Sample Flow Modeling for Rapid Performance and Failure Analysis

Beza Getachew Tassew
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The design that is described in this report has been carried out in accordance with the rules of the TU/e Code of Scientific Conduct.
Thermo Fisher Scientific produces different kinds of microscopes for semiconductor manufacturing process control and defect analysis. The analysis of semiconductor samples involves the processes Sample Preparation, Sample Transport, and Sample Analysis. In order to design new components or upgrade existing devices and workflows, a performance analysis is required as part of a decision-making mechanism. This project explores the use of process modeling and simulation techniques to enable performance (i.e. throughput, time and resource) analysis, optimization and failure modeling. Furthermore, it dives into the use of executable process models to enable process deployments for real-time control, analytics and optimization, using workflow engines.

Keywords
These keywords should be at least the keywords as issued for the SAI report no. request

Preferred reference

Partnership
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This PDEng thesis is approved by the supervisors and the Thesis Evaluation Committee is composed of the following members:

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Supervisors: Marcin Gramza (Thermo Fisher Scientific)
Anton J. Wijs (TU/e)
Members: Paul Janson (Thermo Fisher Scientific)
Arjen Klomp (Thermofisher Scientific)
Foreword

The Thermo Fisher Scientific Electron Microscopy is stepping into a new, fascinating time, where multiple microscopes are connected to work together to deliver optimal results for our customers.

It is a relatively new area for Thermo Fisher. We are exploring design and modelling methodologies that support efficient and high-quality software development for such systems. From the research point of view the investigation field is broad. The methodology that we envision as valuable for us should be:

- easy to understand by different stakeholders, varying from business owners to the software developers
- support fast delivery of the working and reliable software to be deployed at the customer premises
- integrate well with the existing microscope systems
- flexible for future extensions and modifications

Beza took the challenge to find a solution that would fulfill all those requirements. To make her assignment realistic we selected actual problem from our domain as a use case. We have asked Beza to model the semiconductor sample flow from the very beginning (i.e. milling a tiny silicon piece of the semiconductor wafer) to the image acquisition of a semiconductor structure and obtain metrology data. The model was supposed to simulate the flow and to calculate the performance of the system. We selected two key parameters to be optimized: throughput and total time required for the production of the metrology data. Beza created the model that was not only correct and realistic, but also enabled us to simulate the different system configurations. That allowed us to find the optimal system configuration maximizing the throughput and minimizing the time required for getting the customer data.

Beza accomplished another important goal, namely proved usability of the model for rapid system prototyping. She integrated the model execution engine with the microscope software and proved its usability. The concept is very promising. As a matter of fact Thermo Fisher will apply the methodology realized by Beza for rapid functionality development for the upcoming project.

Project mentor,
M.Sc. Marcin Gramza
October 2019
Preface

This report represents a ten-month project entitled “Sample Flow Modeling for Rapid Performance Analysis” conducted at Thermo Fisher Scientific. This project is a part of the graduation criteria for a post masters Professional Doctorate in Engineering (PDEng) degree in Software Technology at Eindhoven technology University.

This project took place in the Semiconductors group within the Material and Structural Analysis Division (MSD) of Thermo Fisher Scientific, under the supervision of Marcin Gramza (Software Architect). The goal of the project is to model the semiconductor sample preparation and analysis flow so that performance can be analyzed and predicted early in the process through modeling and simulation, which in turn aids in informed decision making. This project also explores the possibility of further extending the use of models in real-time through the use executable models.

This report gives an overview of the project and the analysis, design and implementation approaches taken toward achieving the project goals in detail. The target audience for this report includes Engineers, System Designers, System Architects, Process Modelers/designers, as well as Product Managers. Readers interested in the overall context, results and recommendations can focus on chapters 1, 2, and 10, while those interested in the design and implementation details can focus on chapters 7-9.

Beza Getachew Tassew

October 2019
Acknowledgement

I would like to thank all the people who have guided and supported me throughout this project. My deepest gratitude goes to my Supervisor Marcin Gramza for his guidance as well as trust to let me navigate my way through this project. I would also like to thank Martin Verheijen, Koos Den Hollander, Scott MacClay, Sylvia Aerts, Nestor Rodriguez, for providing so much needed domain knowledge and answering the many questions I had. I would also like to thank the Metrios team at Thermo Fisher in general, its Product Manager Paul Verboven and Senior R&D Manger Arjen Klomp for creating a positive environment to work in, giving encouragement and assisting as needed.

I would also like to extend my gratitude to Yanja Dajsuren, Software Technology PDEng Program manager, for enabling this project and overseeing this project. I would like to thank my university supervisor Anton Wijs (Asst. Professor) for the time spent reviewing my work. I would also like to thank Désirée van Oorschot for facilitating all administration related tasks and making sure everything is done correctly and on time. In addition, I would like to thank my colleagues, Software Technology PDEng Trainees of 2017 for the collaboration, support and friendship we had during the two years. A special mention to the Thermo Fisher team Giovanni, Kon and Pranav, for the lunches and coffees together.

Not least of all, I would like to thank my husband Dereje Tesfu Fantaye, for his love and support during my journey through this project sharing both my excited-and-happy days as well as the not-so-perfect ones. I would also like to thank my two sons for providing me with a source of strength, happiness, and drive to succeed.

And most of all I would like to thank God for giving me the strength to start and finish my hurdles.

Beza Getachew Tassew

October 2019
Executive Summary

Thermofisher Scientific is a world renowned brand that provides a wide range of scientific instruments for various industries. The Materials and Structural Analysis Division (MSD) Group at Eindhoven produces High End Transmission Electron Microscopes for Life Sciences, Material Sciences and Semiconductor Industries. This project deals with modeling of the sample flow in the context of semiconductor manufacturing process analysis.

In the analysis of semiconductors, two major processes are involved. The first one involves the preparation of thin samples (lamella) suitable for the desired analysis under a Transmission Electron Microscope (TEM). This process is mainly executed in Wafer Dual Beam (WDB) Microscopes. The second process is the actual analysis or measurement of these lamella in a specialized TEM for measurement (Metrology) and analysis. Since these two processes take place in different machines and (currently) in different locations, a third process, Sample Transport, is involved. The three processes together make up the Sample Flow Process.

The Goal of this project was to model the Sample Flow, i.e., Sample Preparation, Transport, and Analysis to enable performance analysis both in current systems as well as in future designs of hardware and software components. The main criteria to analyze are throughput (number of samples processed per second) and time-to-data (time it takes from a wafer being submitted for analysis until analysis or metrology data is ready). To achieve this goal, the following approaches were followed:

- Model the business processes and subprocesses using a language called Business Process Modeling Notation (BPMN).
- Simulate selected use cases (scenarios) using a business process simulation language called BPSim to analyze the performance characteristics
- Deploy a simple prototype process use case using Camunda Business Process Management Engine.

Based on my observations throughout this project, I would recommend the use of process modelling both as a modelling and documentation tool. Proper modeling and analysis through simulation provides a quantifiable way of suggesting workflow improvements that help optimize the customer’s processes. Furthermore, by enabling the deployment of custom process models for different customers, Thermofisher Scientific can benefit from a better understanding of microscope usage in the real environment and accelerate innovation by using such insights as feedback in the design of new hardware and software products and features. In the long term, the large amount of data that can be gathered from these deployed processes can also be used as input for different data driven approaches for usage pattern recognition, decision making, machine learning and process automation.
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1 Introduction

1.1 Project context

Thermo Fisher Scientific’s Semiconductor Group designs and manufactures transmission electron microscopes (TEM) used for Process Control, Quality Control, and Failure Analysis of the semiconductor manufacturing processes. Due to the demand for smaller and more powerful devices, Semiconductor manufacturers design chips with increasingly small components. These components include logic gates, memory gates, and other features that need to be analyzed at the nanometer scale.

One of the ways manufacturers control the manufacturing process, as well as increase their yield is by using Metrology. Metrology refers to the measurement of various structural features and chemical composition of semiconductor wafers in the production process. For a Transmission Electron Microscope to work, electron beams must pass through the sample and be captured on a screen that is beneath it. This requires that samples be prepared as thin layers before they can be analyzed.

Samples are milled out of a wafer by a dedicated device and examined in the microscope where the sample is parameterized, and its quality parameters are determined. Nowadays customers require maximizing of the microscope usage and minimizing the time spent from creating of the sample to creation of the user data. Moreover, there is increasing demand for full automation of the whole process, from sample milling (preparation) to sample analysis.

The aim of this project is to create a software model of the sample flow that enables the analysis of the system performance and the identification of failure modes of the system. The performance analysis is mainly concerned with two key measures: time to data and throughput.

1.2 Project Goals

The goal of this project was to implement the software model of the sample production, transport and analysis such that:

- the current sample flow is modeled
- different flow variants can be modeled
- performance in terms of time-to-data and throughput can be calculated
- users can change flow parameters and analyze the effect
failure modes of the system are identified and modeled
the developed model can be used for research and development of the workflow automations (proof of concept)

This paper discusses the design process and implementation details of this project. Chapter 2 discusses the problem statement. Chapter 3 describes the stakeholders of the project and their concerns. Chapter 4 talks about the requirements resulting from this stakeholder requirement. Chapter 5 deals with the semiconductor manufacturing process domain and the part Thermofisher Scientific’s different microscopes play. Chapter 6 discusses the different technology and/or approaches evaluated and the selection criteria for comparison. Chapter 7 deals with the modeling of processes and subprocesses within the sample flow. Chapter 8 discusses the simulation scenarios and obtained results. Chapter 9 is about the deployment of process models for real time control and analysis. Chapter 10 concludes the report by summarizing the main points. Chapter 11 provides key recommendations based on observations throughout the project. It also contains some suggestions for possible future works. Chapter 12 discusses the project management approach and lessons learned through this project. Chapter 13 contains the author’s reflections on the project and lessons learned during the duration of this project.
2 Problem Statement

2.1 Context

The main challenges that Thermofisher Scientific and its customers face regarding the sample preparation and metrology workflow are:

- long waiting time for analysis data (up to 24 hours)
- inability to spot gaps in the system (where the bottlenecks are or what component is missing to bridge the performance gap)
- disorganization of information about the various artifacts created and managed in the process
- inability to predict performance gain of new technological advances

In order to address these changes, a software model of the overall workflow was needed. Such a model should provide useful input by creating a common communication media to gather enough detail from the various stakeholders. It would enable decision makers to make design decisions based on a holistic view of the system in question.
3 Stakeholder Analysis

This chapter discusses the different stakeholders of the project. The different parts of the model touch different subjects and departments within the organization, some of whom were not available onsite. Therefore, some of these were represented through representatives internally available, who know the concerns of these stakeholders well enough to provide valuable input to the stakeholder concern analysis.

3.1 Internal and External Stakeholders

Figure 1 lists the external stakeholders of the project.

![Diagram of Stakeholders]

*Figure 1. Internal and External Stakeholders*
3.2 Stakeholder Concerns

The different stakeholders of this project had different concerns which can also be shared in between. The subsystem designers’ and Senior architects’ concern is mainly in identifying performance constraints and enabling innovation by identifying bottlenecks and improvement opportunities.

The senior management concerns were related to gaining competitive advantage in the market and meeting customer demands. The customers share the later concern in addition to an accurate representation of their workflow. Internal to the project, the project teams’ main concerns were related to the project success, both from the university’s and the company’s points of view. In addition, the product owner’s concern was mainly the introduction and integration of model-based approach to design efforts within the company. Figure 2 shows the main concerns associated with stakeholder groups and specific stakeholders.

![Stakeholder Concern Map](image-url)

**Figure 2. Stakeholder Concern Map**
4 Requirements Analysis

4.1 Introduction

The analysis of stakeholder concerns leads to the identification of the main requirements to be fulfilled by the project. Each requirement should address at least one of the stakeholders’ concerns. Therefore, a requirement traceability map was used to trace the listed requirements to the specific concerns. This traceability matrix was also used to identify requirement gaps, therefore aiding in deriving further requirements. Figure 3 shows the stakeholder concern-requirement traceability map.

Figure 3. Requirement Traceability Diagram
The sample flow model has four main requirements which are further detailed into specific requirements. After being identified, these requirements were prioritized by the project supervisor based on the company goals and roadmaps. Table 1 lists the requirements and their priorities.

Enabling performance analysis with regards to time-to-data and throughput were the main objectives of this project and therefore were given a high priority. In regard to modeling, while all the major processes needed to be modeled, the details of metrology and imaging were given a lower priority since, for the purpose of performance analysis at process level, each detailed task within the machine need not be explicitly modeled as long as it remains fairly constant, or the net effect on the higher level task is known already. Furthermore, putting every detail on the process model would overly complicate the model and makes it much less useful.

*Table 1 Modeling Requirements*

<table>
<thead>
<tr>
<th>Main Requirement</th>
<th>Child Requirement</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>REQ1</strong>-The software model of the sample production system should be modelled</td>
<td><strong>REQ1.1</strong>-Metrology data production should be modelled</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td><strong>REQ1.2</strong>-Sample Imaging should be modelled</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td><strong>REQ1.3</strong>-Sample Preparation should be modelled</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td><strong>REQ1.4</strong>-Sample Transport should be modelled</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td><strong>REQ1.5</strong>-The failure modes of the system should be modelled</td>
<td>High</td>
</tr>
<tr>
<td><strong>REQ2</strong>-Software model shall be extensible</td>
<td><strong>REQ2.1</strong>-The model should be extendible by people without software background</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td><strong>REQ2.2</strong>-The model should be extendible with different failure modes</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>REQ3</strong>-The model shall be configurable</td>
<td><strong>REQ3.1</strong>-The model shall be configurable with respect to different flow parameters</td>
<td>High</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>-----------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td><strong>REQ3.2</strong>-The model shall be configurable with respect to different parameters of the building blocks</td>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td><strong>REQ4</strong>-The model shall enable performance analysis</td>
<td><strong>REQ4.1</strong>-The model shall enable the analysis on time-to-data</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td><strong>REQ4.2</strong>-The model shall enable the analysis on throughput(samples/sec)</td>
<td>High</td>
</tr>
</tbody>
</table>

4.2 **Design Opportunities**

In this project there were certain design opportunities that were identified. These are mentioned below:

- **Extensibility**: The model created should be easily extendable in terms of additional workflows, resources and control conditions.
- **Ease of Use**: The model should be easy to use for designers and easily understandable by developers as well as managers. This will determine how the model and related tools might be adopted by the team.
- **Reusability**: The designed model should be composed of reusable components to avoid multiple modifications. This also requires abstraction of certain details at the proper level.
- **Configurability**: The main aim of this project is to enable performance analysis for various setups of microscopes and workflows. This requires the ability to configure different properties and observe the change in performance.
5 Domain Analysis

In this chapter, the domain of sample preparation and analysis in the semiconductor context is discussed.

5.1 Introduction to the Sample Flow Process

In order to manufacture high quality semiconductor chips, manufacturers use specialized microscopes to analyze their wafers so that they can monitor the manufacturing process and identify defects. This is done by analyzing the underlying features, such as memory and logic gates at the nanometer scale. To be analyzed under the Transmission Electron Microscopes, very thin samples of the semiconductor are needed. For this purpose, semiconductor samples are cut out of a wafer using special Electron Microscopes called Wafer Dual Beams. The thin samples of semiconductor are called Lamella (Figure 6). The thickness of the lamella is determined by the analysis type and can be as thin as 18 nm.

