model; this model allows engineers to solve tickets across all clusters, followed by the model per cluster in Section 5.3, this model restricts solving capacity to specific clusters. Finally, Section 5.4 compares three different methods with the historic method.

5.1 Introduction to Model

This model aims to help decide which tasks (in the model referred to as ticket), either a procedure comment, sequence comment, auto-comment or a de-nesting task with a certain priority and comment type should be prioritised and solved each week while tracking tasks that are not completed (backlog) and trying to solve them in future weeks. The model aims to maximise the value derived from maintaining and updating procedures and sequences. It prioritises tasks by using an integer linear programming model, which optimally allocates tasks across periods (e.g. weeks).

The model helps prioritise and solve tickets weekly, ensuring efficient use of limited resources. It evaluates new and unresolved tickets from the previous weeks (backlog) each week. Tickets are assigned based on their importance. The goal is to maximise the value of tasks solved each week, ensuring that engineers handle the most critical tasks first without exceeding the available work capacity.

If a task is not solved in the current week, it is added to the backlog and reconsidered in future weeks. The backlog is re-prioritised, along with new tasks arriving each week, ensuring that no important tasks are missed. This process continues until all tasks are completed or the planning period ends.

In the practical implementation of the model, human safety comments are always prioritised above other types of comments. This is because ASML's focus is on human safety (ASML, 2020). This is also the reason why Human Safety comments are not incorporated in the prioritisation model but the time required to address them is deducted from the available capacity.

The model uses arrival rates for different types of comments based on historical data from April 2023 to February 2024. Incorporating historical data allows the model to simulate realistic conditions. These arrival rates represent how often each Service MIX type appears each week:

- 12 Sequence Comments per week
- 80-100 Auto-Comments per week
- 4 Denesting comments per week
- 80 Procedure Comments per week

Resource Availability: As noted in Chapter 2, the number of competence engineers remains constant, while the inflow of comments increases. This makes effective prioritisation essential. On average a competence engineer works 10%-20% of his time on comment solving. The number of competence engineers that are working on comment solving is around 50. This means that on average, there are around 200-400 hours available for comment-solving each week. With 10% representing limited capacity and 20% representing sufficient capacity.

5.2 General Model

This general practical model provides an overview of the prioritisation process used to solve tickets over a multi-period planning horizon. Before solving the model, tickets are sorted by period with human safety tickets always prioritised above all others to ensure they are processed as soon as they become available. This implies that human safety tickets impact the capacity but not the model. Given that the workload on Human Safety tickets is significantly lower than the available capacity. The model is solved for each week in the planning period, starting from the first week and ending in the final week of the planning horizon.

Each ticket has a specific release week, representing the earliest time it can be processed. If a ticket cannot be solved in its assigned period, it will be added to the backlog for the next period. Thus, a ticket cannot be solved partly in period n and partly in $n+1$. The model uses historical data from April 2023 to February 2024, allowing for an evaluation of the model's performance over an extended planning horizon.

Indexing:

- m: Comment ID, uniquely identifying each SMIX-related ticket (Procedure Comment, Sequence Comment, Auto-Comment, and De-nesting).
- t: The current time bucket in the planning horizon.

Parameters:

- N_t: Set of new tickets in current time period t.
- W_m: Weight of SMIX ticket m, determined by the SMIX Feedback type, comment type, and priority determined in Section 4.1.1.
- I_m: Impact of ticket m, based on sequence and procedure characteristics determined in Section 4.1.2.
- V_m: The value of ticket m, Which is W_m multiplied by I_m.
- CE_t: Number of Competence Engineers available to solve comments in each period t.
- C_m: The hours required to solve ticket m, representing the cost in hours for a Competence Engineer.
- p: Percentage of time competence engineers spend on comment solving each week; one full work week is 40 hours.

Decision Variables:

- $x_{m,t}$: A binary decision variable that indicates whether ticket m is processed in period t (1 if processed in period t, 0 otherwise). This variable helps determine the period in which the task is executed.

Supporting Variables and Formulas:

- T_t: Set of tickets available in current time period t.
- B_t: Set of backlog tickets at the start of time t.

The set of all tickets available in time period t consists of the backlog set (B_t), which are carried forward from previous periods, and newly arriving tickets (N_t) for the current period:

$$T_t = B_t \cup N_t \tag{5.1}$$

The following formula calculates the value of each SMIX ticket m, considering the SMIX type and the prioritisation factors from Section 4.5:

$$V_m = I_m * W_m \tag{5.2}$$

Tickets that are not solved in the current period are added to the backlog for the next period t + 1. Thus, B_{t+1} represents the set of tickets from T_t for which $x_{m,t} = 0$. This ensures that all unsolved tickets are reconsidered in future weeks:

$$B_{t+1} = \{m \in T_t \mid x_{m,t} = 0\} \tag{5.3}$$

Objective Function:

The objective function maximises the total value derived from solving the SMIX Feedback tickets per period:

$$Maximize \sum_{m \in T_t} V_m * x_{m,t} \tag{5.4}$$

This function considers the value of the tickets, their weight based on comment type and priority, and the decision variables indicating whether a ticket is processed in a given period t.

Constraints

Resource Constraint: Ensures that the total time spent by Competence Engineers on solving tickets in each period does not exceed the available hours. The total available hours represent the fraction of time spent by Competence Engineers on solving comments multiplied by the hours the engineers work in one week (40 hours):

$$\sum_{m \in T_t} C_m * x_{m,t} \leq CE_t * 40 * p \tag{5.5}$$

The model is solved with the PuLP (Python universal Linear Programming) solver; this is an optimisation modelling package that enables users to solve linear and integer programming problems. PuLP helps determine the optimal selection of items (tickets) to maximise the objective function while adhering to capacity constraints.

The general model utilises the cost and weight factors for the various SMIX Feedback Types, as detailed in Table 4.1. The cost factors are derived from Section 4.1.1, particularly from Table 4.1. These standards have been slightly adjusted, especially for typographical comments, which are generally easier to solve. As a result, the typographical cost of solving for both sequence and procedure comments has been standardised to one hour.

The weights are based on the prioritisation method discussed in Section 4.2.2, concerns Table 4.5.

Results

To provide the first model results, it is important to note that the Advanced Impact method is used. Later, in Section 5.4, the Simple, Medium, and Advanced Impact methods are compared, but for now, the results are presented using the Advanced Impact method to demonstrate the model's performance.

Figure 5.1 shows the cumulative value of tickets processed and the total value of tickets processed per week. The bright orange and the less bright orange lines indicate that a competence engineer dedicates 10 percent of their time to solving comments, which translates to 4 hours per week, assuming a 40-hour workweek. The bright blue and the less bright blue lines indicate that a competence engineer dedicates 20 percent of their time, meaning 8 hours per week. The total value of tickets processed is 11.54 for 13 weeks when the competence engineer works 4 hours per week on comments. For 8 hours per week, the total value increases to 12.10, which represents a 4.9 percent increase in value. However, Figure 5.1 shows that, despite limited capacity in weeks 15, 16, and 18, the total value of tickets solved per week can still be higher.

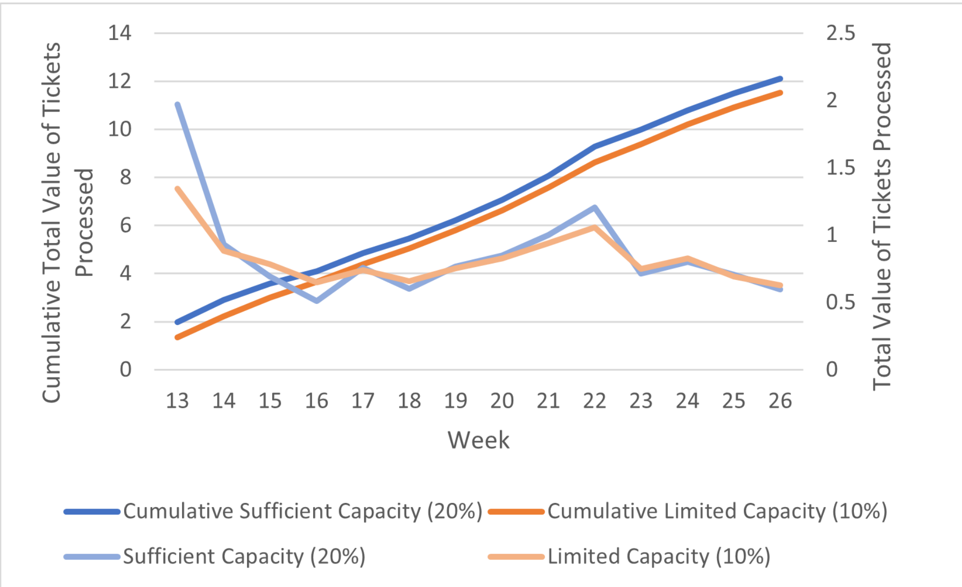


Figure 5.1: Cumulative Total Value and Total Value of Tickets Processed for Limited (10%) and Sufficient (20%) Capacity

Figure 5.2 shows the utilized capacity versus the total capacity available. As seen in week 13, the model starts with an initial backlog, which persists throughout the modelling period. This backlog influences the behavior observed in Figure 5.3, where an increase in backlog occurs if no solving capacity is available.

Little's Law, which states that WIP (Work In Progress) = Throughput × Cycle Time, can help explain the model's performance. In this case, when the solving capacity is fully utilized, as shown in Figure 5.2 at 10% focus on comments, there is no idle time. This implies that the available resources are fully committed, leading to an increase in WIP, or backlog, as the demand exceeds the solving capacity. The absence of idle time ensures that no resources are left unused, but it also results in the buildup of unresolved comments in the backlog, as reflected in Figure 5.3.

This dynamic illustrates how capacity constraints directly affect the backlog, and the model highlights that increasing engineer capacity or focus may help balance the throughput and avoid bottlenecks in the process.

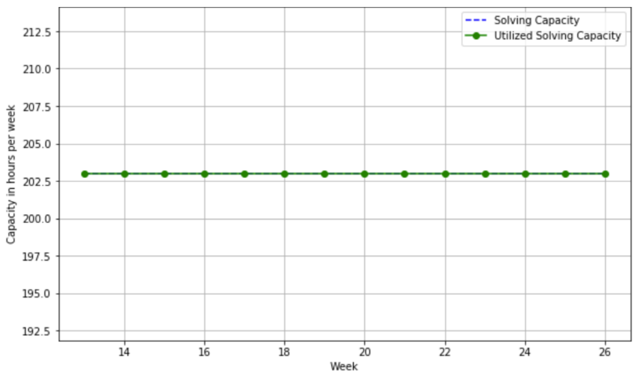


Figure 5.2: Capacity vs. Utilized Capacity with 10% Competence Engineer Capacity

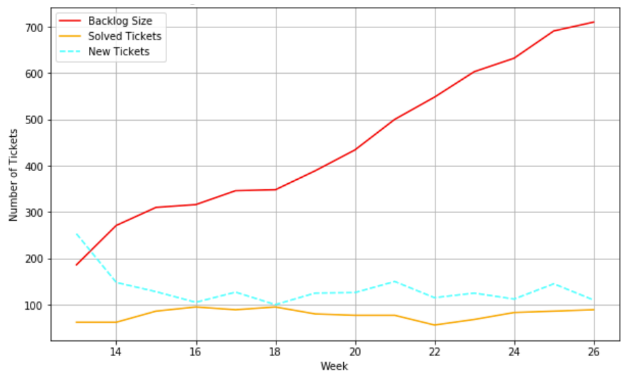


Figure 5.3: Backlog, Solved and New Comments with 10% Competence Engineer Capacity

Figures 5.4 and 5.5 show how the focus of a competence engineer helps balance the backlog. While capacity was previously fully utilized at 100%, it is now utilized at an average of 70%, as depicted in Figure 5.4.

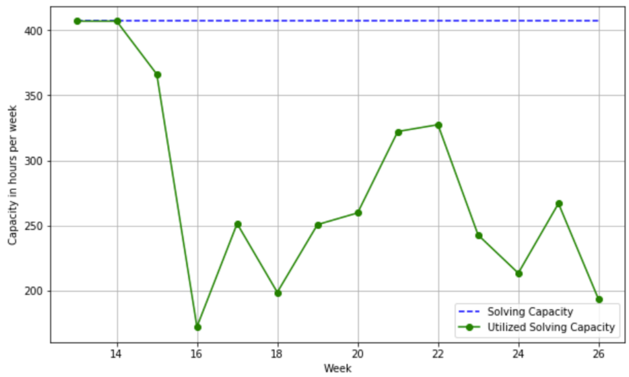


Figure 5.4: Capacity vs. Utilized Capacity with 20% Competence Engineer Capacity

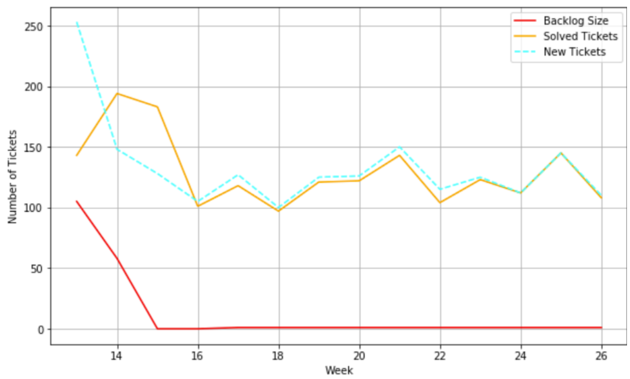


Figure 5.5: Backlog, Solved and New Comments with 20% Competence Engineer Capacity

However, comments are not solved as in the general model because the machine is divided into clusters, where engineers specialize in specific areas. As a result, using the general model is impractical, since comments are resolved at the cluster level, where each cluster has a specific capacity determined by the number of engineers available. Therefore, the next section, Section 5.3, focuses on solving comments and developing the prioritisation model at the cluster level.

5.3 Model per Cluster

The general practical cluster serves as a fundament for the practical model per cluster. The model per cluster only changes within thee capacity constraint. In this Section, only the changes will be mentioned.

Table 5.3 provides the division of competence engineers per cluster.

Table 5.1: Division of Comptence Engineers per cluster

	Cluster	**Number of Competence Engineers (FTE)**
1	A	5
2	B	6
3	C	3.5
4	D	3.9
5	E	5
6	F	2
7	G	3.9
8	H	2.5
9	I	5
10	J	3
11	K	1.6
12	L	1.4
13	M	8.1
	Total	**50.9**

Index:

- c: Represents the cluster connected to ticket m.

Parameter:

- $CE_{t,c}$: The number of Competence Engineers available to solve comments in each cluster c for each period t.

Objective Function: The objective function maximises the total value derived from solving the SMIX Feedback tickets per period, per cluster:

$$Maximize \sum_{m \in T_t} V_m * x_{m,t,c} \tag{5.6}$$

This function considers the value of the tickets, their weight based on comment type and priority, and the decision variables indicating whether a ticket is in a certain cluster and processed in a given period t.

Constraints:

Resource Constraint: Ensures that the total time spent by Competence Engineers per cluster on solving tickets per cluster in each period does not exceed the available hours. Here the total available hours per cluster for the competence engineers represents the number of Competence Engineers per cluster multiplied by the number of hours an engineer is available to solve work on the Service MIX Feedback.

$$\sum_{m \in T_t} C_m * x_{m,t,c} <= CE_{t,c} * 40 * 0.2 \tag{5.7}$$

Results

This section presents the results for three clusters, each showcasing their utilised capacity, backlog development, and ticket processing dynamics. First, the E cluster is examined, which experiences full capacity utilisation throughout the period. Following this, the D cluster is analysed, with its capacity fully utilised for approximately 50% of the time. Finally, the H cluster is discussed, where the capacity is utilised on average for less than 25%. These results highlight the varying levels of capacity utilisation across clusters and the impact on backlog accumulation.

Important to note is that for the results, the advanced impact method is used. In total, there are 13 clusters used in the model.

Figures 5.6 and 5.7 demonstrate the fully utilised capacity in Figure 5.6 As a consequence, the backlog begins to increase even when a competence engineer allocates 20% of their time to addressing these tickets. This suggests that the current capacity is insufficient to handle the volume of incoming tickets, resulting in a continuous accumulation of backlog. This is a notable difference from the general model, which is able to solve all tickets at this capacity level.