Sample Preparation

This refers to the part of the process where a customer identifies locations of interest on the wafer for analysis. They therefore provide a CAD file, image or PowerPoint document that specifies what they would like to analyze and which locations to take the sample from. This information is then fed to a dedicated sample preparation station which will produce several lamellas from the specific locations. This process happens at the sample preparation site that can be close to the manufacturing site (near-line) or in the lab. After being created, these lamellas are then put on tiny structures called Grids for identification and transport. The grids can be of two types, the half-moon grid (Figure 5) and the 3
mm grid (Figure 4). There are two ways a sample can be created. In the first case, lamellas are created in a single machine (Helios Dual Beam, Figure 7), taken out of the wafer, and then mounted on a grid. In the second case, lamellas are created on the wafer in one machine (ExSolve, Figure 8) and then picked up (plucked) in another machine dedicated to this purpose (TEMLink, Figure 9). These processes are discussed in detail in later sections of this document.
Sample Transport

Once lamellas are produced and put on a grid, they need to be put in containers for transport to the analysis lab (TEM station). This process is a manual phase where a human puts the grid containers in an enclosure and takes them to the TEM which can be in the fab, but also in the lab.

Sample Analysis

Once a sample arrives at a TEM location, it is loaded onto a sample holder (Figure 10) and then into a TEM (Metrios, Figure 11) for analysis. Here, measurements of the semiconductor features are made and saved for analysis. This process is executed using the Metrios TEM.
Figure 12. The Sample Flow Domain

The domain model (Figure 12) shows the relationship between the various components of the Sample Flow process and summarizes the actions mentioned above. Here, it can be seen on most of the relations that, at a higher level, the entities are: the physical stations, the sample that travels through these different stations, and devices that are used to load, unload or transport the system.
6 Technology Evaluation

6.1 Context

After analyzing the requirements from stakeholders, technology solutions that support process modeling and model-based systems engineering approach were investigated. In this investigation, capability to be able to model performance and process flow were key filtering mechanisms used. After an investigation of the available methodologies and tools, the investigation was narrowed to three approaches.

6.2 Approach1: Using Process Modelling approach (Enterprise Architect BPMN)

Since the deliverables of this project were highly tied to pre-design analysis, as well as the realization that the nature of the domain and the domain entities are part of a continuous flow involving a sample moving in between multiple stationary or moving devices, the most obvious approach was to use process modeling techniques. One of the most widely used techniques for business process analysis is modeling using BPMN.

6.2.1 BPMN

BPMN is one of the standards specified by the Object Management Group (OMG) Consortium, an organization behind the open specification of computer industry standards like UML, SysML as well as architectural standards like Model Driven Architecture (MDA).

“The primary goal of BPMN is to provide a notation that is readily understandable by all business users, from the business analysts that create the initial drafts of the processes, to the technical developers responsible for implementing the technology that will perform those processes, and finally, to the business people who will manage and monitor those processes.” (Object Management Group (OMG), 2011)

BPMN offers notations for modeling process activities, activity sequences, events, triggers and other process relevant concepts. (Object Management Group (OMG), 2011) explains the basic modeling elements of BPMN as specified by the Object Management Group.

Table 2. BPMN Basic Elements (Object Management Group (OMG), 2011)
<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event</td>
<td>An Event is something that “happens” during the course of a Process. These Events affect the flow of the model and usually have a cause (trigger) or an impact (result). There are three types of Events, based on when they affect the flow: Start, Intermediate, and End.</td>
<td>![circle]</td>
</tr>
<tr>
<td>Activity</td>
<td>An Activity is a generic term for work that company performs in a Process. An Activity can be atomic or non-atomic (compound). The types of Activities are: Sub-Process and Task.</td>
<td>![rectangle]</td>
</tr>
<tr>
<td>Gateway</td>
<td>A Gateway is used to control the divergence and convergence of Sequence Flows in a Process. Internal markers will indicate the type of behavior control.</td>
<td>![diamond]</td>
</tr>
<tr>
<td>Sequence Flow</td>
<td>A Sequence Flow is used to show the order that Activities will be performed in a Process.</td>
<td>![arrow]</td>
</tr>
<tr>
<td>Message Flow</td>
<td>A Message Flow is used to show the flow of Messages between two Participants that are prepared to send and receive.</td>
<td>![message]</td>
</tr>
<tr>
<td>Association</td>
<td>An Association is used to link information and Artifacts with BPMN graphical elements. Text Annotations and other Artifacts can be Associated with the graphical elements. An arrowhead indicates a direction of flow (e.g., data), when appropriate.</td>
<td>![association]</td>
</tr>
<tr>
<td>Pool</td>
<td>A Pool is the graphical representation of a Participant in a Collaboration (sending of Messages between two BPMN Processes). A Pool MAY have internal details or it can be a &quot;black box.&quot;</td>
<td>![pool]</td>
</tr>
<tr>
<td>Lane</td>
<td>A Lane is a sub-partition within a Process, sometimes within a Pool, and will extend the entire length of the Process, either vertically or horizontally. Lanes are used to organize and categorize Activities.</td>
<td>![lane]</td>
</tr>
<tr>
<td>Data Object</td>
<td>Data Objects provide information about what Activities require to be performed and/or what they produce. Data Objects can represent a singular object or a collection of objects. Data Input and Data Output provide the same information for Processes.</td>
<td>![data_object]</td>
</tr>
<tr>
<td>Message</td>
<td>A Message is used to depict the contents of a communication between two Participants</td>
<td>![message]</td>
</tr>
<tr>
<td>Group</td>
<td>A Group is a grouping of graphical elements that are within the same Category.</td>
<td>![group]</td>
</tr>
<tr>
<td>Text Annotation</td>
<td>Text Annotations are a mechanism for a modeler to provide additional text information for the reader of a BPMN Diagram.</td>
<td>![text_annotation]</td>
</tr>
</tbody>
</table>
6.2.2 Business Process Simulation (BPSim)

BPSim is a standard developed by the Workflow Management Coalition (WfMC) (WfMC, 2016) to enable the simulation of business process model. It also allows going through execution steps one by one and generating reports and graphs out of the simulation executions. Enterprise architect provides BPSim Engine that integrates with Enterprise Architect versions 12 (BPSim 1.x) and later (BPSim 2.x). With the BPSim Engine, it is possible to create multiple flow configurations with different time, resource and cost values and run simulations.

The BPSim standard is designed to support two process/workflow modeling languages, Business Process Modeling Notation (BPMN) and XML Process Definition Language (XPDL) to enable simulation of models described in those standards (Workflow Management Coalition, WfMC, 2016). Figure 13 explains the relationship between BPSim, BPMN and simulation scenarios.

Figure 13. BPSim Conceptual Model (Workflow Management Coalition, WfMC, 2016)

6.3 Approach2: MBSE approach with SysML (Enterprise Architect MBSE Workbench)

6.3.1 SysML

SysML is a general-purpose graphical modeling language for specifying, analyzing, designing, and verifying complex systems that may include hardware, software, information, personnel, procedures, and
facilities (Object Management Group (OMG), 2019). It is a subset of UML with extensions for systems modeling and is implemented as a UML 2 Profile (SysML.org, 2019).

Figure 14 shows the diagram elements offered by SysML.

![SysML Diagram Elements](image)

Figure 14 SysML Diagram Elements (Object Management Group (OMG), 2019)

SysML is widely applicable in industry and is a key tool for Model Based Systems Engineering (MBSE) efforts. SysML version 1.4.1 has also been recognized as an ISO standard and published as ISO/IEC 19514:2017 (Object Management Group (OMG), 2019).

For this project SysML was considered as a viable option since:

- It is a well-known industry standard.
- It has tool support from various vendors.
- It helps to models structural as well as behavioral aspects of a system.
- Its parametric diagram may capture constraints of the system.

6.3.2 SysML Simulation in Enterprise Architect

Enterprise Architect offers SysML simulation capabilities by integrating OpenModelica, a mathematical modeling language. This capability enables specifying parameters in terms of equations, which allows evaluation of design variants and complex system interactions early in the modeling process.
6.4 Approach 3: MBSE with Domain Specific Tool (*Capella MBSE Workbench*)

Another approach evaluated is a model-based system design using a domain specific tool for architecture called Capella, which is based on the eclipse Sirius workbench.

6.4.1 Capella Workbench and The ARCADIA Method

Capella workbench is an integrated MBSE tool that was developed by Thales following an architecture method known as **ARC**hitecture **A**nalysis **D**esign **I**ntegrated **A**pproach (ARCADIA). Capella MBSE follows a methodical approach of designing a system in different phases: from operational analysis to product structure. Figure 15 (Wikipedia, 2019) shows the different phases of ARCADIA method. It also offers different viewpoints for the various stakeholders of a system.

*Figure 15 ARCADIA Engineering Phases (Capella, Thales, 2019)*

Capella offers similar diagraming options as SysML but uses its own Domain Specific Language (DSL) that is based on Eclipse Meta-model Framework (EMF) and the Eclipse Sirius Workbench.
The ARCADIA method follows a guided, top-down approach to system design. In the operational analysis phase, the operational capabilities of the system are identified. This is a high-level description of what the users of the system want to accomplish. This is described in business/domain terms and not in terms of the system.

In System Analysis phase, the question of what the system needs to do to accomplish to meet the user needs is answered. A functional chain is also created here that creates different paths in the system. In the logical Architecture phase, the main question to be addressed is how the system works to meet the set of System needs identified in the previous step. Here, the system is also broken down and organized into logical components.

In the physical design phase, a physical functional breakdown is made, and physical components are designed with their interfaces. In addition to these, it is also possible to extend the tool by adding plugins for constraint checking for timing and price analysis.

6.5 Approach4: Using Functional Mocking Units

A functional mocking unit (FMU) is a modeling component that implements the Functional Mockup Interface (FMI) standard which was initially initiated by Daimler and further developed by the MODELISAR Consortium which is now taken over by the Modelica Association Project “FMI” (MODELISAR consortium, Modelica Association Project “FMI”, 2014).

The FMI standard is a tool independent standard that allows the exchange of dynamic models for Co-Simulation. These components are defined in XML and C. Although this standard is known in the Automotive industry, it is still not widely used by the rest of the manufacturing industry. The FMI standard defines two parts: FMI for Model exchange and FMI for Co-Simulation (Blochwitz, et al., 2012). The FMI for Model exchange describes the model behavior using different equations with time, state and step events while the FMI for Co-Simulation defines the data communication between two or more models.

6.6 Technology Evaluation based on Customer Criteria

Comparison of the above-mentioned technology options was made based on criteria specified by the product owner (Marcin Gramza) and the trainee (Beza G. Tassew).
6.6.1 Ability to model timing/performance

This criterion is based on the requirement “REQ4: The Model shall enable performance analysis.” The two elements of performance, i.e., time-to-data and throughput, are of high interest to the client. Enabling analysis on throughput and time to data allows the client to identify performance bottlenecks and avoid innovation efforts that do not have much significance in the overall sample flow process. Therefore, the selection of technology or modeling tool heavily depended on this requirement.

BPMN is specifically made for business level modeling of processes using easy to understand graphical symbols. Combining this with BPSim simulation support, that enables time, resource and cost analysis, makes the first approach a good choice.

SysML is a generic system design tool that covers almost all aspects with different views (Structural and behavioral, including simulation). While SysML has different notations that allow modelling the components of the sample flow as well as activities and interactions between them, it lacks the dynamic capability of analyzing timing and throughput characteristics. It should be noted here that SysML offers parametric models which can enable analysis of performance requirements based on system variables as well as failure modelling. However, this requires a detailed design of the system and subsystem components and parameters, which was not the aim of this project. In addition, some of the components of the workflow to be simulated are in conception stage. Furthermore, the aim was to analyze the flow so that the company can analyze top down rather than bottom up from the solution.

Although Capella is a good modelling environment that helps the designer in following the systems engineering approach in a guided design environment, it was not found to be suitable for timing and throughput analysis of the sample flow process. Performance modelling in Capella is offered through eclipse plugins. This offers constraint checking in models and dependency analysis in a static way. The option of evaluating different configurations and simulation is not yet supported optimally.

Building simulation model components with interface specifications as Functional Modeling Units (FMU’s) so that they can interact in an FMU Simulation environment appeared to be a promising avenue. However, in practice, it was found to be very difficult. One problem was finding a tool that supports Functional Modeling Interface (FMI) modelling, export for inter-tool exchange, as well as simulation. In most cases the models are exported from other tools such as Matlab, Modelica, and others. Based on the time and resource scope of this project, a way of creating high level behavioral models for simulation was desired.
Two ways of achieving this were investigated. The first one was using the open source UML modelling environment called papyrus to model FMU’s using UML. This effort was not successful since model export is not supported anymore by papyrus. The other option was to take Simulink models of existing as well as future systems from the component teams and export these as FMU’s using MATLAB Simulink plugin. This was also unsuccessful since the components did not have Simulink models already available.

6.6.2 Ability to model failure modes

While BPMN is not the ideal candidate for all types of failure modeling, it supports analysis of the effect of failures on the overall flow i.e. by using process failures rather than design failures. These effects can also be seen in simulation once the effect of the failure and alternative process paths are identified.

SysML, being a standard system modelling language offers a variety of diagrams to model both structural and behavioral characteristics of a system. Nevertheless, it would be difficult to model the dynamic characteristic of a system with regards to failures and their effect on performance.

Capella does not support failure modeling out of the box but offers the capability of using a tool called Safety Architect on top of Capella models to conduct detailed failure analysis. This approach is not selected since detailed failure analysis such as FMEA is beyond the scope of the project. In theory, failure analysis with this approach should be possible although this was not investigated since this approach did not fulfil the main requirement as mentioned above.

6.6.3 Visualization of the flow

BPMN is designed for process modelling and, therefore, offers the best option to visualize the flow for all kinds of users and stakeholders.

SysML Activity diagrams can be used to model workflows but have limited capabilities compared to BPMN.

Capella offers the ability to model functional chains through the system that will later be implemented in subsystem components as features. Capella’s integrated approach allows delving deeper into functional chains to define subsystem functions and interfaces.

FMU’s are not designed for process visualization but rather simulate component behavior, although different FMU’s can be simulated in a simulation environment to execute processes according to the defined behavior. Whereas this project requires analysis on workflows involving devices as well as humans which happens on a higher level of abstraction than component interaction.
6.6.4 Time to workable model

Easy notations of BPMN allow the modeler to design processes using a drag and drop interface. This allows easy prototyping of process models and early review by domain experts and stakeholders. The addition of BPSim Simulations makes testing different scenarios possible.

Structural modelling of components and interfaces is relatively easier to develop in SysML. However, analysis via simulation using parametric models requires extensive analysis and a detailed design of the subsystem component behaviors using mathematical equations.

In terms of system design, Capella’s Domain Specific Language (DSL) based guided design helps in speeding up the design process while minimizing the risk of overlooking key system requirements.

The FMU approach can provide a fast mechanism for prototyping depending on the situation. If simulation models and CAD files from existing system designs exist, then it would provide a fast way to get to a workable solution. Otherwise it would require expertise from other disciplines (mechanical, electrical and possibly applied sciences) to make a meaningful model that simulates the real system.