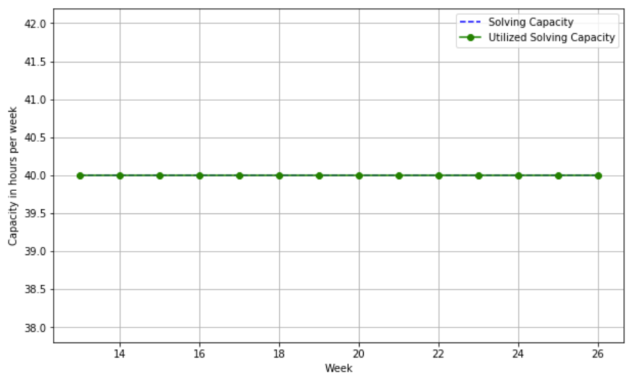


Figure 5.6: Utilised Capacity for E Cluster with 20% Competence Engineer Capacity

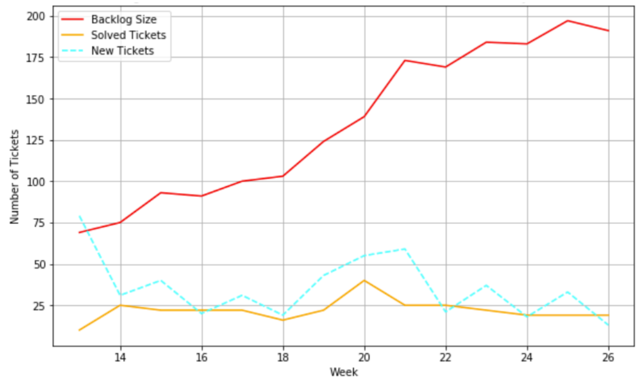


Figure 5.7: Backlog, Solved, and New Tickets for E Cluster with 20% Competence Engineer Capacity

Figure 5.8 illustrates the results for the D cluster, which is fully utilised during the first seven weeks. Starting from week 20, additional capacity becomes available, allowing the backlog to be gradually reduced. However, in week 21, although the model has the capacity to solve a ticket, the ticket requires more time than available, resulting in a small backlog increase of 1. A similar situation occurs in week 25, as shown in Figure 5.9.

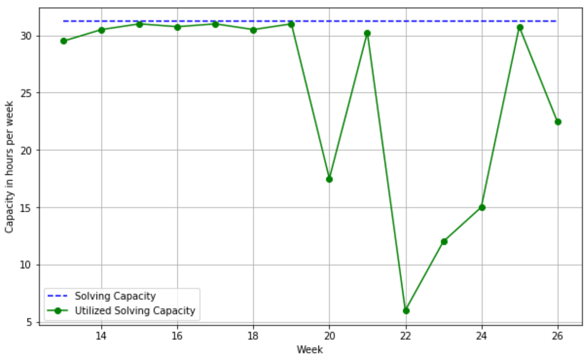


Figure 5.8: Utilized and solving capacity D cluster with 20% Competence Engineer Capacity

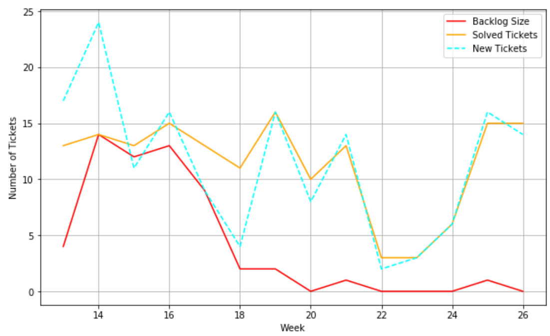


Figure 5.9: Backlog, Solved, and New Tickets D Cluster with 20% Competence Engineer Capacity

Figure 5.10 illustrates that the solving capacity is higher than the number of comments arriving at the cluster level. This indicates that while some clusters are operating at full capacity, others, such as the H Cluster, are less occupied and have more available time for tasks other than comment resolution. This variation across clusters highlights the importance of a cluster-specific approach in the model, as the workload distribution differs significantly between them.

While additional clusters were analyzed, not all graphs are presented here. However, the data clearly demonstrates that workload distribution varies significantly between clusters. Some clusters consistently operate at full capacity, while others function at reduced levels or are nearly idle. This variation, while potentially influenced by factors within the model, generally highlights that certain clusters are more heavily involved in comment

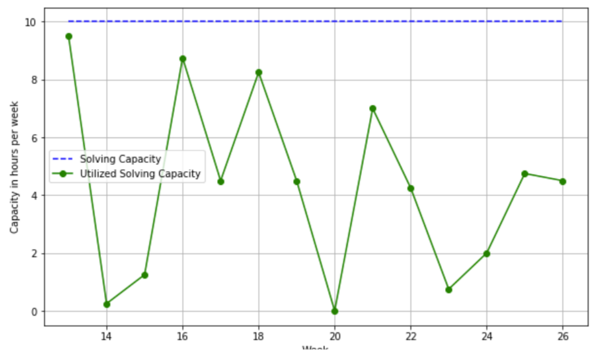


Figure 5.10: Utilized and solving capacity H Cluster with 20% Competence Engineer Capacity

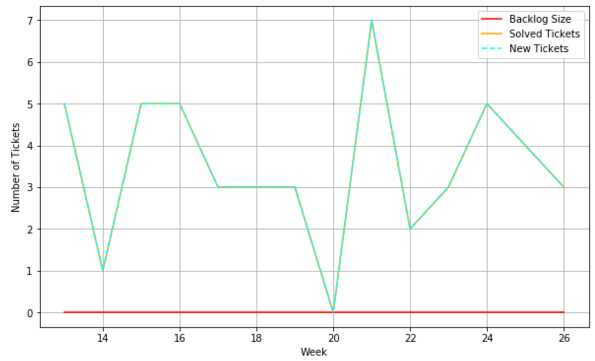


Figure 5.11: Backlog, Solved, and New Tickets H Cluster with 20% Competence Engineer Capacity

resolution than others. Table 5.2 further underscores the importance of adopting a cluster-specific approach in the model.

Table 5.2: The Utilized Capacity with a limited capacity (10%) in Engineers

Cluster	**Utilized Capacity (%)**
A	100.00
B	100.00
C	22.19
D	91.58
E	100.00
F	0.22
G	55.63
H	43.04
I	14.20
J	1.64
K	3.07
L	0.00
M	4.24
Average	**41.22**

With a capacity of 20%, three clusters—namely the E, B, and A clusters—show a steadily increasing backlog. Additionally, when the capacity is reduced to 10%, five clusters, including the E, B, and A clusters as well as the G and D clusters, experience backlog growth. This development indicates that prioritisation becomes critical, as the backlog increase suggests that not all tickets can be resolved within the available capacity, making prioritisation necessary to address the most impactful comments first.

With a 20 % engineer capacity, three clusters have an increasing backlog due to fully utilised capacity. Similarly, at a 10% engineer capacity, five clusters experience an increasing backlog, while the remaining eight clusters have sufficient capacity. This imbalance in resource allocation highlights an unbalanced division of capacity across clusters.

Aggregating the average capacity utilisation across all clusters shows an overall utilisation below 100%, suggesting that, in theory, there is enough capacity to address all comments. However, due to the unbalanced distribution of workloads, backlogs continue to grow in the clusters. This unbalanced load results in backlogs in three clusters with 20% engineering capacity and in five clusters with a 10% engineering capacity.

5.4 Comparison with the Current Way of Working

How to assess the improvement of the new method? How to compare the old method with the data-driven prioritisation model, what if the work will not be prioritised, and what if it will be using the new prioritisation method? Is it possible to focus on the tickets that are the most impactful, and is there a significant difference with the old way of working?

Figure 5.13 illustrates the cumulative benefit of procedure comments over a period of 13 weeks, representing one quarter. If the competence engineer capacity is 20 % that equals 8 hours a week. This comparison highlights the current method alongside the new prioritisation approaches. The purple line depicts the cumulative benefit per week based on the actual solved dates of procedure comments from historical data, while the blue line represents the cumulative benefit generated by the advanced prioritisation method. The red and green lines correspond to the medium and simple prioritisation methods, respectively. After 13 weeks, the cumulative benefit achieved is at least 54% higher for the advanced, medium, and simple methods compared to the historical approach. The three methods have equivalent scores due to the fact that there is no significant backlog, so all tickets can be solved.

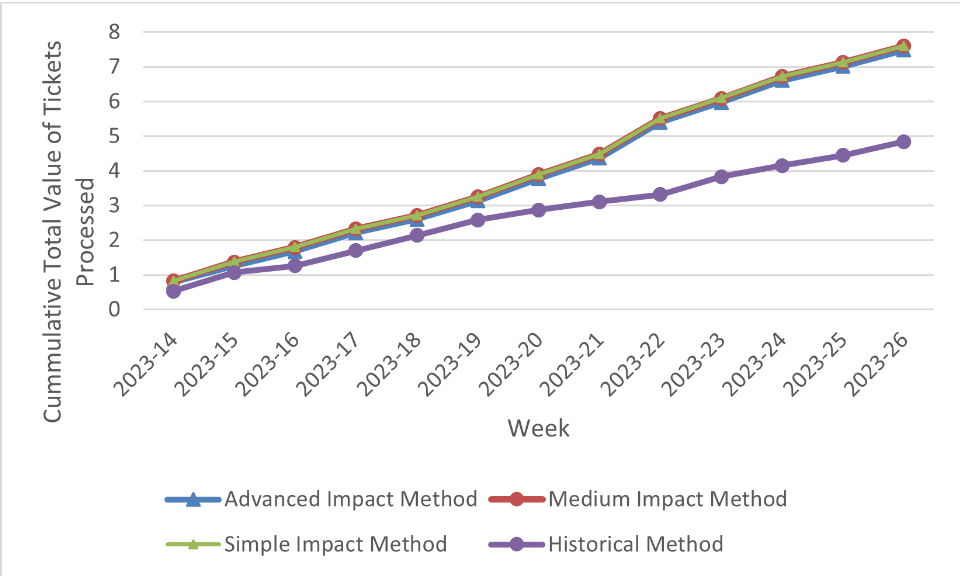


Figure 5.12: Historic compared to the Advance, Medium and Simple Impact Method with 10% Competence Engineer Capacity

However, the 20% capacity assumption is less realistic, which is why the model was also evaluated with 10% of the engineers' capacity. Under this scenario, the general model is unable to solve all tickets, necessitating active prioritisation of comments. After 13 weeks, the cumulative benefit achieved is at least 48% higher for both the medium and simple methods compared to the historical approach, while the advanced method shows an increase of nearly 59% of the total value of all the tickets. The advanced method also outperforms the simple and medium impact methods by 7% in the total value of tickets, further emphasising its benefit.

The historic method reaches a total value of tickets of 4.85 after 13 weeks, whereas the new advanced method achieves the same value in under 9 weeks. This indicates that, with the Advanced Impact prioritisation method, the total value of tickets processed is met significantly faster, accelerating results by nearly a month.

The models performs better under conditions of limited capacity. When capacity is available, all tickets can be resolved regardless of the prioritisation method, resulting in an equally high cumulative total tickets value across all three methods.

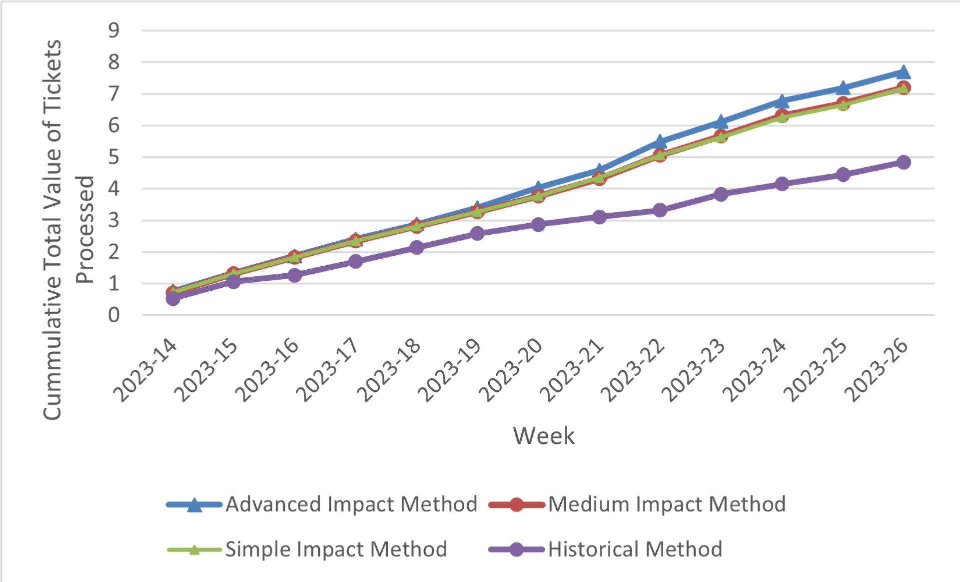


Figure 5.13: Historic compared to the Advance, Medium and Simple Impact Method with 20% Competence Engineer Capacity

5.5 Conclusion

The research demonstrates that improvement actions and their impact can be effectively measured by assigning a score to processed tickets, using survey results and the AHP method. The model highlights significant differences in workload across clusters, as illustrated by the graphs on utilised capacity, backlog resolution, and ticket development. Further, the model performs better under conditions of limited capacity. Finally, with the Advanced Impact prioritisation method, the total value of tickets is met significantly faster, accelerating results by nearly a month.

Prioritisation proves to be particularly beneficial for 3 to 5 clusters, where fully utilised capacity and increasing backlog indicate that not all tickets can be processed within the available resources. By prioritising tasks, the model can address the most impactful comments first, ensuring better resource allocation.

Additionally, the general model indicates a clear benefit for the newly developed prioritisation method, with an increase of nearly 59% in the self-developed score over a 13-week period. This demonstrates the effectiveness of the prioritisation approach in improving ticket processing efficiency and managing workload.

6 Conclusion, Recommendation and Limitations

This concluding chapter summarises the key findings of the research in Section 6.1, followed by actionable recommendations in Section 6.2, identified limitations in Section 6.3, and suggestions for future work in Section 6.4. The chapter also discusses the theoretical and practical contributions of the study in Section 6.5, emphasising the significance of the developed prioritisation model and its potential impact on workload management and procedure and sequence optimisation.

6.1 Conclusion

It started with one problem: the available data on procedure opens and sequence exports not being utilised. This problem has been stated in Chapter 1. It leads to the main research question:

How can the procedure and sequence improvements be effectively enhanced within the CS EUV Service Engineering department?

The answer is found through the measurement of the comment impact in Chapter 4 and the application of both general and cluster specific models in Chapter 5, resulting in a data-driven prioritisation model for improving service procedures and sequences.

Using the MPSM methodology, it was important to analyse the current system, identifying existing practices, performance metrics and a detailed breakdown of procedure comments, sequence comments, auto-comments, and de-nesting process.

The research was conducted with the AHP method, allowing for comparison between identified prioritisation factors. These factors, detailed in Chapter 4, encompass 7 prioritisation factors based on procedure and sequence characteristics and the 18 Service MIX feedback type factors with corresponding comment type and priority. Due to a lack of available data on the comment details and procedure or sequence types, the AHP is applied for 5 prioritisation factors. Additionally, human safety comments are always prioritised; thus these comments are excluded from the model, resulting in 17 Service MIX feedback type factors considered within the AHP framework.

The weight of each ticket m is assigned by its specific Service MIX feedback type, with a corresponding weight (W_m). The impact of each ticket m (I_m) is measured through three distinct methods: Simple, Medium, and Advanced Impact methods.

- The **Simple Impact method** is solely based on the frequency (F_m), the number of service executions per week, where $I_m = F_m$.
- The **Medium Impact method** builds on this by incorporating execution time, calculated as $I_m = F_m \times ExecutionTime_m$
- Finally, the **Advanced Impact method**, based on the AHP approach, accounts for all normalised prioritisation factors: frequency, number of comments, whether it is also used in NPI, execution time and the number of involved Field Service Engineers.