6.6.5 Interoperability with other tools

BPMN is an open standard adopted by many tool vendors and, therefore, there is no significant problem in sharing models between systems. BPSim on the other hand, was found to be implemented by a company called LannerSim (Lanner Group, 2019) of Houston, Texas, which provides the execution engine for three vendors that currently use it: Enterprise Architect (Sparx Systems, 2019), Bizagi (Bizagi, 2019), and ARIS (Software AG, 2019). Even though exporting XML with the configurations is possible in Enterprise Architect, it is unlikely that it will work as is after importing it. This was tested in Enterprise architect and the models were found to be intact while the simulations did not work as before.

SysML models can be exported to any tool that supports the modeling language since it is an open standard.

Capella offers modeling components that look like SysML, but these components are not the same as SysML. Therefore, the models are not exchangeable between tools. On the other hand, the models can be exported to EMF models which is an advantage in terms of extensibility.

6.6.6 Availability of tool support

BPMN and SysML are Open standards that are supported by multiple vendors which offer both community and commercial licenses. Capella (Polarsys, 2019) is supported by Thales and has an
ecosystem of software that integrate with it but it still single vendor support. Tool support around FMU’s is not widely available. Different such tools exist but are proprietary with some level of training required. Thus, it was considered not feasible to work with these tools in the time and resource scope of this project.

6.6.7 Cost of tool

As mentioned in the previous section, although all the standards are open, there can be licensing requirements on the specific tools used. For example, a commercial license required for Enterprise Architect to use the BPSim simulation Engine. Table 3 summarizes the findings from the comparison as follows.

Table 3 Technology Comparison

<table>
<thead>
<tr>
<th>Ability to model timing/performance</th>
<th>BPMN Simulation (EA)</th>
<th>MBSE with EA (SysML)</th>
<th>Capella MBSE</th>
<th>FMI Simulation tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out of the box</td>
<td>complex parametric models</td>
<td>Timing – static No throughput</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td>Ability to model failure modes</td>
<td>Process Level Design Level Added plugin Component level</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visualization of the flow</td>
<td>Out of the box Possible (Activity Diagram) Possible - Terms of functional chains</td>
<td>Not designed for flow visualization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to workable model</td>
<td>Fast Reasonable Fast</td>
<td>Fast (depending on available models to be exported from other model e.g. Simulink)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interoperability with other tools</td>
<td>Import/export as xml Migration between tools – not fully supported Limited to Capella environment</td>
<td>Import export using C code and XML</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Availability of tool support</td>
<td>Open standard - widely adopted Open standard - widely adopted Limited to Capella environment</td>
<td>mostly automotive domain, proprietary. E.g. Ansys, Dymola (Daimler), Siemens.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of tool</td>
<td>Commercial License Commercial License Free</td>
<td>Free + Commercial</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.7 Decision Rationale

After the technology analysis and early sample projects, it was decided to continue modelling with BPMN and BPSim. The main reasons for selecting this approach are:

- BPMN is a visual modeling tool that allows modeling of process flows (REQ1).
- BPMN is understandable by both technical as well as managerial stakeholders (REQ2.1).
- BPMN is an open standard that can be used across multiple modeling tools.
- BPMN allows an easy visualization of the Sample Flow (REQ2.1).
- BPSim allows the analysis of performance bottlenecks as well as time and throughput analysis via simulation of multiple scenarios (REQ3, REQ4, High Priority).
- BPMN models can be used as a basis for building an actual system using process management engines (which was demonstrated in the later phase of the project)
7 Modeling / Process Design

7.1 Modeling Techniques

BPMN Modelling of the Sample Flow model was accomplished using Enterprise Architect. Figure 16 shows the layout of the model in the Project explorer.

![Project Folder Structure](image)

**Figure 16. Project Folder Structure**

- **Configurations** contains the BPSim Simulation configuration files.
- **Events** contains the different kinds of event definitions used in the model (Error, Signal, Escalation...)
- **Images** contains images used in the models and documentations
- **Resources** contains the definitions of Resource elements
- **Simulation Result Graphs** contains the graphs made from simulation results
- **Metrology Subprocesses** contains the detailed subprocesses of the metrology use cases
- **Sample Flow Collaboration Model** contains the main process model

Certain conventions were used in the modeling process which are listed below.

7.2 Modeling Conventions used in this project

- Sample Preparation, Sample Transport and Sample Analysis units were modeled as Pools. This is so that the sample preparation units could be separately designed and are not directly controlled under the same process. One might choose, as well, to combine them into one continuous process
and categorize them with lanes. In this case, sequence flows must be used instead of Message flows.

- All sub processes inside a single machine were modeled as a task. If subtasks need to be defined under such a task, this can be changed by opening the properties dialog and selecting Type as subprocess.

- Transfers between Sample Preparation, Sample Transport, and Sample Analysis were modelled as Message flows

- Looping behaviors were represented with gateways and sequence flows. Although BPMN provides notations for looping events, they are not used in this project. This was to enable property tracking during simulation. The default looping symbols from BPMN are ignored during simulation by the simulation execution engine.

The following sections present the Sample Flow Process and subprocess details.

### 7.3 Sample Preparation Workflow

The sample preparation step refers to the step of the process starting from when a wafer with an associated preparation job request is submitted to the prep site, until a thin lamella is prepared and ready for analysis.

The job requests for this step can be submitted in form of PDF files, PowerPoint, or a file with coordinates. The job request can contain information such as which area to analyze and what kind of analysis is required. Depending on the customer requirements, the thickness of the lamella to be prepared, the machine to use, or the kind of process to use can be different from job to job. Figure 17 shows the Sample Preparation Process Diagram.
There are two main kinds of processes considered for this project scope, as there are many different workflows as per different customer needs. These are the Top Down and the Inverted Processes. The selection of top down process and inverted processes is driven by lamella thickness requirements.

7.3.1 Top Down process (ExSolve)

This process involves the ExSolve Dual Beam and the TEMLink machines (Figure 18). For this process, Lamella chunks are created in the Dual beam machine and transported on the wafer itself to be plucked in the plucking station (TEMLink).

Figure 17. The Sample Preparation Process

Figure 18. The Top down Sample Preparation Process
Prepare Final Lamella (ExSolve)

Preparing a lamella starts with loading the wafer in the Sample Preparation Station i.e Exsolve. The ExSolve is used in processes with a lamella thickness down to 25 nano meters. After loading the wafer, a Job is created based on the workflow requirements. The initial job (recipe) creation can take days or months depending on whether the wafer is a new type or not. For the sake of this project, the process here has been simplified to “Load Prep Job” task. This is taking the assumption that a recipe file has been created beforehand and this is loaded in the machine. During simulation, the timing used for this task might be configured to simulate the total tool time needed including the time to create a recipe or only the time needed to associate a preexisting recipe to the current job.

![Diagram of Prepare Final Lamella Process]

Figure 19. Prepare Final Lamella Process

After creating/ loading a recipe, the next step in this process is to create a number of thin lamellas according to the job specification. This process takes about 43 minutes per lamella. At the end of this process, the thin lamellas remain attached to the wafer. Once completed, the wafer will be unloaded and taken to a plucking station to pluck the samples.
Pluck Sample (TEMLink)

The “Pluck Sample” subprocess describes the process of picking (plucking) up the thin lamellas from the wafer and placing them onto the 3mm grids. Once this is completed, the wafer and the grids with prepared sample are unloaded from the machine respectively. The timings of these activities are displayed in the Text Annotation blocks in the diagram above (Figure 20).

![Figure 20. Pluck Sample Process](image)

7.3.2 Inverted process (Helios)

This process involves the Helios NanoLab A1200 AT, which can create ultra-thin lamella down to 10 nm thickness. In this preparation process, a separate machine for plucking samples is not needed since all the steps are completed in the Helios itself. The process of sample preparation inside the Helios (Figure 21).
Figure 21. The Inverted Sample Preparation Process

The completion of either the top down or the inverted process ends the sample preparation process for a single job.

7.4 Sample Transport Process

Sample transport process depicts the transport of samples from a sample preparation station to a Sample Analysis lab. These two stations can also be in the same room. It was chosen to separate this from both the sample preparation and the sample analysis process for two reasons:

1. There are planned automations that may handle the transport task (the lower path in the process diagram, Figure 22)
2. The sample preparation and analysis stations can also be in separate locations (Preparation in the fab and analysis in the lab)

Figure 22. The Sample Transport Process
7.5 Sample Analysis Process

The sample analysis process includes the steps starting from placing the holder carrying the sample, into the TEM for analysis, until the end of analysis whereby the grids are unloaded from TEM holder into a storage container.

Figure 23. The Sample Analysis Process

In this process model (Figure 23), the automatic grid handling is included as an alternative to the current manual process. The automatic grid handling is depicted as a subprocess based on Nestor Rodriguez’s report for the design of the auto Grid Handler (Rodriguez, 2017). The purpose here is to show modeling of errors/failure modes in subprocesses and analyze the effect during model simulation. The errors modeled here are retrieved from Failure Mode Effect Analysis (FMEA) document prepared by the Grid Handler team.

It is visible from this model that the processes from sample analysis are of a more detailed nature that the sample preparation models. This is because the project took place inside the Metrios team where more detailed information was readily available.
7.5.1 Online Sample Analysis Process

The Online sample analysis includes all the steps that are executed inside the Metrios TEM station.

Figure 24. Online Sample Analysis

Although the main desired outcome of this process is the metrology data, it was seen from discussion with domain experts in the team as well as field service engineers that tool time in Metrios is mainly used for TEM/STEM/EDS image acquisitions, while the measurement/metrology mostly takes place offline (outside Metrios), using a less expensive tool or the offline PC provided from Thermofisher Scientific for this specific purpose. The offline metrology is therefore modeled separately in the main sample analysis process (Figure 25).

Figure 25. Metrology Use cases Subprocess

It was of interest to the Metrios team to model and analyze the metrology process in more detail to see the effects of different metrology workflows on the overall performance. Therefore a few use cases were
suggested for modeling in this project. Table 4 summarizes the five scenarios of metrology that were identified with the stakeholders (Martin Verheijen and Koos den Hollander). Out of the five, two were selected for modeling and simulation in this project, since these were the most common ones.

7.5.2 Acquisition and Metrology Use cases

Table 4 discusses the metrology use cases supplied by the domain experts and were used as a starting step for modeling.

Table 4. Metrology Use cases detail

<table>
<thead>
<tr>
<th>Case 1:</th>
<th>Case 2:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Switch to TEM Mode</td>
<td>1. Switch to TEM Mode</td>
</tr>
<tr>
<td>2. Navigate to lamella</td>
<td>2. Navigate to lamella</td>
</tr>
<tr>
<td>3. Align zone axis</td>
<td>3. Align zone axis</td>
</tr>
<tr>
<td>4. Center on first feature</td>
<td>4. Center on first feature</td>
</tr>
<tr>
<td>5. Optimize TEM beam</td>
<td>5. Optimize TEM Beam</td>
</tr>
<tr>
<td>6. Do TEM Metrology for all features</td>
<td>6. Do TEM Metrology for all features</td>
</tr>
<tr>
<td>6.1. Re-center on feature</td>
<td>6.1. Re-center on feature</td>
</tr>
<tr>
<td>6.2. Acquire TEM</td>
<td>6.2. Acquire TEM</td>
</tr>
<tr>
<td>6.3. TEM Metrology</td>
<td>6.3. TEM Metrology</td>
</tr>
<tr>
<td>6.4. Repeat 6.1 – 6.3 for all features</td>
<td>6.4. Repeat 6.1 – 6.3 for all features</td>
</tr>
<tr>
<td>7. Switch to STEM Mode</td>
<td>7. Repeat 2-6 for all Lamella</td>
</tr>
<tr>
<td>8. Optimize STEM Beam</td>
<td>8. Switch to STEM Mode</td>
</tr>
<tr>
<td>9. Do STEM Metrology for all features</td>
<td>9. Navigate to lamella</td>
</tr>
<tr>
<td>9.1. Re-center on feature</td>
<td>10. Reuse zone axis TEM</td>
</tr>
<tr>
<td>9.2. Acquire STEM</td>
<td>11. Optimize STEM beam</td>
</tr>
<tr>
<td>9.3. STEM Metrology</td>
<td>12. Do STEM Metrology for all features</td>
</tr>
<tr>
<td>9.4. Repeat 9.1 – 9.3 for all features</td>
<td>12.1. Re-center on feature</td>
</tr>
<tr>
<td>10. Switch to EDS Mode</td>
<td>12.2. Acquire STEM</td>
</tr>
<tr>
<td>11. Optimize Beam</td>
<td>12.3. STEM Metrology</td>
</tr>
<tr>
<td>12. Do EDS Metrology for all features</td>
<td>12.4. Repeat 12.1 – 12.3 for all features</td>
</tr>
<tr>
<td>12.1. Re-center on feature</td>
<td>13. Repeat 9-12 for all lamella</td>
</tr>
<tr>
<td>12.2. Acquire EDS</td>
<td>14. Switch to EDS Mode</td>
</tr>
<tr>
<td>12.3. EDS Metrology</td>
<td>15. Navigate to lamella</td>
</tr>
<tr>
<td>12.4. Repeat 12.1 – 12.3 for all features</td>
<td>16. Reuse Zone axis</td>
</tr>
<tr>
<td>13. Repeat 2-12 for all lamella</td>
<td>17. Optimize EDS Beam</td>
</tr>
<tr>
<td></td>
<td>18. Do EDS Metrology for all features</td>
</tr>
<tr>
<td></td>
<td>18.1. Re-center on feature</td>
</tr>
<tr>
<td></td>
<td>18.2. Acquire EDS</td>
</tr>
<tr>
<td></td>
<td>18.3. EDS Metrology</td>
</tr>
<tr>
<td></td>
<td>18.4. Repeat 18.1 – 18.3 for all features</td>
</tr>
<tr>
<td></td>
<td>19. Repeat 15-18 for all lamella</td>
</tr>
</tbody>
</table>
### Case 3:

1. Switch to TEM Mode  
2. Navigate to lamella  
3. Do TEM Metrology for a single feature  
   3.1. Center on Feature  
   3.2. Acquire TEM  
   3.3. TEM Metrology  
4. Switch to STEM Mode  
5. Do STEM Metrology for a single feature  
   5.1. Center on feature  
   5.2. Acquire STEM  
   5.3. STEM Metrology  
6. Switch to EDS Mode  
7. Do EDS Metrology for a single feature  
   7.1. Center on feature  
   7.2. Acquire EDS  
   7.3. EDS Metrology  
8. Repeat 3-7 for all features  
9. Repeat 2-8 for all lamella

### Case 4:

1. Switch to TEM Mode  
2. Navigate to lamella  
3. Do TEM Metrology for a single feature  
   3.1. Center on Feature  
   3.2. Acquire TEM  
   3.3. TEM Metrology  
4. Repeat 3 for all features  
5. Repeat 2 and 4 for all lamella  
6. Switch to STEM Mode  
7. Navigate to lamella  
8. Do STEM Metrology for a single feature  
   8.1. Center on feature  
   8.2. Acquire STEM  
   8.3. STEM Metrology  
9. Switch to EDS Mode  
10. Do EDS Metrology for a single feature  
    10.1. Center on feature  
    10.2. Acquire EDS  
    10.3. EDS Metrology  
11. Repeat 8-10 for all features  
12. Repeat 7-11 for all lamella

### Case 5:

1. Switch to TEM Mode  
2. Navigate to lamella  
3. Do TEM Metrology for a single feature  
   3.1. Center on Feature  
   3.2. Acquire TEM  
   3.3. TEM Metrology  
4. Repeat 3 for all features  
5. Switch to STEM Mode  
6. Re/Center on feature  
7. Do STEM Metrology for a single feature  
   7.1. Center on feature????  
   7.2. Acquire STEM  
   7.3. STEM Metrology  
8. Switch to EDS Mode  
9. Do EDS Metrology for a single feature  
   9.1. Center on feature  
   9.2. Acquire EDS  
   9.3. EDS Metrology  
10. Repeat 7-9 for all features  
11. Repeat 2-10 for all lamella

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From the above table, only case 1 and Case 2 were modelled as UC1 and UC2 respectively. These use cases were the most common ones that were in use by customers as mentioned by the domain experts as well as field service specialists. The detailed process model for the use cases are explained below.