An analysis of ten example procedures shows that the Simple and Medium Impact methods produce similar results; however, the Advanced Impact method differs because it takes into account all the prioritisation factors. This forms the basis for the model's prioritisation.

$$V_m = I_m * W_m \tag{6.1}$$

This study demonstrates the feasibility of a data-driven prioritisation model to enhance procedure and sequence improvements within the CS EUV service engineering department. The simple, Medium and Advanced impact methods score better than the Historical method. The Advance Impact method shows that the proposed method outperforms the Historical method with 59%. The historical method reaches a total ticket value of 4.85 after 13 weeks, whereas the new advanced method achieves this same value in under 9 weeks. Simulating the evaluation model, it was shown that the cluster-specific approach is more practical, as it reflects the way workload arrives per cluster, revealing the impact of resource constraints per cluster.

The general model achieves a higher overall objective score due to fewer capacity constraints but lacks the practical accuracy of the cluster-specific model. With a competence engineer capacity of 20% (8 hours per week), result shows that 3 of the 13 CS clusters experience an increase in backlog due to fully utilised capacity. Reducing the Competence Engineer capacity to 10% (4 hours per week) increases this effect to 5 out of 13 clusters. The other 8 clusters have spare capacity. This indicates an unbalanced division of capacity on cluster level and ASML could benefit from educating competence engineers more broadly, allowing them to work across multiple clusters rather than focusing on a single cluster. Furthermore, this indicates that for five clusters, work prioritisation would be relevant due to their fully utilised capacity.

The prioritisation model performs more effectively under the conditions of limited capacity. However, as more new machine types are introduced in the field, the available capacity will become tighter. With a constant number of engineers, prioritisation will become increasingly valuable, allowing resources to be directed where they are most needed and enhancing overall efficiency.

6.2 Recommendations

- **Broader Engineer Education:** ASML could enhance the flexibility of competence engineers by providing education that is less focused on individual machine clusters and more generalized across the machine. As the E, B and A clusters have their capacity fully utilised, while the other 9 clusters have spare capacity.
- **Monthly Data Updates:** Regularly updating usage and opening metrics (e.g., monthly) allows the prioritisation model to align with recent trends and reflect current operational data.
- **Tooling for Worldwide Service Action Measurement:** Introducing tools that track the number and duration of service actions at a global scale would significantly enhance data accuracy. If these tools are implemented, the CS Service Engineering department should adjust its methods to integrate this real-time data into the prioritisation model, to focus on the procedures and sequences that have a higher importance.
- **Safety Alignment:** Ensure that human safety comments for sequences are incorporated, and aligned with the company's code of conduct to prevent safety issues from being overlooked or incorrectly logged.

6.3 Limitations

- In Section 4.1.2, seven prioritisation factors were identified, including comment details and the comment or sequence type. The survey indicated the importance of the comment details with an average ranking of 3 and the importance of the procedure or sequence type, with an average ranking of 4.1 among the total seven prioritisation factors. Unfortunately, due to the absence of data on these factors, they could not be incorporated into the model.
- The frequency: procedures or sequences executed per week in the field is based on procedure opens, sequence export and spare parts usage, although these metrics serve as a representation of the number of service actions executed in the field, they do not imply a procedure or sequence is executed. Thus, frequency currently serves as a proxy variable, as the number of service activities—and consequently the executed procedures or sequences—are not accurately measured in the field.
- The cost of solving a ticket in Labour Hours (LH) for a competence engineer is based on established norms, but these norms may not accurately represent reality. Measuring the actual time required to process a ticket would provide a more realistic reflection of the resource demand.
- Normalising the prioritisation factors based on procedure and sequence characteristics in the Advance Impact Method can result in very small values, particularly if outliers remain in the dataset. These outliers can affect the scale and decrease the model's reliability.
- Although balancing engineering capacity among clusters is recommended, the complexity of the NXE machine means that engineers are typically limited to working within their assigned machine clusters. Additionally, ticket or comment resolution occupies only up to 20% of a competence engineer's time, with the remaining 80% dedicated to other responsibilities. This implies that if an engineer is not occupied with solving Service MIX Feedback, they will be available for other tasks within their machine cluster.

6.4 Future Work

- The model's data-driven prioritisation approach offers several advantages, particularly through factors like frequency. For example, prioritising tasks by frequency could provide engineers with guidance on which procedures or sequences are performed most often and may benefit most from improvement. Although prioritisation may not be directly beneficial for 8 out of the 13 clusters, having this prioritised guidance could be valuable for engineers, helping them to understand which tasks have higher relevance based on factors like frequency and actual execution time. Receiving a comment on a procedure with visibility into such metrics could enhance decision-making. Future research should aim to quantify the added value of this prioritisation in improving efficiency and resource allocation.

- Using large language models (LLMs) to analyse comment details could provide insights into the impact of each comment. The process of labeling comments based on their content and evaluating whether they have a high or low impact would result in a more refined prioritisation model.
- The increase in comments per cluster could be more accurately measured to determine the impact on workload and resource allocation. Currently, the change in comments is managed by adjusting the competence engineer's capacity. However, with the introduction of multiple machine types, it is possible to extrapolate the increase in comments based on the introduction of new machine types and forecasting the additional workload per cluster.
- Prioritisation can support new machine types, but it requires frequent data updates. This will enable a more responsive prioritisation process, as engineers gain hands-on experience and report feedback.

6.5 Contribution to Practice and Theory

Practical Contribution: The model provides the CS EUV Service Engineering department with valuable insights on how to prioritise feedback systematically using data. It can be applied to address the current backlog of tickets, particularly within clusters as the E, B and A, to identify and act on the most critical items. For de-nesting work, where large lists of interlinked procedures require denesting, the model helps prioritise by identifying the most important procedures to de-nest first.

Theoretical Contribution: This research demonstrates that the Analytical Hierachy Process (AHP), combined with the knapsack problem, can be applied to create a data-driven prioritisation model. This model uses a self-developed scoring system to rank tickets, proving that the theoretical methods support a systematic approach to ticket prioritisation.

References

ASML. (n.d.-a). *Coach Comment Process.* Retrieved from https://wiki.asml.com/wiki/confluence/pages/viewpage.action?spaceKey=csnavigator&title=Coach+Comments+process%0A%0A

ASML. (n.d.-b). *EUV lithography systems – Products — ASML.* Retrieved from https://www.asml.com/en/products/euv-lithography-systems

ASML. (n.d.-c). *Sequences.*

ASML. (2020). Code of Conduct. , 26.

ASML. (2022a). *De-nesting Procedures Process.* Retrieved from https://wiki.asml.com/wiki/confluence/display/csnavigator/De-nesting+Procedures+Process

ASML. (2022b). *SEMI E10, E79 used.*

ASML. (2023a). 3800E amount of comments prediction.

ASML. (2023b). *B-Bucketing Factory A.*

ASML. (2023c). *B-category disturbances.* Retrieved from https://wiki.asml.com/wiki/confluence/display/csnavigator/B-category+disturbances

ASML. (2023d). *Detailed delivery planning KPI* (Tech. Rep.).

ASML. (2024a). *ASML Discovery* . Retrieved from https://asmldiscovery.com/

ASML. (2024b). *Availability Loss due to CS Operations* (Tech. Rep.).

ASML. (2024c). Claim Allocation Template.

ASML. (2024d). *CS Contribution to Availability 2024-2025* (Tech. Rep.).

ASML. (2024e). *Customer Support EUV Service Engineering System* (Tech. Rep.).

ASML. (2024f). *Non Design Related Solutions Dashboard* (Tech. Rep.).

ASML. (2024g). *Standard of Procedures* (Tech. Rep.).

Dumas, M., La Rosa, M., Mendling, J., & Reijers, H. A. (2018, 3). Fundamentals of business process management: Second Edition. *Fundamentals of Business Process Management: Second Edition*, 1–527. doi: 10.1007/978-3-662-56509-4/COVER

Elmaraghy, W., Elmaraghy, H., Tomiyama, T., & Monostori, L. (2012, 1). Complexity in engineering design and manufacturing. *CIRP Annals*, *61*(2), 793–814. doi: 10.1016/J.CIRP.2012.05.001

Haas, R., & Meixner, O. (2005). An Illustrated Guide to the ANALYTIC HIERARCHY PROCESS. Retrieved from http://www.boku.ac.at/mi/

Heerkens, H., & van Winden, A. (2017). *Solving Managerial Problems Systematically.* Noordhoff Uitgevers.