7.5.2.1 Use case 1 – All analysis (TEM-STEM-EDS) Per Lamella

In this use case, navigation to a lamella is done once per lamella, where all acquisition (and metrology) is completed for that specific lamella. This aims to reduce the number of stage moves and therefore save time spent on navigation and centering of first feature. Figure 26 shows the process model for this use case.

![Use case 1: All analysis per Lamella](image)

Figure 26. Use case 1: All analysis per Lamella

7.5.2.2 Use case 2 – TEM all Lamella – STEM all Lamella – EDS all Lamella

In this use case, the microscope stays in one mode until all features in all the lamellas are processed. Specifically, this means executing all TEM acquisition (and metrology) for all lamella, switching mode and performing all steps in STEM mode, and finally, switching mode and performing all steps in EDS Mode.
Figure 27. Use case 2 All Analysis on One Lamella
7.5.3 Common Building Blocks in Metrology Subprocesses

In both the use cases, there are common elements to the process that can be reused for the current as well as future extensions of use cases. These are modelled as subprocesses and referenced by callSubprocess tasks whenever needed. These are represented in the above diagrams as bold bordered boxes. Notice here that all the tasks inside the subtask boundary for both use cases are callSubprocess tasks. The main difference is in the order of execution and looping behaviors. This approach is similar to the reusability principles of software design where we define functions once and reuse them as needed. This allows us to add more use cases later by simply using callSubprocess Tasks and organizing them in the desired way using loops, sequence flows, and gateways.

The building blocks of this process are show in detail below

- **Navigate and Center TEM/STEM/EDS**
  This subprocess refers to the step where an operator navigates to a given lamella on a grid and centers on the first feature. This step also includes zooming to that feature and aligning the zone axis. Once the zone axis is aligned examining the contiguous features only requires small shifts and takes much less time. This process can be done in TEM, STEM, or EDS Mode. Since optimizing the beam takes different amounts of time for the different modes, it was chosen to model it outside this subprocess and reuse the Navigate and Center subprocess model for all the three modes, which are the same in principle.

![Figure 28. Navigate and Center TEM Subprocess Metrology on Feature](image-url)
This subprocess refers to the process of acquiring an image (TEM/STEM/EDS) modes and performing metrology tasks. It is common in this subprocess for customers to only acquire the image and perform metrology offline on a dedicated machine (called Microscope PC). While Acquiring in TEM takes the least amount of time (around six seconds), acquiring in EDS mode takes a significantly longer time (about four minutes). Figure 29 shows this subprocess with the timings for the individual tasks involved.

![Figure 29. Metrology on Feature Subprocess](image)

7.5.4 Design Rationales Behind Approach

It can be seen from the metrology use case models that additional usecases / workflow variants can be added by adding more use cases to the metrology subprocess (Figure 25). This allows the reuse of the subprocesses and global tasks that were already defined for the other usecases. In such a case all tasks of a new subprocess will be modeled as `callGlobalTaskActivity` or `callSubprocessActivity` that refer to an already existing task or subprocess respectively. The main rationale was based on two factors:

- Extensibility of the Model
The initial approach was to model a single generic process with all possible paths (use case options) modelled using gateway decisions and sequence flows. This will result in a complicated process diagram with lots of connections which would be difficult to understand and extend. By factoring out the common processes and reusing them, it is possible to keep use cases separate and avoid cascading changes.

- Limitations with regards to Simulation

The BPSim language specification defines rules for allowed time and control parameters for the different elements of a BPMN. In terms of time parameters, these are supported only for tasks that do not contain a sub-processes (Workflow Management Coalition, WfMC, 2016), in which case, the timing on the subprocess tasks will be aggregated to the parent task. Figure 30 explains this in detail.

<table>
<thead>
<tr>
<th>Events</th>
<th>Time Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Event</td>
<td>No - BPMN Events map to time point and thus cannot have Time Parameters which are time intervals</td>
</tr>
<tr>
<td>Intermediate Event</td>
<td></td>
</tr>
<tr>
<td>End Event</td>
<td></td>
</tr>
<tr>
<td>Task</td>
<td>Yes</td>
</tr>
<tr>
<td>Sub Process</td>
<td>Yes - but only for activities without decomposition</td>
</tr>
<tr>
<td>Transaction</td>
<td></td>
</tr>
<tr>
<td>Call Activity</td>
<td></td>
</tr>
<tr>
<td>Event Sub Process</td>
<td></td>
</tr>
<tr>
<td>Gateways</td>
<td>No - BPMN Gateways do not map to time intervals as they are only visualizations of branching logic</td>
</tr>
<tr>
<td>Sequence Flow</td>
<td></td>
</tr>
<tr>
<td>Message Flow</td>
<td></td>
</tr>
<tr>
<td>Data Association</td>
<td></td>
</tr>
<tr>
<td>Association</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>No - BPMN Data Elements have no impact on the Simulation or the Analysis of the Process</td>
</tr>
<tr>
<td>Data Object</td>
<td></td>
</tr>
<tr>
<td>Data Store</td>
<td></td>
</tr>
<tr>
<td>Swimlanes</td>
<td>No - BPMN Swimlanes have no impact on the Simulation or the Analysis of the Process</td>
</tr>
<tr>
<td>Lane</td>
<td></td>
</tr>
<tr>
<td>Pool</td>
<td></td>
</tr>
<tr>
<td>Artifacts</td>
<td>No - BPMN Artifacts have no impact on the Simulation or the Analysis of the Process</td>
</tr>
<tr>
<td>Artifact</td>
<td></td>
</tr>
<tr>
<td>Attributes</td>
<td>No</td>
</tr>
<tr>
<td>Resource Role</td>
<td></td>
</tr>
<tr>
<td>Resource</td>
<td></td>
</tr>
</tbody>
</table>

Figure 30. Applicability of BPSim Time Parameters to BPMN Elements (Workflow Management Coalition, WfMC, 2016)
In terms of control parameters, there are also elements where the control parameters are not applicable. Figure 31 explains this in detail.

<table>
<thead>
<tr>
<th>Events</th>
<th>Control Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Event</td>
<td>Yes</td>
</tr>
<tr>
<td>Intermediate Event</td>
<td>Yes - but for Catch Event only</td>
</tr>
<tr>
<td>End Event</td>
<td>No</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Activities</th>
<th>Control Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task</td>
<td>Yes - but only for activities without decomposition without incoming sequence flow</td>
</tr>
<tr>
<td>Sub Process</td>
<td>No</td>
</tr>
<tr>
<td>Transaction</td>
<td>No</td>
</tr>
<tr>
<td>Call Activity</td>
<td>No</td>
</tr>
<tr>
<td>Event Sub Process</td>
<td>Yes - but only for Event Sub Process without decomposition</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gateways</th>
<th>Control Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gateway</td>
<td>Yes - but only for Event Based Gateway starting a process</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Connecting Objects</th>
<th>Control Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence Flow</td>
<td>No</td>
</tr>
<tr>
<td>Message Flow</td>
<td>Yes</td>
</tr>
<tr>
<td>Data Association</td>
<td>No</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data</th>
<th>Control Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Object</td>
<td>No - BPMN Data Elements have no impact on the Simulation or the Analysis of the Process</td>
</tr>
<tr>
<td>Data Store</td>
<td>No - BPMN Data Elements have no impact on the Simulation or the Analysis of the Process</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Swimlanes</th>
<th>Control Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane</td>
<td>No - BPMN Swimlanes have no impact on the Simulation or the Analysis of the Process</td>
</tr>
<tr>
<td>Pool</td>
<td>No - BPMN Swimlanes have no impact on the Simulation or the Analysis of the Process</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Artifacts</th>
<th>Control Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artifact</td>
<td>No - BPMN Artifacts have no impact on the Simulation or the Analysis of the Process</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Control Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>ResourceRole</td>
<td>No</td>
</tr>
<tr>
<td>Resource</td>
<td>No</td>
</tr>
</tbody>
</table>

**Figure 31. Applicability of BPSim Control Parameters to BPMN Elements (Workflow Management Coalition, WfMC, 2016)**

One additional limitation was that in addition to these parameters, looping behaviors modeled in BPMN were not taken into account by BPSim. This led to the modelling of loops with gateways and sequence flows instead of a more concise representation of looping tasks. Figure 32 demonstrates this concept.

**Figure 32. Looping task representations**
7.6 Evaluation of the Process Model

The resulting model was evaluated by domain experts, both from the preparation and analysis side. These experts had been involved from the requirement gathering phase up to modeling and simulation. Both parties have concluded that the process models reflect the real workflow variants selected for modeling. This was further clarified by customer site service agents for the metrology usecases.
8 Model Simulation

Model Simulation allows the evaluation of different flow variants and resource usage scenarios in order to be able to analyze the effect on performance.

The BPSim language allows the simulation of BPMN models from time, resource, and control perspectives. In addition to these perspectives, it is also possible to add cost parameters in the simulation. For this project, cost analysis was out of scope and therefore, not implemented.

A BPSim configuration can be created in Enterprise Architect by dragging and dropping a Business process Simulation Artefact from the Business Modeling Toolbox or through the Project Browser by using the “add element” feature in a specific package.

8.1 Creating a Simulation Configuration

The BPSim artefacts can be created in three ways:

- Create a new BPSim Configuration from scratch
- Copy an existing configuration and modify it
  - Copy a selected configuration and paste as new element. This helps to test different scenarios where most of the base configurations are the same.
- Use Configuration inheritance
  - In cases where only a few parameters need to be changed from a base configuration to do what-if analysis.

![Figure 33. Enterprise Architect BPSim Configuration Window](image)
The configuration window for BPSim (Figure 33) contains some default parameters for overall scenario parameters which can be updated as desired. The configuration options used in this project are explained below.

**Global Scenario Parameters**

- **Start time**: Configures the start time for the simulation
- **Duration**: The duration of time to simulate
- **Time Unit**: The time unit to be used throughout the simulation
- **Expression language**: The language to use for expressions. This can be Java or XPath1.0. For this project, XPath 1.0 (default) was used.
- **Seed**: A value to set to have multiple runs generate repeatable results

8.1.1 Defining properties

To add flexibility to the simulations, properties are used extensively in simulation configurations instead of constant values. Enterprise Architect BPSim allows the configuration of parameters as properties and using these properties in evaluation expressions (XPath 1.0 or Java). All timing properties used in the simulations as well as conditional properties for gateways are configured as property parameters.

The process of defining properties is analogous to declaring variables in class definitions and later initializing them in a calling program, in languages like Java (which is the underlying implementation in the simulation engine).
The properties defined are visible throughout the simulation, i.e., they are Global variables. The analogy to initializing variables in the main method of a Java class is initializing these variables in the first start event of the Sample Flow process (Start Sample preparation Event).
For this project, two levels of simulations are configured:

- Timing simulations for two different metrology use cases and
- Overall simulations for the Sample Flow Process

The main reason for this hierarchy is reducing complexity of the overall Sample Flow Model. The Metrology use cases are very detailed subprocesses that are executed within the Metrios (manually or using recipes) and the effect of selecting a specific use case can be represented by simply updating the time for Metrology subprocess in the overall workflow.

The other reason is that, due to the applicability rules of BPSim timing properties to subprocesses (as mentioned in section 7.5.4), when assigning resources to a decomposable task, the aggregated time is not reflected in the resource usage time.

One might ask here, why not configure the resource on the subtasks? While this is possible, it also means that the simulation will try to parallelize the resource usage of sequential tasks that should be part of the same subprocess inside the same machine, i.e., it assigns resources to them from the resource pool at the same time, which violates the actual scenario.

Therefore, as a solution, a decision was made to use non decomposable tasks (Activity) to represent processes that take place in the same machine for the simulation. The subprocess that such a task represents was still modelled in the BPMN model and linked as a child diagram element. On the other hand, the timings of each of these subtasks will be configured as property parameters in the default simulation. This approach was used to configure timings for Prepare Final Lamella and Pluck Sample subprocesses in Sample Preparation process.

8.2 Usecases Selected for Modeling

8.2.1 Metrology Use cases Selected for Simulation

The Metrology Process can have numerous scenarios based on the type of analysis required (TEM, STEM, EDS), the number of features to be analyzed, the number of lamellae on the grid and so on. The timings for tasks are gathered from System Acceptance Tests and can be reconfigures as is necessary. To run either one of the use cases only setting the value of “metrology_usecase” property to either usecase 1 and usecase 2 property values is needed. The resulting runtimes of the metrology use cases were defined
as properties inside the full process flow simulation. In this simulation, only timing characteristics were considered since it is a subprocess of one resource (in this case Metrios.)

8.2.2 Results of the metrology Simulation

The results of the simulation for the metrology tasks is represented by Figure 36.

![Metrology Usecases Simulation Result](image)

**Figure 36. Metrology Usecases Simulation Result**

It could be noted here that, while most of the tasks take the same amount of time, the main difference comes from the fact that in Usecase2, there is an additional overhead of navigating to a lamella and centering the first feature for each mode (TEM/STEM/EDS) while this is done once per lamella in TEM mode in the case of Usecase1.
The time difference caused by the overhead of repeated navigation to lamella is reflected in the total time for the Run Metrology task which is shown in Figure 37. Since Usecase2 takes longer time than Usecase1, Usecase2 runtime was used for metrology processing time configuration to evaluate the worst-case scenario.

8.3 Example Configurations and Scenarios

Different scenarios were configured and simulated for performance and failure analysis. Simulation configurations with similar settings but slight variations are grouped together. The first Configuration made was for a single run test. That is, the simulation was run for a single job (Trigger count=1). This was to allow the testing of timing properties and reviewing conditional routing of tokens.
The second group of simulations was based on a scenario that was inspired by a customer setup. A real customer scenario was difficult to obtain since this project was not executed in customer premises and this information is confidential in some cases. A Sample setup from a company visit to one of the customers was used as a base for machine ratios (prep-TEM) and employee schedules. The base scenario (ETM_311_301_shiftbreaks_prep_baseline) for this group is as follows:

- **Starting Conditions**
  - 3 Exsolve Dual Beams – 3 Operators (1 per machine)
  - 1 TEMLink Plucking Station
  - 1 Metrios – 1 TEM Operator
- **Assumptions**
  - One job = 1 wafer
  - Each job consists of 5 lamellae with 3 features to analyze per lamella
  - Jobs (wafer to analyze) come every hour (1Job/hour)
  - Working hours are 24 hours
  - Employees work in 10-hour shifts with 2 shifts per day
  - TEM preparation takes place every day for 30 minutes
  - Only a single machine runs TEM Prep at a given time
  - All jobs include TEM, STEM and EDS analysis (taking worst case scenario)
  - Metrology is done offline.

The third group of simulations was made for purpose of failure analysis.

### 8.4 Simulation Results

Two main kinds of Simulations were carried out in this project.

- Simulation set 1: Performance (time, throughput, and resource) analysis assuming no error conditions
- Simulation set 2: Performance (time and throughput) analysis with error conditions

#### 8.4.1 Simulation Set 1 Scenarios

Performance (time, throughput, and resource) analysis assuming no error conditions

For this set of simulations, the base case scenario in section 8.3 was used as baseline and 4 other scenarios were built on top of it with a slight change of parameters to see the effect of varying resources. These
were built incrementally looking at the results of each simulation and taking possible measures to improve performance.

Scenario 2 is built by introducing the daily APM schedule to the base scenario. Scenario 3 adds one more Exsolve with a technician. Scenario 4 introduces one extra technician on the sample preparation side. Scenario 5 adds one more TEM operator.

Table 5. Scenario Configurations 1

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Configuration</th>
<th>#ExSolve</th>
<th>#TEML</th>
<th>#Metrios</th>
<th>#Prep</th>
<th>#TEM Operator</th>
<th>Metrology Use</th>
<th>Changes Made</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>311_301_shift_breaks</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>UC2</td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>311_301_shift_breaks_prep</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>UC2</td>
<td>Daily APM</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>411_401_shift_breaks_prep</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>UC2</td>
<td>1 more Exsolve with operator</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>411_501_shift_breaks_prep</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>UC2</td>
<td>1 more Prep Technician</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>411_502_shift_breaks_prep</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>UC2</td>
<td>1 more TEM Operator</td>
</tr>
</tbody>
</table>

8.4.2 Remarks on the Simulation Results

The simulation results above can be interpreted as follows:

Scenario 1: This was the base case scenario. The simulation base case was initially selected to be one without an employee break and TEM preparation schedules taken into account. However, the base case should try to simulate the existing scenario as much as possible. Figure 39 shows the BPSim calendar configuration window that enables this configuration.

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Using these calendars, different values can be set for the same property at different times. In this case, the ‘quantity’ property of the resource Prep Technician was configured to be 3 during normal hours and 0 during shift breaks. Likewise, the ‘quantity’ property of the resource TEM Operator was configured to be one during normal hours and 0 during shift breaks.

![Figure 39. Calendar Configuration for Employee Shift Breaks](image)

This meant that although the working hours can be 24 hrs. per day, employees take intermediate breaks, which should be considered. In this scenario, it can be seen that we can complete two jobs (10 lamellas) out of the 24 that were started (Figure 40).

![Figure 40. Scenario 1 Throughput](image)

Looking at the time aspect, more than 1200 minutes were spent waiting for a resource (a total of about 20 hrs.).
These waiting times eventually had an effect on the time to data which could be seen from the average time it took to complete the three major processes, Sample Preparation, Sample Analysis, and Sample Transport as shown in Figure 42. Summing up these times, with the configurations of scenario 1 it took 1396 minutes (about 23 hrs.)

The other interesting fact was that, while most of the resources had small utilization rates (Utilization = Total time busy / Total time available), the Exsolves and the Prep technicians have a much higher utilization (Figure 43). This indicated that a bottleneck was created by having fewer Exsolves and prep technicians than needed. This was further evident in the high average waiting times of activities that involve both resources.
Scenario 2: Scenario 2 was an effort to analyze the effect of daily TEM preparation schedules (APM). For APM processing time of 30 minutes/day/machine, there was no change in performance that was observed as compared to only employee shift break schedules. This is mainly because there is a big delay in sample preparation, which means more idle time for the Metrios waiting for jobs. In such a situation, a 30-minute preparation time was much less significant.

Scenario 3: In this scenario, the aim was to solve the bottleneck problem in the sample preparation part of the process by adding one more Exsolve with a prep technician.

**Figure 44. Scenario 3 Throughput**

This showed a throughput increase of 2 jobs (20 lamellae, i.e., twice as much) as shown in Figure 44. The waiting times were also reduced by half (646.25 minutes ≈ 11 hrs.) and more distributed across different activities than before (Figure 45). However, it could still be noticed that there was a much higher utilization rate for the prep technicians (Figure 46). This was also because a dedicated TEMLink operator have not been assigned, which made the prep technicians very occupied.

**Figure 45. Scenario 3 Waiting Times**
Scenario 4: In this scenario, one more prep technician was added to relieve the bottleneck that was observed in the previous case. Here, a rise in throughput was seen by two jobs/day (six jobs in total, 30 lamella).

In this scenario, it is also important to notice that, while it was possible to perform offline metrology for 6 job requests(wafers), this number reduced to three when looking at ‘End Online Analysis’. This seemed counterintuitive but could be explained by looking at the ‘End Online Analysis’ event, which comes after ‘Unload TEM Holder’ and ‘Load Grid in Storage’ tasks. In addition, the same TEM Operator was configured to be in charge of the Unloading and Storage tasks in addition to sample loading and acquisition. This meant that while some grids are still in the process of being loaded into storage containers, the data from these grids could be already processed on the Offline PC. Of course, here it should be assumed that there was no constraint on the number of TEM Holders i.e while we are in the process of removing sample from a loaded TEM holder, another can be used to load samples into the microscope.

The total average waiting time had also decreased by about two hours (around 140 min). It is also interesting to notice that in this case, the waiting times shifted to the Metrios side.
Figure 48. Scenario 4 waiting times

Figure 49 shows that this configuration also improved the utilization of Metrios significantly (from 49% to 63%).

Figure 49. Scenario 4 Resource Utilization

Scenario 5: In this last scenario, one more extra TEM operator was added based on the observation of larger waiting times at the sample analysis activities. This would simulate the situation that one TEM operator would only be dedicated to the process flow from loading TEM holder to analyzing and unloading TEM holder, while the other could be dedicated to loading grids into storage containers.

The impact here was quite significant. The total average waiting time also decreased by about two hours (130 mins) (Figure 50). It was also possible to finish the loading of 3 grids in the storage container (Figure 51).

Figure 50. Scenario 5 Waiting Times
Figure 51. Scenario 5 Throughput

The results of the successive simulations can be summarized in the three graphs below: Sample Flow Throughput (Figure 52), Sample Flow Timing (Figure 53), and Sample Flow Resource Utilization (Figure 54).

Figure 52. Simulation Result 1 - throughput graph
Throughout the incremental analysis, it could be seen that the throughput could be increased up to five times. More than ten hours of total waiting time had also been reduced. This analysis may also continue further to optimize the process by looking more deeply at the different constraints.
8.4.3 Evaluation of the Simulation Result

Based on the limited customer data available, it was attempted to compare the results of these simulation outputs with a real customer usecase. This usecase refers to the configuration we used as a base case scenario for the simulations. It was observed from a visit by a systems integration specialist (Sylvia Aerts, Thermo Fisher) that 20 lamellas per shift (12 hrs.) are processed. Unfortunately, the data from customer lab refers to the Sample Analysis phase only, furthermore the 20 lamellas/ shift includes only imaging and not metrology. Nevertheless, this information could still be used to evaluate the time taken for sample analysis per a single lamella. The time for metrology of a single lamella (about 2-4 sec) can be safely approximated here.

As a result, 20 lamellas per 12 hours would mean that analysis on a single lamella takes about 36 minutes for that specific customer in the given arrangement. Looking at the simulation results for a similar usecase (Figure 53), the average time for sample analysis is 150 minutes. Since the BPSim configuration used 5 lamellas per grid, it meant that analysis on a lamella took around 30 minutes. This result is close to the result from the customer scenario.

Nevertheless, the simulation scenario was based on assumptions taken from the number and type of machines present and employee shift patterns, without specific information into the detailed workflow the customer was following. Further investigation and more information on customer usage would reveal a more dependable validation result.

8.4.4 Simulation Set 2: Performance analysis with error conditions

For this set of simulations, the automatic grid handling use case was used for sample transport, although it was still in the design stage. The error events were all modeled in the analysis section of the model. Figure 23 shows the sample analysis section of the process model, which contains all the error events modeled for this project.

For these set of simulations, the grid handler automated process was used instead of the manual process to simulate possible error conditions. This was selected since the Grid Handler Project carried out an FMEA analysis and defined error thresholds for acceptance criteria. For these simulations 1000 jobs were used as a baseline and an error rate of 0.01 (99.99% error free) and 0.001(99.999% error free) were used to simulate the effect on performance. These simulations were made only for time and throughput analysis. The resource effects were not simulated here. In other words, the results of this simulation assume no resource constraints. (The net effect of the errors on processing time and throughput).
The reasons behind this choice were the following:

- Limitations of BPSim in assigning resources to subprocesses (see section 7.5.4)
- The interpretability of the simulation result in the case of multiple resources:
  - Analyzing the effect of both resources and errors at the same time might be misleading since the resources are considered identical and the error rates are just multiplied in this case. It is possible to add some randomness to the simulation but still the results would be difficult to understand, and the net effect cannot be analyzed meaningfully.

The following failure modes were modeled.

- Grid Undetected: This refers to the situation that the grid recognition mechanism fails to detect the grid, which prevents the Grid Handler from being able to pick up the grid.
- Grid Lost: This refers to the situation where a grid is lost/damaged due to vacuum suction while trying to place it on the TEM holder
- Grid Handler Error: This is an aggregate error which can be the effect of failures in grid detection or pick-and-place mechanism, whereby a quick fix by an operator fails.
- Vacuum Levels Low: This is the case where, after loading the TEM holder, the correct vacuum levels cannot be attained, which has to be adjusted right away to prevent pollution.
- Data Services Error: This refers to the situation where acquisition has been made but failure in data services connection occurs. In which case, the images will still be available on the Microscope PC but not in data services, which causes some delay in offline metrology due to the need to match records manually.

The simulation results show the effect of failure rates on throughput. Looking at the ‘End Offline Metrology’ element in the throughput table below (Figure 55), it can be observed that 4 and 42 jobs are lost from a total of 1000 with error rates of 0.001% and 0.01% respectively (Figure 55).

<table>
<thead>
<tr>
<th>Element</th>
<th>Parameter</th>
<th>1000 jobs - Result</th>
<th>1000 jobs 0.001 percent - Result</th>
<th>1000 jobs 0.01 percent - Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>End Auto GH</td>
<td>Number Completed</td>
<td>1000</td>
<td>998</td>
<td>977</td>
</tr>
<tr>
<td>End Offline Metrology</td>
<td>Number Completed</td>
<td>1000</td>
<td>996</td>
<td>950</td>
</tr>
<tr>
<td>End Online Analysis</td>
<td>Number Completed</td>
<td>1000</td>
<td>998</td>
<td>968</td>
</tr>
<tr>
<td>Grid handler Error</td>
<td>Number Completed</td>
<td>2</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Grid Lost</td>
<td>Number Completed</td>
<td>2</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>grid undetected</td>
<td>Number Completed</td>
<td>1</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Metro</td>
<td>Number Completed</td>
<td>1000</td>
<td>998</td>
<td>968</td>
</tr>
<tr>
<td>Offline PC</td>
<td>Number Completed</td>
<td>1000</td>
<td>996</td>
<td>958</td>
</tr>
<tr>
<td>TEMOperator</td>
<td>Number Completed</td>
<td>2000</td>
<td>1997</td>
<td>1945</td>
</tr>
</tbody>
</table>

*Figure 55. Simulation result 2: Failure Rates and Throughput*
Analysis of the number of completed parameters showed that, in addition to the lost jobs, an error rate of 0.001% caused 1 job to be repeated, while a 0.01% caused 9 (Figure 56).

8.5 Modeling Limitations and Best Practices.

In this section, the limitations found while working with the tool and some good practices to avoid the pitfalls are discussed.

- **Assigning resource to subprocesses**

  Although EA BPSim configuration allows assigning resources for subprocesses, it ignores this configuration while running. Therefore, the results would show that the resource was idle the whole time. An alternative used in this project is to model this subprocess as an activity/task if resource analysis is required. In case subtasks need to be defined under this activity(task), this was achieved by dragging and dropping activities inside the activity/task. In some cases, the subprocess tasks were also drawn in a child diagram (for a subprocess carried out by/within a given resource). However, in both cases, you should keep the BPMN type of the parent activity as “task” (see configurations for “Prepare Final Lamella” subprocess).

  Why not model these as separate tasks and assign a resource to each?

  The reason is that, if sequential tasks of the same machine are modelled separately and each assigned the same resource, this would only make sense if the resource available is only one. If the number of resources is increased, the simulation would share these resources as they become available between these tasks, while in fact all of these actually happen in one single machine. In other words, there is no constraint that ties a task to an instance of a resource.
Workaround for tasks that were modeled separately but take place in the same machine (take the same resource time)

In some cases, it would be of interest to define tasks that are separate but take the same tool time. For example, “Load holder in TEM” and “Online Sample Analysis.” It was preferred to model them separately because:

1. Loading holder is a possible candidate that could be automated (a robot instead of a human operator) OR
2. Modeling error characteristics while loading holder in TEM was of interest

The simulation should reflect that these two things happen in the same machine and are done by the same operator (for the manual case). To achieve this effect, the processing time for online analysis was configured as follows:

\[
\text{ProcessingTime} = \{t_{\text{load\_holder\_in\_tem}}\} + \{t_{\text{load\_tem\_job\_metrios}}\} + \{t_{\text{metrology}}\} + \{t_{\text{unload\_tem\_holder}}\}
\]

and the resource as \text{getResource('Metrios',1)} and \text{getResource('TEMOperator',1)}. Notice here that the timing calculations also include “Unload TEM Holder” task which was modelled as a separate task. This was to allow time and resource simulation as well as error condition modeling in between the subtasks.

- **Very Limited Error Message for configuration errors**

This was a limitation of Enterprise Architect BPSim Simulation. It was difficult to find a configuration error since only generic error messages were provided. The workaround was to make changes incrementally. This meant saving a working version of the model before each major change so that the model can be rolled back to that version if an unidentified breaking error is introduced. Using Java as expression language helps a little, since this provides an execution log. However, this was not a significant change since it was not helpful for debugging a specific error. Java expressions were not used in this project since this required configuration changes in some cases such as setting parameters (for example, counters) on sequence flows instead of in start events.

- **Global Task Configurations**

While modeling global task properties, the configuration window did not show property and control configurations. The workaround used in this case was to first change the type of these elements to task and configure them. Once configured, they were changed back to Global tasks.
• **Inheritance and Calendars**

BPsim inheritance, as shown in the Sparx user guides (Sparx Systems, 2019) allows defining base scenarios and inheriting them in other scenarios so that only the changed parameters are defined in the inheriting configurations. This also means that the children will inherit any changes made in the parent, unless they override them. The differences can be seen in the configuration review page by opening both. Only the new changes are shown on the child configuration's column. The problem faced here was that, since the parent configurations could not be seen from the child configuration, calendar-based conditions could not be modified. Therefore, in cases where calendar-based parameters are, it was found to be better to duplicate configurations instead of using inheritance.

• **Boolean Condition Values**

In exclusive gateways, using values like a=true and a=false for opposite gateway sequence flows, although valid, makes the simulation evaluate incorrectly or stop. The workaround used for this case was assigning two separate integer values for the two cases. For example, to define a condition for transport type, instead of using `automated=true` and `automated=false` as evaluating conditions, the following method was used.

```plaintext
{transport_type}={automated_transport} and {transport_type}={manual_transport}
```

for selecting between automated and manual transport as mentioned above.

• **Exporting Configurations**

Although both CSV and XML exports for BPsim configurations are supported by Enterprise Architect, it was observed that only the XML export contained all the configurations, including the BPMN models. On the other hand, the CSV export contained only the parameter values. In case of calendar related values, for example Quantity of TEM Operators (let's say five during normal working hours and three during shift breaks, this would not be present in a csv export. Only one of the properties were exported.