Kuhnle, A., Jakubik, J., & Lanza, G. (2019, 2). Reinforcement learning for opportunistic maintenance optimization. *Production Engineering*, *13*(1), 33–41. Retrieved from https://link.springer.com/article/10.1007/s11740-018-0855-7 doi: 10.1007/S11740-018-0855-7/TABLES/1

Little's Law - Defined, Formula, Example, Origin. (n.d.). Retrieved from https://corporatefinanceinstitute.com/resources/data-science/littles-law/

Ngandam Mfondoum, A. H., Tchindjang, M., Mefire Mfondoum, J. V., & Makouet, I. (2019). Eisenhower matrix

* Saaty AHP = Strong actions prioritization? Theoretical literature and lessons drawn from empirical evidences. Retrieved from https://luxafor.com/the-eisenhower-matrix/

Pomorski, T. (2009). *SEMI E10 Specification for Equipment Reliability, Availability and Maintainability — SEMI.* Retrieved from https://www.semi.org/en/Standards/CTR_031244

Saaty, R. (1987, 1). The analytic hierarchy process—what it is and how it is used. *Mathematical Modelling*, *9*(3-5), 161–176. doi: 10.1016/0270-0255(87)90473-8

Saaty, T. (2010). *Mathematical Principles of Decision Making (Principia Mathematica Decernendi) - Thomas L. Saaty - Google Books.* Retrieved from https://books.google.nl/books?hl=en&lr=&id=rhhlQ0FyBTkC&oi=fnd&pg=PT13&dq=Mathematical+Principles+of+Decision+Making&ots=SfuXH7LeQQ&sig=JoA1AwzK3xPBnTfAuhq5RVCAo8U&redir_esc=y#v=onepage&q=MathematicalPrinciplesofDecisionMaking&f=false

Shafi, M. (n.d.). *Agile Estimating and Planning by Mike Cohn.* Retrieved from https://www.academia.edu/41614300/Agile_Estimating_and_Planning_by_Mike_Cohn

Triantaphyllou, E., & Baig, K. (2005, 5). The impact of aggregating benefit and cost criteria in four MCDA methods. *IEEE Transactions on Engineering Management*, *52*(2), 213–226. doi: 10.1109/TEM.2005.845221

Ungan, M. C. (2006). Standardization through process documentation. *Bus. Process. Manag. J.*, *12*(2), 135–148. Retrieved from https://doi.org/10.1108/14637150610657495https://consensus.app/papers/standardization-process-documentation-ungan/0ff20bff45595770a34001a9a89e70b0/https://www.semanticscholar.org/paper/ebc35de6edca68e3a973fd858bc37c5becd020db doi: 10.1108/14637150610657495

Vargas, R. V. (2010). Analytic Hierarchy Process Prioritize Projects — PMI.. Retrieved from https://www.pmi.org/learning/library/analytic-hierarchy-process-prioritize-projects-6608

Winston, W. L., & Goldberg, J. B. (2004). Operations research : applications and algorithms. , 1418.

Yang, X.-S. (2014, 1). Multi-Objective Optimization. *Nature-Inspired Optimization Algorithms*, 197–211. doi: 10.1016/B978-0-12-416743-8.00014-2

Zhu, M., Yang, Y., & Hsee, C. K. (2018). The Mere Urgency Effect. , *45*. Retrieved from https://academic.oup.com/jcr/article-abstract/45/3/673/4847790 doi: 10.1093/jcr/ucy008

A Appendix: Procedure Template

This appendix provides detailed support for Section 2.3.1, where a procedure is introduced. The template included serves as an example, as incoming procedure comments are made on such procedures. Comments can be for the entire procedure or for specific sections within it. The focus here is on the **Service** destination.

Gxxxxx.ins
Version: 1.0

ATTACH SSF ACTUATOR 1/2

FAMILY:

☒ TWINSCAN SOURCE

SUBSYSTEM:

☒ MECHANICAL LAYOUT

SOFTWARE RELEASE:

☐ N/A	☐ 3.1.7	☐ 3.1.8
☐ 3.2.6	☐ 3.2.7	

MACHINE TYPE:

☐ SOURCE_P1	☐ SOURCE_S1	☐ SOURCE_S2
☐ SOURCE_S3	☐ SOURCE_S3_GV	☐ SOURCE_S3_GWE
☐ SOURCE_S3_MV		

DESTINATION:

☐ Destination (All)		
☐ Assy	☐ DeInstall	☐ CabinEquipment
☐ Fasy	☐ Test	☐ FactoryUpgrade
☐ PrePack	☒ MechanicalInstall	☐ IntegrationInstall
☐ Proto	☐ Upgrade	☐ Service

HUMAN SAFETY RISKS:

N/A

ESTIMATED TIME TO COMPLETE:

5 min

NECESSARY PERSONS:

1

REQUIRED SKILLS:

Confidential

No special skills

PERSONAL PROTECTIVE EQUIPMENT:

LOTO:

LOTO Required?

☐ Yes
☒ No

TOOLS:

12NC	Qty	Description	Remarks

Make sure that you know the safety risks for any tools used in this procedure. The section "How to find Tool Safety Manuals" on the Coach start page shows how to find the tool safety manuals.

TOOLS OUT:

12NC	Qty	Description	Remarks

In this Header part mention the tools that are taken out in the procedure, but not build in. So tools that were already in the system/module and taken out here.
(only used for Operations procedures)

If no tools out in this procedure, remove this part.

PARTS:

12NC	Qty	Description	Remarks

SERV.xxx.xxxxx			

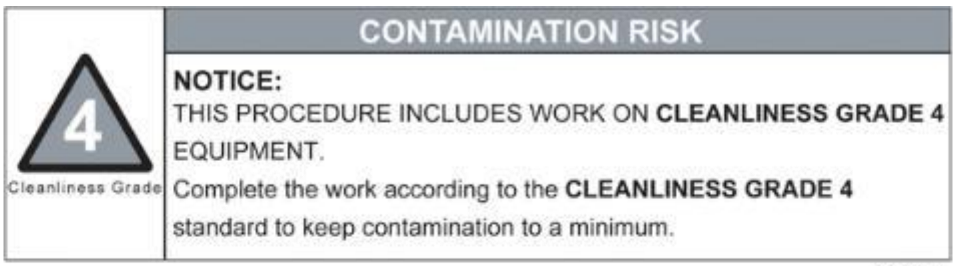
SUPPORT DOCUMENTATION:

☒ Not applicable
☐ Document 1 (Mention the supporting document)
☐ Document 2 (Mention the supporting document)

FUNCTION:

To [fill in what the function of this procedure is]

1. OBEY THE APPLICABLE CLEANLINESS GRADE:



1856610 (Section id: 1725871)

2. REFERENCED PROCEDURES

2.1. Refer to Table 2.1, for a list of referenced procedures used in this procedure

Table 2 . 1 - REFERENCED PROCEDURES

PROCEDURE	PROCEDURE ID
REMOVE THE SSF EARTH CABLE SET	ProcedureA
REMOVE THE SSF COOLING SET	ProcedureB
REPLACE THE SSF FLEXIBLE DRIVE SHAFTS (1-6)	ProcedureC
ADJUST THE LENGTH OF A SSF ACTUATOR	ProcedureD
INSTALL THE SSF COOLING SET	ProcedureE
INSTALL THE SSF EARTH CABLE SET	ProcedureF
REMOVE FINE DROPLET STEERING CAMERA (FDSC)	ProcedureG
DRAIN MW ASSY FRAME COOLING CIRCUIT	ProcedureH

3. PRECONDITIONS

3.1. Make sure that vessel has been hoisted out of the pit and it is standing in the transport tool.

3.2. Move the Source Vessel / TT through the Service area according to procedure ght001.pac.

3.3. Make sure that you know how the Actuators are numbered in the Source Vessel (1-6, Figure 1).

3.4. Remove the Banjos (A, Figure 2) from the Source Vessel Actuators 3,4,5 and 6 (Figure 1). (is it needed??)

4. PREPARE

4.1. Mention the prepare steps to execute the procedure.

4.2. Bulk material table: add bulk material table when needed.

12NC	Qty	Description	Remarks
4022.xxx.xxxxx			
SERV.xxx.xxxxx			

4.3. Xxx

5. PROCEDURE SECTION 1….

5.1. Add procedure content as applicable….

6. COMPLETE THE PROCEDURE

NOTE: No more steps are necessary.