• **Simulating error conditions in subprocesses**

To simulate the effect of errors in a subprocess, error throwing events inside subprocesses were used. Boundary catching events (blue circles) were then put on the parent task that catch these the thrown events as shown in the figure above (Error! Reference source not found.). In addition, simulation for error analysis should be conducted separately from resource analysis since these two are separate concerns.
9 Model Deployment

This part of the project was included in the scope of the project after discussing it with the project supervisor and weighing the impact on the project.

The insights to deploy the process models was based on the observation that actual customer data was scarce and different customers have found a way of creating their own workflows which were not apparent to the supplier (Thermofisher Scientific). The question of analyzing performance is therefore highly dependent on how the customer uses these machines in addition to the machine performance by itself.

It was also visible, from discussion with domain experts, that planned changes or automations are not always preferred by customers for different reasons. This raises a question of which processes or solutions should be offered to which customer to improve their performance. Although the analysis with BPMN and BPSim Simulation gives a good indication of performance bottlenecks and allows us to develop different versions of optimized processes, the actual usage at the customer might still be different or might evolve in its own direction. In the age of Big Data, Machine learning and customized services, deployable processes would be a great advantage to the company.

In order to mitigate the risk of investing resources in optimization and automation efforts and to solve the problem of not having enough knowledge of customer workflows, one possible solution is to offer these processes as services in addition to the machines and their application software. The benefits of this approach are:

- **Control**: deploy flexible and optimized processes as per customer needs
- **Optimization**: analyze performance in real time (resource allocation, parallelization)
- **Data**: store detailed process data in databases which can be used for data analytics and machine learning

To this end, a sample system was deployed to demonstrate how this can be done using a process deployment engine. For this project the Camunda BPM Engine was used since it is an open source tool and allows customizations based on demand.
9.1 Sample Deployment Architecture

To build this demo application, a kind of publish-subscribe model was used with Camunda engine publishing certain external tasks and two of Metrios’ services (Tool Readiness and Auto Recipe Runner), acting like subscribers (worker nodes) implementing tasks (TEM Preparation and Metrology, respectively).

![Diagram of Demo Deployment Architecture](image)

**Figure 57. Demo Deployment Architecture**

The following software components were used for this purpose:

- Metrios Virtual Machine (The version used for this Demo is Metrios DX4.0 TEM 6.15.0.53323)
- Tool Readiness Setup files (Setup-ToolReadiness.1.0.0.113.exe)
- Camunda BPM Modeler (camunda-modeler-3.0.1-win-x64.zip)
- Camunda BPM Engine (camunda-bpm-tomcat-7.10.0.zip)
- Camunda Worker node for tool readiness API
- Camunda Worker node for auto recipe API

A simplified process model was used for deployment, which has the necessary elements configured.
Figure 58 shows how these were configured in Camunda Modeler.

The tasks were configured as follows:

- **Transfer Sample**: This was implemented as user task for simplicity. A form was used to receive the grid_id(string), grid_type(enum) and num_of_lamella(long).

- **Load Holder in TEM**: This was implemented as user task. An input form was configured to receive holder_loaded as boolean field.

- **Run Tool Readiness**: This was implemented as external service task. (From properties panel, select “External” as implementation and put “chk_tool_readiness” as topic (the topic name will be used by the external workers to subscribe to this task).

- **Metrology**: This was implemented as a subprocess with a boundary (error catching) event. For the boundary event, error name was configured as Recipe_Failed_Error which will be used for error handling by the external task client.

- **Run Recipe**: This was implemented as external service task. (From properties panel, select “External” as implementation and put metrology as topic.

- **Notify Customer**: This was implemented as user task. Default configurations used.

- **Notify Operator**: This was implemented as user task. Default configurations used.

Figure 58. deployed model details
Sequence flows were configured as follows:

- Gateway "tem ready?"
  - sequence flow to Metrology (condition Type: javascript, Script Type: Inline Script, Script: Alignments!='" (If tool readiness worker returns alignment data continue to metrology)
  - sequence flow to TEM Prep (condition Type: javascript, Script Type: Inline Script, Script: Alignments=='" (If tool readiness worker does not return alignment data go to TEM Prep)

Note: for the external tasks, the polling method was used, i.e., worker nodes will subscribe to a given topic(task) and will claim the task to complete it and return control back to the process engine.

After configuration of the model as shown above, the process was deployed to the process Engine directly from the Camunda Modeler environment (Figure 59).

![Figure 59. Model Deployment](image)

The two external tasks were configured based on an opensource project called camunda-external-task-client-js on GitHub, which implements a NodeJS worker node for Camunda external tasks. Once the process was deployed on the engine, these worker nodes were started, and they were polling the main process waiting for a task to be assigned to them. Both processes should be installed on the Microscope PC.
The worker nodes are subscribed to different topics, which allows them to take tasks assigned to them specifically. Running the workers in a node server showed a polling log as shown below (Figure 60).

![Node.js command prompt - node auto_recipe_worker.js](image)

*Figure 60. Running Worker Node Terminal*

9.1.1 Running process with no BMPN Error

To test the process, a process instance was run on the engine with a correctly running recipe file as input. This recipe file was the one we wanted the AutoRecipeRunner to execute. This was to simulate the case of a fully automated process whereby the instructions to a job(recipe) file can be uploaded remotely by a client, a technician or a work scheduling program. In real life scenarios, the output expected in this case would be the result of TEM/STEM/EDS analysis (Metrology Data). These details can be specified in the recipe file.

However, the Recipe file used for this simulation was made only for demo purposes and was not expected to accomplish any useful work except demonstrating the concept of running a job. The instructions included in this recipe were simply loading a TEM image from a predefined location, run annotation and angle activities on it and save it in a specified location (Figure 62). At the end of a successful run, an image file was expected to be saved in the location specified by the recipe file.
Once a recipe was given as a parameter and a process was started, monitoring that process from the Camunda cockpit interface was possible. Each process ran as an instance and the instance specific data was visible as well. Tokens representing a single job instance were visible on the current task and moved forward as the process progresses (Figure 62).

The first task in the process flow was the “Transfer Sample to Holder” task, which was implemented as a user task for simplification. This could also be configured as a service task assigned to the grid handler. In such an automated case, the GridId, GridType and Number of Lamella fields shown on the form could be gathered from image recognition by the Grid handler.
In the demo implementation, this process was simulated by simply filling this form from the Camunda task list webapp interface, which could be accessed through a web browser from a different machine than that of the process engine deployment server (Figure 63).

![Figure 63. Transfer Sample to Holder Interface](image)

After completing this task, the token could be seen moving to the next task in the Camunda cockpit. The next task was then assigned to the specified user automatically by the process engine (all manual tasks in the demo implementation were assigned to the demo user provided by default). It is possible to assign different kinds of users to a task according to their role, in which case only the assigned user will get a notification for a new task.

![Figure 64. Load Holder in TEM Tasks Interface](image)

After the “Load Holder task” (Figure 64), “Run Tool Readiness” was next in line and the server published this task for an available subscriber. The tool readiness worker then took over control of this task and sent a request to the Tool readiness API to check if alignment data was available. This worker was configured in such a way that If alignment data was available, it would set a process variable called “Alignments” with the alignment data and pass this to the process control, finishing its task.
In the first run alignment data was available and this led the process to continue execution of the “metrology” task (Figure 65, left). If this data was not available, the Alignment variable would have been null, leading to the execution of the TEM Prep task.

When the metrology task is initiated, the process engine again published this task and this time, the Auto Recipe Runner worker node took this task (Figure 65, top right). The Auto Recipe Worker node was configured such that it will initiate the command line client of the AutoRecipeRunner and runs the specific recipe and saves the output in the specified location. This step was successfully completed as and a .tif image was created in the specified location (Figure 65, bottom right).

![Figure 65. Log output of worker nodes -success](image)

Since no error was caught by the boundary event the system execution continued to the “Notify Customer” task, which should notify the customer that the data is ready.
This was also visible in the process view inside the Camunda cockpit. Figure 66 shows this view with the data registered for this process instance.

Note: The two worker nodes were implemented similarly with only one difference. The Tool Readiness API is accessible through a REST interface, and therefore, the Tool Readiness Worker node needed to send an HTTP POST request to this API to get this response. In the case of Auto Recipe Runner Worker node, it needed to initiate a shell command locally to start the Auto Recipe Runner.

It is worth noting here that in a real system, more constraints need to be checked before actually assigning the Metrology task to a TEM. Only a TEM which passed the tool readiness check for the job to be executed should be able to subscribe to the task. These details were left out of this demonstration since the purpose of this project was not to design such a system but to show the possibilities of using BPMN models in production.

### 9.1.2 Running process with BPMN Error

In addition to the success scenario, it was also important to see how business errors are handled by the deployment engine. It should be noted here that these errors are BPMN errors that are part of the process model and not to be confused with other system or connection errors that might be handled differently.

To demonstrate this, a new recipe file was created by modifying the one used in the success scenario to make it fail. The process remained the same except that the provided recipe file pointed to the erroneous recipe instead of the correct one. Once the process execution reached the metrology subprocess it was
visible in the logs that auto recipe error has terminated and a “Recipe_Failed_Error” is returned to the process engine as shown (Figure 67, left).

![Figure 67. Log output of worker nodes - Error](image)

The boundary event then caught this BPMN error and the process went to the “Notify Operator” task. This flow and the data associated could also be seen in Camunda cockpit. Figure 68 demonstrates this.

![Figure 68. Process View inside Engine – No Error](image)

This deployment demo was successfully implemented, deployed and demonstrated to stakeholders.
10 Conclusion

In this project, the main challenges were being able to analyze performance based on process flow variables and being able to model failure characteristics. Solutions were developed at different phases to enable these requirements.

10.1 Design Opportunities Revisited

Section 4.2 discussed the design opportunities identified during this project. In this section, those design opportunities are revisited to evaluate the results of the project against them.

- Extensibility: The developed process models can easily be extended to include more workflow variants. Some of the subprocesses are modeled in subprocesses that can be reused in future extensions as well.

- Ease of Use: BPMN is a visual language that is easy to understand with a basic introduction of the symbols their meaning. Designers within Thermofisher are already familiar with designing workflows with tools like Visio as well as SysML activity diagrams. Some concepts are transferable from this tools and languages as well.

Setting up simulations is also graphically supported in Enterprise Architect, although this requires some more effort to setup in a complex model.

- Reusability: While modelling common aspects of the model are extracted and modeled as subprocesses so that they are reusable. This also holds true for the simulation configurations. Which can be extended through inheritance (in some cases).

- Configurability: This criterion mostly concerns the simulation configurations in BPSim. This is implicitly satisfied by the choice of the simulation standard.

The first part of the project addressed modeling of the process workflow using Business Process modeling Notation (BPMN). The high-level business processes were taken as Sample Preparation, Sample Transport, and Sample Analysis. To identify the key process flow components, domain analysis was made in the form of interviews, document reviews, meetings, and stakeholder demonstrations. One of the challenges here was that the knowledge needed to construct these models was dispersed within the different domain experts across different locations. It is my belief that having a central repository of business models is an important step in process analysis for better performance.
The second part of the project addresses the client’s requirement to have a tool that enables a configurable environment where the impact of different variables on performance (Throughput and time-to-data) can be analyzed. This was achieved with the open standard BPSim that enables simulation of BPMN models. BPSim offers different analysis perspectives such as time, control, resource, and cost. For this project, all perspectives except cost were used to simulate use cases. Simulation of use cases using BPSim showed that it is possible to identify performance bottlenecks, perform what-if analysis, and analyze effects of failure rates.

The third part of the project, although not initially in scope, was influenced by the observation that real customer data is scarce, and it would be more meaningful if there was a way to use models in actual production environment. In such a way, the loop from analysis to a model-based solution can be closed. We can use detailed models to benchmark our processes and design optimized solutions for customer specific workflows, which can be offered as additional services that are deployed on their systems. These services in turn will provide analytics data we can feed back into analysis to come up with better solutions. This allows the application of an iterative design approach to processes as shown below.
11 Recommendations and Future Work

Based on my observations, I recommend the documentation of workflows in Semiconductor analysis using BPMN which serves the purposes of an easy-to-understand documentation in an open, tool independent standard. In addition to that, it provides the basis for simulation through BPSim for performance analysis. Another benefit is that, such a model can be used as a basis for process level Failure Mode Effect Analysis (PFMEA). A more significant use of this approach is the fact that executable models can be derived from the analysis models, which can then be used in workflow engines to orchestrate events and resources in a managed environment. Tools like Camunda BPM Engine allow us to benefit greatly from process automation by providing time, resource and event management in real-time, as well as a data repository that can be used for data driven analysis.

Based on feedback from stakeholders and possible users of the system, I would like to mention certain points. There seems to be quite an interest in finding out the theoretical maximum performance to be achieved given a set of constraints. This seems theoretically possible, given that multiple simulation scenarios and the resulting performance changes can be used to calculate such a maximum performance. However, this is not investigated practically and could be one future area of investigation. Another point mentioned is the inclusion of cost calculations in the simulations. Although BPSim supports cost analysis, this project was limited to time, throughput and resource perspectives. This can easily be added in the current simulation to give another dimension to the analysis.
12 Project Management

This section describes how the project was managed throughout its lifecycle, methods used and evaluation of progress.

12.1 Purpose Scope and objectives

The aim of this project was to create a sample flow modelling tool which enables the analysis of the system performance and the identification of failure modes of the system. The performance analysis was mainly concerned with two key measures: time to data and throughput.

The stakeholders of the project have described the following interests:

- Fully documented sample flow
- Configurable parameters to analyze effect on overall performance
- Improve Throughout
- Improve time-to-data
- Identify weak spots in the flow
- Code generation

After an initial discussion of the various interests the initial project was defined as follows

- Modelling the current sample flow
- Modelling the semi-automated workflow with a few of the use cases
- Enable users have a rough performance indication
- Enable users adjust flow parameters and analyze effect on the overall flow
- Identify the system failure modes and build it into the model

12.2 Project deliverables

- Project Management Plan
- Stakeholder analysis document
- A requirements specification document
- A software model of the transport flow
- A project report
12.3 Project Schedule

- Start Date – January 2, 2019
- End Date – October 29, 2019

12.4 Management Methodology

For this project the Agile methodology was followed using the idea of Sprints and the Kanban board. At the start of the project a few epics were selected as target and adjusted as needed. The initial planning for the project is shown in the figure below.

![Roadmap](image)

**Figure 69. Project Initial Plan**

User stories were then put in the backlog or defined at the start of each sprint by the product owner (Marcin Gramza) together with the project manager (Beza Tassew). The epics are defined according to the requirements set by the client and the priorities of those requirements.