B Appendix: BPM Model of Comments Process

This appendix provides detailed support for Section 2.3.1, where the flowchart of the comments process is explained. It outlines the roles and interactions of stakeholders, including the Competence Engineer, the Technical Writer, and the Line Manager, who collaborate to address and resolve comments. The appendix offers a thorough breakdown of their responsibilities, the flow of information between them, and how they coordinate efforts to ensure that comments are processed efficiently and effectively.

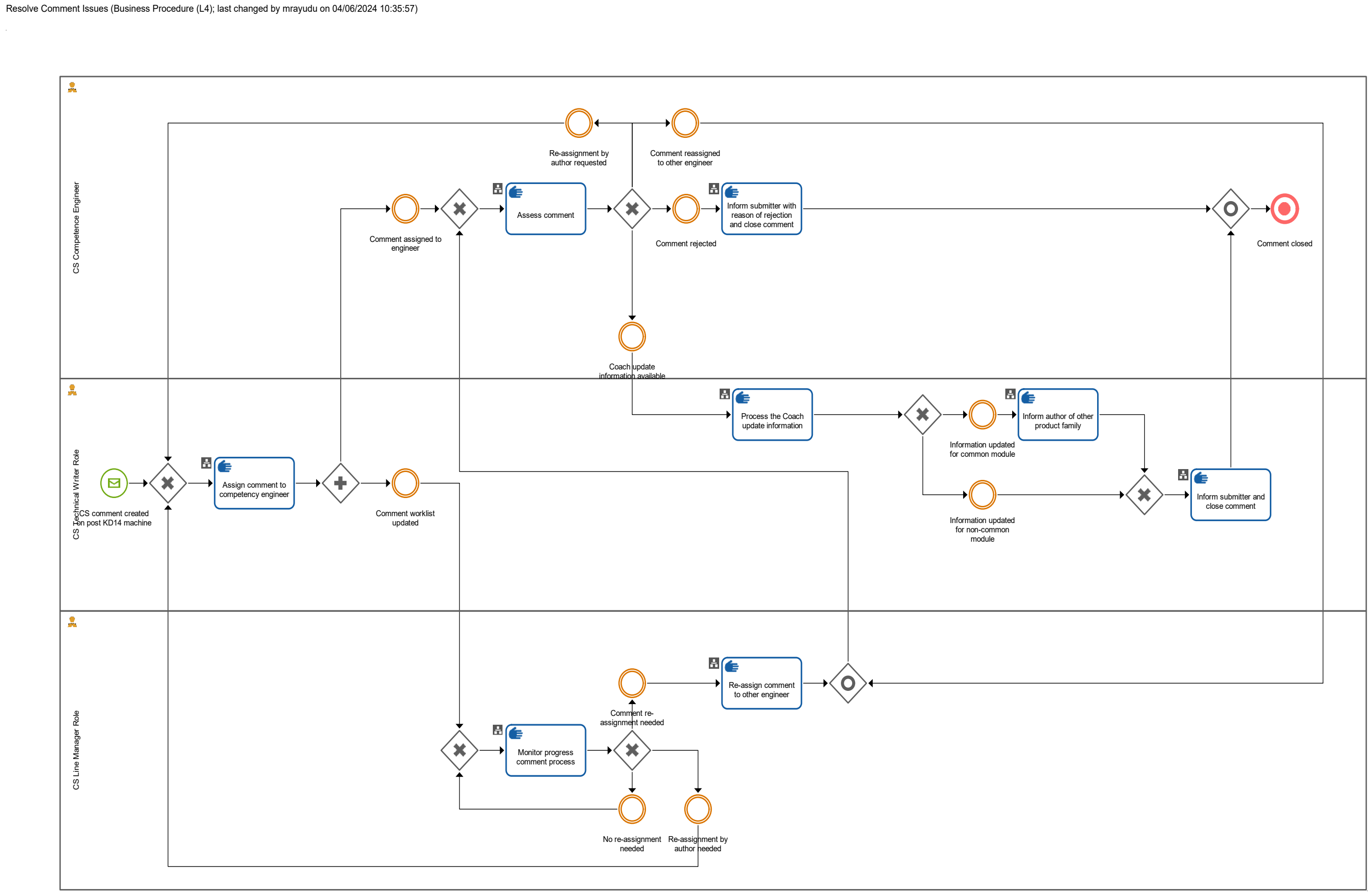


Figure A.1: BPM model of Comment Process

C Appendix: List of Data Filters

This appendix provides the data filters mentioned in Section 2.4.1. These filters show the date range (01-04-2023 – 29-02-2024), correct department (CS), machine (NXE), and destination (Service). These data filters ensure that the research stays within scope and provides detailed information in the data model.

Procedure Opens	Status = 'Final'
	Family = TWINSCAN_SOURCE; TWINSCAN_NXE; TWINSCAN_DRIVELASER
	Date range: 01-04-2023 – 29-02-2024
	Department: CS; CS, MP
Sequence Exports	Event = BlueprintExported(SVG); Sequence Exported (EXCEL)
	Bucket = CS
	Tech = EUV
	Double = 0
	Location <>Veldhoven
	Date range: 01-04-2023 – 29-02-2024
Parts Usage	Activity_Category_Desc = Service
	Date range: 01-04-2023 – 29-02-2024
SimbaData	SimbaStartData range: 01-04-2023 – 29-02-2024
ProcedureMetaData	Status = Null or "Published"
	Family = TWINSCAN_SOURCE; TWINSCAN_NXE; TWINSCAN_DRIVELASER
ProcedureandSpareParts	Family = TWINSCAN_SOURCE; TWINSCAN_NXE; TWINSCAN_DRIVELASER
Procedure Comments	Date range: 01-01-2023 – 29-02-2024
	Department = CS
	FAM = NXE, TWINSCAN_DRIVERLASER, TWINSCANSOURCE
	Destination = Service

D Appendix: Survey ranking Prioritisation Factors and SMix Feedback Types

This appendix provides the survey referenced in Section 4.2.1. The first question focuses on prioritisation factors related to procedure and sequence characteristics, while the second question addresses the various Service Mix Feedback Types. Both questions are aimed at assessing the relative importance of these factors, providing insights into how they influence the prioritisation process.

Ranking Prioritization Factors and SMIX Feedback Types for Work Prioritization

We are conducting a survey to gather expert opinions on prioritizing comments on procedures and sequences for the NXE Installed Base. Your input will help us refine our prioritization model and ensure that the most impactful factors are given appropriate weight. It takes 5-10 minutes of your time.

In this survey, you will be asked to rank two set of criteria:

1. Prioritization Factors
   - **Procedure/ Sequence Execution Time:** The execution time for a procedure or sequence.
   - **Also Used in NPI:** Procedure/Sequence used in both existing and new products.
   - **Procedure/Sequence Type:** The type of procedure or sequence, for example, a performance check is something different than a part swap.
   - **Number of Field Service Engineers:** The number of Field Service Engineers involved in the particular procedure or sequence.
   - **Comments per Procedure/Sequence:** The total number of comments per procedure or sequence since release.
   - **Comment Details:** The specific content of each comment.
   - **Frequency:** Procedure/Sequence executed per week in the field.
2. SMIX Feedback Types
   - **Denesting**
   - **Sequence Comment** with Comment Type: **Typographical, Technical** and **Configuration**
   - **Auto-Comment**
   - **Procedure Comment** with Comment Type: **Human Safety, Typographical, Technical** and **Configuration**

Instruction:

- For **each question**, please rank the given items from most important to least important based on your experience.
- Drag and drop each item in the order of importance, with the most important at the top and the least important at the bottom.

We appreciate your valuable insights and thank you for taking the time to complete this survey. Best regards, Jimmy van Santen CS EUV Service Engineering Intern "Data-driven priority setting for the improvement on procedures and sequences"

1. Please rank the following prioritization factors from most important to least important when prioritizing comments on procedures and sequences.