The Sprints were initially two weeks, but some were shortened to one week, especially during prototyping, in order to have faster cycles. At the end of each week, a project alignment session is scheduled to assess the progress and be prepared for the upcoming week.
### 12.5 Project Milestones

*Table 6. Project Milestones*

<table>
<thead>
<tr>
<th>Sprint Name</th>
<th>Sprint Dates (2019)</th>
<th>Available Working Hours (In days)</th>
<th>Key Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprint 1</td>
<td>Jan 9 – Jan 23</td>
<td>9</td>
<td>Initial Scope Definition</td>
</tr>
<tr>
<td>Sprint 2</td>
<td>Jan 23 – Feb 6</td>
<td>9</td>
<td>First Working demo</td>
</tr>
<tr>
<td>Sprint 3</td>
<td>Feb 6 – Feb 20</td>
<td>9</td>
<td>Technology Selection</td>
</tr>
<tr>
<td>Sprint 4</td>
<td>Feb 20 – Mar 14</td>
<td>11</td>
<td>Project Management Plan and Initial draft of Project Report</td>
</tr>
<tr>
<td>Sprint 5</td>
<td>Mar 14 – Mar 27</td>
<td>9</td>
<td>Initial process model and simulation demo</td>
</tr>
<tr>
<td>Sprint 6</td>
<td>Mar 27 – Apr 3</td>
<td>9</td>
<td>Initial process model and simulation demo</td>
</tr>
<tr>
<td>Sprint 7</td>
<td>Apr 4 – Apr 10</td>
<td>5</td>
<td>Initial process model and simulation demo</td>
</tr>
<tr>
<td>Sprint 8</td>
<td>Apr 10 – Apr 19</td>
<td>7</td>
<td>Define/Investigate lamella processing times</td>
</tr>
<tr>
<td>Sprint 9</td>
<td>Apr 23 – Apr 26</td>
<td>9</td>
<td>Investigate tool interoperability (BPMN execution outside EA &amp; Metrios App Interface)</td>
</tr>
<tr>
<td>Sprint 10</td>
<td>May 6 – May 17</td>
<td>9</td>
<td>Investigate Integration of Tool Readiness and Metrios Auto Recipe Runner</td>
</tr>
<tr>
<td>Sprint 11</td>
<td>May 20 – June 03</td>
<td>8</td>
<td>Demonstrate BPM integration to Metrios</td>
</tr>
<tr>
<td>Sprint 12</td>
<td>June 03 – June 07</td>
<td>5</td>
<td>Identify error situation in sample flow</td>
</tr>
<tr>
<td>Sprint 13</td>
<td>June 11 – Jun 24</td>
<td>9</td>
<td>Build customer usecase simulation</td>
</tr>
<tr>
<td>Sprint 14</td>
<td>Jun 24 – Jun 28</td>
<td>5</td>
<td>Sample flow simulation and deployment stakeholders’ demo</td>
</tr>
<tr>
<td>Sprint 15</td>
<td>July 2 – July 16</td>
<td>9</td>
<td>Assess tool usability and simulate error conditions</td>
</tr>
<tr>
<td>Sprint 16</td>
<td>July 17 – July 26</td>
<td>8</td>
<td>Prepare User manual and Update report regarding modeling and Simulation</td>
</tr>
<tr>
<td></td>
<td>(Jul 29 – Aug 9, holiday, Jul 19 -23, Supervisor holiday)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprint 18</td>
<td>Sep 2 – Sep 16</td>
<td>9</td>
<td>Introduce modeling and simulation environment to stakeholders, Update Report based on Comments</td>
</tr>
<tr>
<td>Sprint 19</td>
<td>Sept 16 – Sept 30</td>
<td>9</td>
<td>Finalize report and deliverables for submission</td>
</tr>
</tbody>
</table>
12.6 Infrastructure plan

Infrastructure Tools used for the project are

- Jira – for task and project management
- Gitlab – as project repository and documentation
- SharePoint – access to company services including file server, calendar, mail, Instant messaging

12.7 Methods, Tools and Techniques

The design approaches used in this project are

- Model Based Analysis
- Process modeling
- Process Simulation
- Executable process (Process deployment)

To enable these approaches a set of tools, standards, and frameworks were used. These are:

- BPMN
- BPSim
- Sparx Enterprise Architect
- Camunda BPM Engine
- Node.js

12.8 Project organization

12.8.1 Internal Stakeholders

The internal stakeholders of this project are those who are involved in the project via implementation, planning or supervision. Table 7 lists these internal stakeholders and the identified communication mechanism.
Table 7. Project Internal Interfaces

<table>
<thead>
<tr>
<th>Stakeholder Group</th>
<th>Role</th>
<th>Contact Person</th>
<th>Communication Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company representatives</td>
<td>Company Supervisor / Mentor</td>
<td>Marcin Gramza</td>
<td>Company email, Meetings, sprint planning and review sessions and consultation</td>
</tr>
<tr>
<td>University Representatives (NDA Signed)</td>
<td>University Supervisor/ Advisor</td>
<td>Anton Wijs</td>
<td>Email, Biweekly Progress Meetings, Monthly PSG Meetings</td>
</tr>
</tbody>
</table>

12.8.2 External Stakeholders

The external stakeholders of this project are those stakeholders outside the team but influence the project in different ways. Table 8 lists the external stakeholders of this project and communication methods used with them.

Table 8. Project External Stakeholders

<table>
<thead>
<tr>
<th>Stakeholder Group</th>
<th>Role</th>
<th>Contact Person</th>
<th>Communication Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Component representatives</td>
<td>TEM representative</td>
<td>Martin Verheijnen</td>
<td>Company email, in person meetings and presentations</td>
</tr>
<tr>
<td></td>
<td>TEM representative</td>
<td>Koos Den Hollander</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grid Handler representative</td>
<td>Nestor Rodriguez</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Robotic Arm representatives</td>
<td>Marcin Gramza</td>
<td>(may change)</td>
</tr>
<tr>
<td></td>
<td>Smart Stage representatives</td>
<td>to be established</td>
<td></td>
</tr>
<tr>
<td>Customer Representatives</td>
<td>Product Owner</td>
<td>Marcin Gramza</td>
<td>Company email, Meetings, sprint</td>
</tr>
</tbody>
</table>
12.8.3 Team structure

- Project Manager/Designer - Beza Getachew Tassew,
- Project Scrum Master – Beza G. Tassew / Marcin Gramza
- Product Owner – Marcin Gramza

12.8.4 Project Artefacts and owners

The artefacts of the project and their owners have been defined in Table 9.

Table 9. Project Artefacts and owners

<table>
<thead>
<tr>
<th>Artefacts</th>
<th>Owners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Scope</td>
<td>Project Manager</td>
</tr>
<tr>
<td>Project schedule</td>
<td>Project Manager</td>
</tr>
<tr>
<td>Epics</td>
<td>Scrum Master</td>
</tr>
<tr>
<td>Tasks</td>
<td>Software Architect/Designer</td>
</tr>
<tr>
<td>Backlogs</td>
<td>Scrum Master</td>
</tr>
<tr>
<td>Progress reports</td>
<td>Project Manager</td>
</tr>
<tr>
<td>Project Deliverables</td>
<td>Product Owner</td>
</tr>
</tbody>
</table>
12.9 Feasibility Analysis

12.10 Risk Management

The project manager maintains a list of risks and proposed mitigation action (to reduce the chance of the risk materializing) and contingency actions (to reduce the impact of the risk). This list is visible to all team members (https://bro-gitlab.w2k.feico.com/beza.tassew/asf-metrios/Documents/PMP).

12.10.1 Identified Risks

The following table summarizes the risks identified and associated mitigation plan.

*Table 10 Risk Analysis*

<table>
<thead>
<tr>
<th>Risk</th>
<th>Severity</th>
<th>Mitigation Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Broad Scope</td>
<td>Medium</td>
<td>Limit the scope within the resources and capability available</td>
</tr>
<tr>
<td>No Stakeholder Consensus on Deliverable</td>
<td>High</td>
<td>Follow agile methodology. Get quick feedbacks and iterate.</td>
</tr>
<tr>
<td>Steep Learning Curve for MBSE tools</td>
<td>High</td>
<td>Identify tool and technology to be used very early. Select a tool or technology with some level of expertise</td>
</tr>
<tr>
<td>A selected modelling tool might not address the full requirement list</td>
<td>High</td>
<td>Make a pros and cons document and discuss with stakeholders. Limit the scope and select a tool early. Try out the tools with a small prototype</td>
</tr>
</tbody>
</table>

12.11 Measurement

The outputs of the project can be measured from the perspectives of deliverables and how progress was made.

12.11.1 Project Final Deliverables

The following deliverable were successfully delivered to the client and put in shared locations accessible within Thermo Fisher Scientific.

- Final version of Model
- Modeling and Simulation Guide
- Deployment Guide
- Presentation Materials
12.11.2 Project Progress

At the end of the project an assessment was made on the project progress based on the road map and cumulative flow diagram. The road map Figure 70 shows the planned epics for the whole project. These have been slightly changed from the initial version.

**Figure 70. Project Road Map (as of End of Sept, 2019)**

**Figure 71. Cumulative Flow Diagram (as of End of Sept, 2019)**
13 Project Retrospective

13.1 Project Reflection

In this project, I have learned lots of new things and I have been challenged in different ways. One of the biggest challenges was, especially at the start of the project, understanding the multidisciplinary domain of semiconductor sample analysis at a level suitable to this project. Another related challenge being the fact that the knowledge exists not in readily accessible repository of knowledge but in multiple written documents, presentations as well as in the minds of the experts, some of whom are situated in other Thermo Fisher locations outside The Netherlands. I was able to overcome this with the support of my supervisor, by interviews with experts, documenting meetings, presenting findings to stakeholders and getting feedback as often as possible both in person and remote communication.

In the beginning of the project, it was quite challenging to play all the roles within the project, i.e. gathering domain knowledge, understanding stakeholder needs, identifying requirements, identifying possible technology solutions, while also managing the administrative tasks. This was of course to be expected since this is an individual project. What helped here was to simply ask people for more information. It is usually the case that the problem you are asked to address has been tackled before probably from a different viewpoint. I was able to use such experiences as inputs for my project.

Another aspect that was both a benefit and a challenge was the level of independence I had during this project. Being in between separate teams, I did not belong to any specific team’s current line of work, although I had close collaboration with the Metrios team. This gave me lots of independence to come up with creative solutions and devise my own way of working but at the same time increased the level of responsibility and a limit of resources on a day to day basis. Nevertheless, I had sufficient communication with my supervisor and key stakeholders which was very positive.

13.2 Lessons Learned

Based on my reflections regarding this project I have some lessons learned that I would like to share.

- Start Simple
  If there are too many uncertainties in a project, implement the simplest solution that captures the things you already know rather than starting from the most complex design. Continue incrementally. I was initially thinking about very complex solutions that do not fully address the problem. Therefore, I had to take the ‘simple’ approach that answers my client’s questions. in such cases it is always good to start from the simplest solution and add details later.
• Do not start thinking about technology or methods from the beginning.

Start your project by asking why it is needed. I observed this during the first weeks of my project as I was trying to find a suitable approach. The choice of technology options and methodologies was very wide and each of these were really good at something. Having the why’s of the project helped me choose the fitting solution.

• If no one is taking the decision about certain aspects of your project, take the decision yourself and put assumptions.

Sometimes during the project, you notice that you could not get some information as input for your next step, in such cases it is better to make reasonable assumptions and document those. If you are waiting for the exact answers to your questions, you risk not ever finding those answers because there might not be an exact answer in the first place.

• Do not assume the client knows everything about the solution

This one also applies to any project, I believe. Sometimes project descriptions point to approaches, or technology specific issues. Do not take that for granted. Make sure you know why those specific details are mentioned. Is it because there are constraints related to them or simply because they think it might be one option? This is very important because you are supposed to give the solution and you are expected to be an expert in the solution space. Get as much domain knowledge as is relevant from your client. But do not expect them to give you hints on how to come up with a solution. Even if they do, you have to question why.

• Do not focus only on your project. Understand the dynamics of your team, the management, or even the customers as much as you can.

This is very critical since not all answers will be in your project team or in documents. Some answers will be in the dynamics of the team, the management or even the company. Knowing about these environmental factors can be as important as the technical details of your project.

• Communicate results (outside your immediate team as well) as much as possible. Don’t wait until you have a complete picture

This is often mentioned but not as often applied rule. By communicating early, not only do you get feedback, but you might find out someone has been down the road you have taken and might give you great insights (as was in my case)
14 Glossary

- MSD – Material and Structural Analysis Division
- AIG – Analytical Instrumentation Group
- TEM – Transmission Electron Microscope
- WDB – Wafer Dual Beam
- STEM – Scanning Transmission Electron Microscope
- EDS - Energy-dispersive X-ray spectroscopy
- OMG – Object Management Group
- BPMN – Business Process Modeling Notation
- BPSim – Business Process Simulation
- FMI – Functional Mockup Interface
- FMU – Functional Mockup Units
- MBSE – Model Based Systems Engineering
- ARCADIA – ARChitecture Analysis & Design Integrated Approach
- TU/e - Technische Universiteit Eindhoven
- PDEng – Profession Doctorate in Engineering
- SysML – System Modeling Language
- PSG – Project Steering Group
- ST – Software Technology
- BPM – Business Process Modeling
- API – Application Programming Interface
15 References


About the Author

Beza Getachew Tassew graduated from Haramaya University (Ethiopia) in 2011 with a BSc. in Electrical Engineering. Since then, she has been working as a developer for more than 5 years in various companies. Also, while working she studied for a master’s degree in computer science at HiLCoE School of Computer Science and Technology (Ethiopia) and graduated in 2017.

Beza joined the Software Technology PDEng program in 2017 and worked at Thermofisher Scientific on a design project that enables performance analysis of semiconductor analysis workflows and explores the possibility of process deployment via workflow engines.