- Comment Details
- Also Used in NPI
- Procedure/ Sequence Type
- Number of Field Service Engineers involved
- Comments per procedure/ sequence
- Frequency (Procedure or Sequence Executed per Week)
- Procedure/ Sequence Execution Time

2. Please rank the following SMIX Feedback Types from most important to least important.

- **Denesting**
- **Sequence Comment** with Comment Type: **Typographical**
- **Procedure Comment** with Comment Type: **Typographical**
- **Auto-Comment**
- **Sequence Comment** with Comment Type: **Configuration**
- **Sequence Comment** with Comment Type: **Technical**
- **Procedure Comment** with Comment Type: **Human Safety**
- **Procedure Comment** with Comment Type: **Configuration**
- **Procedure Comment** with Comment Type: **Technical**

E Appendix: Absolute difference average ranking Service Mix Feedback Types

This appendix provides an explanation of Section 4.1.1 in which the results of the survey are converted as such so they can be used for the AHP method. The following abbreviations are used for formatting simplifications: Technical (Tech), Procedure Comment (PC), Sequence Comment (SC), Configuration (Config), Typographical (Typo), Low Priority (4), Medium Priority (3), High Priority (2), and Critical Priority (1).

Table E.1: Absolute Difference Average Ranking Service Mix Feedback Types(1/2)

SMix Feedback Type	Tech PC	Tech SC-1	Tech SC 2	Tech SC-3	Tech SC-4	Config PC	Config SC-1	Config SC-2	Config SC-3
Techical PC	0.00	0.96	1.35	1.73	2.12	2.50	2.83	3.03	3.23
Technical SC - 1		0.00	0.39	0.77	1.16	1.54	1.87	2.07	2.27
Technical SC - 2			0.00	0.38	0.77	1.15	1.48	1.68	1.88
Technical SC - 3				0.00	0.39	0.77	1.10	1.30	1.50
Technical SC - 4					0.00	0.38	0.71	0.91	1.11
Configuration PC						0.00	0.33	0.53	0.73
Configuration SC -1							0.00	0.20	0.40
Configuration SC -2								0.00	0.20
Configuration SC -3									0.00

Table E.2: Absolute Difference Average Ranking Service Mix Feedback Types(2/2)

SMix Feedback Type	Config SC-4	Denesting	Auto-C	Typo SC-1	Typo SC-2	Typo SC-3	Typo SC-4	Typo PC
Techical PC	3.43	3.63	4.90	5.30	5.48	5.67	5.85	6.03
Technical SC - 1	2.47	2.67	3.94	4.34	4.52	4.71	4.89	5.07
Technical SC - 2	2.08	2.28	3.55	3.95	4.13	4.32	4.50	4.68
Technical SC - 3	1.70	1.90	3.17	3.57	3.75	3.94	4.12	4.30
Technical SC - 4	1.31	1.51	2.78	3.18	3.36	3.55	3.73	3.91
Configuration PC	0.93	1.13	2.40	2.80	2.98	3.17	3.35	3.53
Configuration SC -1	0.60	0.80	2.07	2.47	2.65	2.84	3.02	3.20
Configuration SC -2	0.40	0.60	1.87	2.27	2.45	2.64	2.82	3.00
Configuration SC -3	0.20	0.40	1.67	2.07	2.25	2.44	2.62	2.80
Configuration SC -4	0.00	0.20	1.47	1.87	2.05	2.24	2.42	2.60
Denesting		0.00	1.27	1.67	1.85	2.04	2.22	2.40
Auto-Comment			0.00	0.40	0.58	0.77	0.95	1.13
Typo SC - 1				0.00	0.18	0.37	0.55	0.73
Typo SC - 2					0.00	0.19	0.37	0.55
Typo SC - 3						0.00	0.18	0.36
Typo SC - 4							0.00	0.18
Typo PC								0.00

F Appendix: Service Mix Feedback Types AHP Pairwise Comparison

This appendix provides an explanation of Section 4.1.1 in which the results of the survey are converted into the AHP method. The following abbreviations are used for formatting simplifications: Technical (Tech), Procedure Comment (PC), Sequence Comment (SC), Configuration (Config), Typographical (Typo), Low Priority (4), Medium Priority (3), High Priority (2), and Critical Priority (1).

Table F.1: Service Mix Feedback Types AHP Pairwise Comparison(1/2)

SMix Feedback Type	Tech PC	Tech SC-1	Tech SC 2	Tech SC-3	Tech SC-4	Config PC	Config SC-1	Config SC-2
Techical PC	1	2	3	3	4	4	5	5
Technical SC - 1	1/2	1	1	2	2	3	3	4
Technical SC - 2	1/3	1	1	1	2	2	3	3
Technical SC - 3	1/3	1/2	1	1	1	2	2	2
Technical SC - 4	1/4	1/2	1/2	1	1	1	2	2
Configuration PC	1/4	1/3	1/2	1/2	1	1	1	1
Configuration SC -1	1/5	1/3	1/3	1/2	1/2	1	1	1
Configuration SC -2	1/5	1/4	1/3	1/2	1/2	1	1	1
Configuration SC -3	1/5	1/4	1/3	1/3	1/2	1/2	1	1
Configuration SC -4	1/6	1/4	1/4	1/3	1/2	1/2	1	1
Denesting	1/6	1/4	1/4	1/3	1/3	1/2	1/2	1
Auto-Comment	1/8	1/6	1/6	1/5	1/5	1/4	1/4	1/3
Typo SC - 1	1/8	1/7	1/6	1/6	1/5	1/5	1/4	1/4
Typo SC - 2	1/9	1/7	1/7	1/6	1/6	1/5	1/4	1/4
Typo SC - 3	1/9	1/8	1/7	1/6	1/6	1/5	1/5	1/4
Typo SC - 4	1/9	1/8	1/7	1/7	1/6	1/6	1/5	1/5
Typo PC	1/9	1/8	1/7	1/7	1/6	1/6	1/5	1/5

Table F.2: Service Mix Feedback Types AHP Pairwise Comparison(2/2)

SMix Feedback Type	Config SC-3	Config SC-4	Denesting	Auto-C	Typo SC-1	Typo SC-2	Typo SC-3	Typo SC-4	Typo PC	AHP Weight
Techical PC	5	6	6	8	8	9	9	9	9	0.2021
Technical SC - 1	4	4	4	6	7	7	8	8	8	0.1325
Technical SC - 2	3	4	4	6	6	7	7	7	7	0.1135
Technical SC - 3	3	3	3	5	6	6	6	7	7	0.0933
Technical SC - 4	2	2	3	5	5	6	6	6	6	0.0787
Configuration PC	2	2	2	4	5	5	5	6	6	0.0648
Configuration SC -1	1	1	2	4	4	4	5	5	5	0.053
Configuration SC -2	1	1	1	3	4	4	4	5	5	0.0486
Configuration SC -3	1	1	1	3	4	4	4	4	5	0.0453
Configuration SC -4	1	1	1	3	3	4	4	4	4	0.0425
Denesting	1	1	1	2	3	3	4	4	4	0.0385
Auto-Comment	1/3	1/3	1/2	1	1	1	2	2	2	0.0186
Typo SC - 1	1/4	1/3	1/3	1	1	1	1	1	2	0.0157
Typo SC - 2	1/4	1/4	1/3	1	1	1	1	1	1	0.0142
Typo SC - 3	1/4	1/4	1/4	1/2	1	1	1	1	1	0.0133
Typo SC - 4	1/4	1/4	1/4	1/2	1	1	1	1	1	0.0129
Typo PC	1/5	1/4	1/4	1/2	1/2	1	1	1	1	0.0123

G Appendix: The Consistency Ratio for the Service MIX Feedback Types

To evaluate the consistency of the pairwise comparisons in the Analytical Hierarchy Process (AHP), the Consistency Ratio (CR) is computed using the Consistency Index (CI) and the Random Index (RI). The following calculations demonstrate the process.

Given:

- $\lambda_{\max} = 17.48$
- $n = 17$
- $RI = 1.59$

Step 1: Calculate the Consistency Index (CI)
The Consistency Index is calculated using the formula:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Substituting the given values:

$$CI = \frac{17.48 - 17}{17 - 1} = \frac{0.48}{16} = 0.03$$

Step 2: Calculate the Consistency Ratio (CR)
The Consistency Ratio is calculated using the formula:

$$CR = \frac{CI}{RI}$$

Substituting the values:

$$CR = \frac{0.03}{1.59} = 0.0189$$

Step 3: Evaluate Consistency
The Consistency Ratio (CR) for the pairwise comparisons is 0.0189, which falls significantly below the threshold of 0.10. This demonstrates that the judgements made in the pairwise comparisons are consistent and reliable, adhering to the consistency standards outlined in the literature (R. Saaty, 1987).