Beza has a wide variety of interests including Software Design and Development, Smart Connected Systems, Machine Learning and AI.
Appendix

A. Base Case Scenario BPSim Configuration (includes BPMN model)

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    http://www.omg.org/spec/DD/20100524/DC"
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</bpmn:task>

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  <bpmn:incoming>EAID_6C137A37_0A43_458d_AC44_B652EC33FDAD</bpmn:incoming>
  <bpmn:outgoing>EAID_6C137A37_0A43_458d_AC44_B652EC33FDAD</bpmn:outgoing>
</bpmn:sequenceFlow>

<bpmn:endEvent id="EAID_6D9AC887_5053_474_eA4D2_3ECB082986A2" name="End Sample Prep">
  <bpmn:incoming>EAID_1E7572E0_1B71_4060_A242_9DE7C0A78A31</bpmn:incoming>
  <bpmn:endEvent/>
</bpmn:endEvent>

<bpmn:task id="EAID_88E1B7F4_5B9D_4ee7_973D_A1D23844C209" name="End Top Down"/>

<bpmn:incoming>EAID_F4A2F09F_3A87_42ea_AD9E_F9AD903A6BE4</bpmn:incoming>

<bpmn:subProcess id="EAID_04ABB131_566E_4760_B1CB_ED0DFF18890C" name="Top Down Process" startQuantity="1" completionQuantity="1" isForCompensation="false" triggeredByEvent="false">
  <bpmn:incoming>EAID_88E1B7F4_5B9D_4ee7_973D_A1D23844C209</bpmn:incoming>
  <bpmn:outgoing>EAID_88E1B7F4_5B9D_4ee7_973D_A1D23844C209</bpmn:outgoing>
</bpmn:subProcess>

<bpmn:sequenceFlow id="EAID_88E1B7F4_5B9D_4ee7_973D_A1D23844C209" sourceRef="EAID_88E1B7F4_5B9D_4ee7_973D_A1D23844C209" targetRef="EAID_B3A78008_84CF_4c23_A772_2E50992D1B4A" />

<bpmn:endEvent id="EAID_00DBD1B6_503E_4e8A_BFFB_5312BA0068E4" name="Start Top Down" />

<bpmn:task id="EAID_B3A78008_84CF_4c23_A772_2E50992D1B4A" />

<bpmn:sequenceFlow id="EAID_6C137A37_0A43_458d_AC44_B652EC33FDAD" sourceRef="EAID_6C137A37_0A43_458d_AC44_B652EC33FDAD" targetRef="EAID_B3A78008_84CF_4c23_A772_2E50992D1B4A" />

<bpmn:endEvent id="EAID_CCED277E_CDEC_462F_BCF3_605E3ADCF2F2" name="Transfer Sample" startQuantity="1" completionQuantity="1" isForCompensation="false" />

<bpmn:incoming>EAID_6B57D149_6F96_4121_AC4E_70B4714D7394</bpmn:incoming>

<bpmn:outgoing>EAID_816543CF_4CB5_49f9_8FBE_B5F064D99E52</bpmn:outgoing>
</bpmn:task>

<bpmn:sequenceFlow id="EAID_6B57D149_6F96_4121_AC4E_70B4714D7394" />
sourceRef="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F" targetRef="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F"/>
    
    <bpmn:task id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" name="Sample Transport" isForCompensation="false">
      <bpmn:incoming>EAID_E2C763D4_1F76_46c5_8508_F2D31D2E3BC7</bpmn:incoming>
      <bpmn:outgoing>EAID_F4A2F09F_3A87_42ea_AD9E_F9AD903A6BE4</bpmn:outgoing>
    </bpmn:task>
    </bpmn:subProcess>
    <bpmn:sequenceFlow id="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F" targetRef="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F"/>
  
  <bpmn:task id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" name="Notify Transporter" isForCompensation="false">
    <bpmn:incoming>
      <bpmn:sequenceFlow id="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F" targetRef="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F"/>
    </bpmn:incoming>
    <bpmn:outgoing>EAID_F4A2F09F_3A87_42ea_AD9E_F9AD903A6BE4</bpmn:outgoing>
    </bpmn:task>
    </bpmn:subProcess>
    <bpmn:sequenceFlow id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" targetRef="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7"/>
  
  <bpmn:task id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" name="Notify Transporter" isForCompensation="false">
    <bpmn:incoming>
      <bpmn:sequenceFlow id="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F" targetRef="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F"/>
    </bpmn:incoming>
    <bpmn:outgoing>EAID_F4A2F09F_3A87_42ea_AD9E_F9AD903A6BE4</bpmn:outgoing>
    </bpmn:task>
    </bpmn:subProcess>
    <bpmn:sequenceFlow id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" targetRef="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7"/>
  
  <bpmn:task id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" name="Notify Transporter" isForCompensation="false">
    <bpmn:incoming>
      <bpmn:sequenceFlow id="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F" targetRef="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F"/>
    </bpmn:incoming>
    <bpmn:outgoing>EAID_F4A2F09F_3A87_42ea_AD9E_F9AD903A6BE4</bpmn:outgoing>
    </bpmn:task>
    </bpmn:subProcess>
    <bpmn:sequenceFlow id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" targetRef="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7"/>
  
  <bpmn:task id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" name="Notify Transporter" isForCompensation="false">
    <bpmn:incoming>
      <bpmn:sequenceFlow id="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F" targetRef="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F"/>
    </bpmn:incoming>
    <bpmn:outgoing>EAID_F4A2F09F_3A87_42ea_AD9E_F9AD903A6BE4</bpmn:outgoing>
    </bpmn:task>
    </bpmn:subProcess>
    <bpmn:sequenceFlow id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" targetRef="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7"/>
  
  <bpmn:task id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" name="Notify Transporter" isForCompensation="false">
    <bpmn:incoming>
      <bpmn:sequenceFlow id="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F" targetRef="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F"/>
    </bpmn:incoming>
    <bpmn:outgoing>EAID_F4A2F09F_3A87_42ea_AD9E_F9AD903A6BE4</bpmn:outgoing>
    </bpmn:task>
    </bpmn:subProcess>
    <bpmn:sequenceFlow id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" targetRef="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7"/>
  
  <bpmn:task id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" name="Notify Transporter" isForCompensation="false">
    <bpmn:incoming>
      <bpmn:sequenceFlow id="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F" targetRef="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F"/>
    </bpmn:incoming>
    <bpmn:outgoing>EAID_F4A2F09F_3A87_42ea_AD9E_F9AD903A6BE4</bpmn:outgoing>
    </bpmn:task>
    </bpmn:subProcess>
    <bpmn:sequenceFlow id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" targetRef="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7"/>
  
  <bpmn:task id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" name="Notify Transporter" isForCompensation="false">
    <bpmn:incoming>
      <bpmn:sequenceFlow id="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F" targetRef="EAI_D34B0EFC_80C0_43ea_99C1_5872A8CFCC0F"/>
    </bpmn:incoming>
    <bpmn:outgoing>EAID_F4A2F09F_3A87_42ea_AD9E_F9AD903A6BE4</bpmn:outgoing>
    </bpmn:task>
    </bpmn:subProcess>
    <bpmn:sequenceFlow id="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7" targetRef="EAI_D2736D4_1F76_46c5_8508_F2D31D2E3BC7"/>
<bpmn:task id="EAID_ED1BD897_471C_48fa_A8A7_6A1E3D3C0B4C" name="Load WDB Container in FOUP" startQuantity="1" completionQuantity="1" isForCompensation="false">
    <bpmn:incoming>EAID_16282875_7835_4f60_851F_5E1C4E4A3730</bpmn:incoming>
    <bpmn:outgoing>EAID_AAED600E_CC56_4308_BF98_141838182A53</bpmn:outgoing>
</bpmn:task>

<bpmn:task id="EAID_954E1720_3AB0_40a7_AE04_EF2C5DC9096A" name="Transport Grid Container to TEM" startQuantity="1" completionQuantity="1" isForCompensation="false">
    <bpmn:incoming>EAID_16282875_7835_4f60_851F_5E1C4E4A3730</bpmn:incoming>
    <bpmn:outgoing>EAID_21D5C758_EC4B_45aa_B1B6_4B3ED4BF676C</bpmn:outgoing>
</bpmn:task>

<bpmn:task id="EAID_8074BD02_9049_406c_B4F3_57339BD2A4C7" name="Unload Grid from FOUP" startQuantity="1" completionQuantity="1" isForCompensation="false">
    <bpmn:incoming>EAID_16282875_7835_4f60_851F_5E1C4E4A3730</bpmn:incoming>
    <bpmn:outgoing>EAID_2C9F4098_8A38_461b_AB0A_25399322CC42</bpmn:outgoing>
</bpmn:task>

<bpmn:exclusiveGateway id="EAID_E610620B_A837_4add_AFC1_2C0B6BF9535A" name="tranport_type" gatewayDirection="Unspecified">
    <bpmn:incoming>EAID_230733A2_ECD9_48a2_8AAB_EC076884A023</bpmn:incoming>
    <bpmn:outgoing>EAID_954E1720_3AB0_40a7_AE04_EF2C5DC9096A</bpmn:outgoing>
[Diagram of BPMN process flow]
<bpmn:boundaryEvent id="EAIID_927F50D7_A360_43dc_B6DD_91AB98E77C8C" name="Catch Issue" attachedToRef="EAIID_FD262CD8_BFC7_4f31_9380_3E9EC23D5E98" cancelActivity="true" parallelMultiple="false">
  <bpmn:escalationEventDefinition escalationRef="EAIID_C5D3FC4B_9DB7_4B77_A9CB_F47A2B874AC7"/>
</bpmn:boundaryEvent>
  <bpmn:task id="EAIID_FD262CD8_BFC7_4f31_9380_3E9EC23D5E98" name="Online Sample Analysis" startQuantity="1" completionQuantity="1" isForCompensation="false">
    <bpmn:incoming>EAIID_DCC56FCF_C2B0_4b02_B4D3_722FA5B0E69</bpmn:incoming>
    <bpmn:outgoing>EAIID_74F5743F_EE34_4450_994C_A82D5AD2E4CA</bpmn:outgoing>
  </bpmn:task>
  <bpmn:parallelGateway id="EAIID_BF5EE0A7_53F2_4282_8125_3A2622F86CC5" name="End Offline Metrology">
    <bpmn:incoming>EAIID_BF5EE0A7_53F2_4282_8125_3A2622F86CC5</bpmn:incoming>
  </bpmn:parallelGateway>
  <bpmn:boundaryEvent id="EAIID_D7B95346_0E24_4265_9868_8CD908D70FC9" name="Unload TEM Holder" startQuantity="1" completionQuantity="1" isForCompensation="false">
    <bpmn:incoming>EAIID_B9187590_7073_4278_85B6_1E3B65999523</bpmn:incoming>
    <bpmn:outgoing>EAIID_B9187590_7073_4278_85B6_1E3B65999523</bpmn:outgoing>
  </bpmn:boundaryEvent>
<bpmn:sequenceFlow id="EAID_DB01717_C2EA_45ae_AF93_75817E7D5C7D"
sourceRef="EAID_E0B86B57_9AF4_4ad2_BA35_8351F5A1729B"
targetRef="EAID_57B821A9_B1B4_4f36_81D1_9A92821A3E6B"/>
<bpmn:exclusiveGateway id="EAID_B89BAA63_58FD_4c26_A9CF_B28BEC4A8155"
name="sample on holder" gatewayDirection="Unspecified">
  <bpmn:incoming>EAID_BED2DB06_B189_41e5_B8D5_42F0B2555FD3</bpmn:incoming>
  <bpmn:incoming>EAID_C487A6F9_050A_4d1a_AEAA_9C3D1AC0812</bpmn:incoming>
  <bpmn:outgoing>EAID_B07961DA_4AB0_43b1_9084_C2212F301B3D</bpmn:outgoing>
</bpmn:exclusiveGateway>
<bpmn:sequenceFlow id="EAID_B07961DA_4AB0_43b1_9084_C2212F301B3D"
sourceRef="EAID_8B9BAA63_58FD_4c26_A9CF_B28BEC4A8155"
targetRef="EAID_7373A066_6042_4f85_AE5E_D7DC4BE467BA"/>
<bpmn:boundaryEvent id="EAID_2F1114C7_A880_41c1_B678_DBDD19FD2913"
name="Grid Undetected" attachedToRef="EAID_DF72EE9A_CD56_474a_9EF7_6DF5E41F6D73"
cancelActivity="true" parallelMultiple="false">
  <bpmn:outgoing>EAID_E2421F5C_FAD3_44e8_A197_8C119C7EF6F9</bpmn:outgoing>
  <bpmn:outgoing>EAID_E2421F5C_FAD3_44e8_A197_8C119C7EF6F9</bpmn:outgoing>
  <bpmn:incoming>EAID_1F94C805_9532_4071_407C_8FAB_EDEBF5AE9D17</bpmn:incoming>
  <bpmn:boundaryEvent id="EAID_4D6B5158_7E58_4404_8F58_D260E1A72556"
name="Grid Lost/Damage" attachedToRef="EAID_DF72EE9A_CD56_474a_9EF7_6DF5E41F6D73"
cancelActivity="true" parallelMultiple="false">
    <bpmn:outgoing>EAID_B20E6AB9_DB81_4a5a_B5E0_AC1E6B88C820</bpmn:outgoing>
    <bpmn:outgoing>EAID_B20E6AB9_DB81_4a5a_B5E0_AC1E6B88C820</bpmn:outgoing>
    <bpmn:boundaryEvent id="EAID_1F94C805_9532_4071_8FAB_EDEBF5AE9D17"
name="Transfer Sample - Grid Handler" startQuantity="1" completionQuantity="1"
isForCompensation="false" triggeredByEvent="false">
      <bpmn:incoming>EAID_B554078E_71AD_4cbf_9B8C_E83395AAEA4</bpmn:incoming>
      <bpmn:incoming>EAID_95A6206B_253E_420a_B94C_A2DC21734BEC</bpmn:incoming>
      <bpmn:outgoing>EAID_BED2DB06_B189_41e5_B8D5_42F0B2555FD3</bpmn:outgoing>
      <bpmn:startEvent id="EAID_13911586_02E6_47ba_9704_F7CA4AA463DE" name="Start Auto GH"
isInterrupting="true" parallelMultiple="false">
        <bpmn:outgoing>EAID_D6F7E10E_C9FC_4300_87E5_08DC2D36F8C9</bpmn:outgoing>
        <bpmn:outgoing>EAID_D6F7E10E_C9FC_4300_87E5_08DC2D36F8C9</bpmn:outgoing>
        <bpmn:task id="EAID_E64ABE7E_8DB0_4677_8EDA_216D2CDD61B3" name="Recognize Grid" startQuantity="1" completionQuantity="1"
isForCompensation="false">
          <bpmn:incoming>EAID_D6F7E10E_C9FC_4300_87E5_08DC2D36F8C9</bpmn:incoming>
          <bpmn:incoming>EAID_D6F7E10E_C9FC_4300_87E5_08DC2D36F8C9</bpmn:incoming>
        </bpmn:task>
      </bpmn:startEvent>
    </bpmn:boundaryEvent>
  </bpmn:boundaryEvent>
</bpmn:sequenceFlow>
<bpmn:exclusiveGateway
id="EAID_569BE701_13ED_4cf2_A1D0_A1B546F5DDAD" name="grid detected" gatewayDirection="Unspecified">
  <bpmn:incoming>EAIID_41140C0F_2A2E_4ed4_88E7_DD57C236B657</bpmn:incoming>
  <bpmn:outgoing>EAIID_75D8D369_D808_4fb3_9B62_7470237D2AF2</bpmn:outgoing>
  <bpmn:outgoing>EAIID_EC67CF99_29AD_417e_BD85_512C254364F0</bpmn:outgoing>
</bpmn:exclusiveGateway>

<bpmn:sequenceFlow
id="EAID_41140C0F_2A2E_4ed4_88E7_DD57C236B657"
sourceRef="EAIID_E64ABE7E_8DB0_4677_8EDA_216D2CCD61B3"
targetRef="EAIID_569BE701_13ED_4cf2_A1D0_A1B546F5DDAD"/>

<bpmn:task
tid="EAID_DB634C6F_17FC_445e_BFC0_859332A9DF22"
name="Pick Grid" startQuantity="1" completionQuantity="1" isForCompensation="false">
  <bpmn:incoming>EAIID_75D8D369_D808_4fb3_9B62_7470237D2AF2</bpmn:incoming>
  <bpmn:outgoing>EAIID_B082657B_D53E_48a5_B8B9_635FC1D775DA</bpmn:outgoing>
</bpmn:task>

<bpmn:exclusiveGateway
id="EAID_E10BF67C_FC51_478e_AAF6_F09EA5D1C16F" name="grid picked" gatewayDirection="Unspecified">
  <bpmn:incoming>EAIID_B082657B_D53E_48a5_B8B9_635FC1D775DA</bpmn:incoming>
  <bpmn:outgoing>EAIID_DB634C6F_17FC_445e_BFC0_859332A9DF22</bpmn:outgoing>
</bpmn:exclusiveGateway>

<bpmn:sequenceFlow
id="EAID_B082657B_D53E_48a5_B8B9_635FC1D775DA"
sourceRef="EAIID_DB634C6F_17FC_445e_BFC0_859332A9DF22"
targetRef="EAIID_E10BF67C_FC51_478e_AAF6_F09EA5D1C16F"/>

<bpmn:task
tid="EAID_B50D26C7_DFA6_4332_A85B_0CCDE70FCC06"
name="Move to Holder" startQuantity="1" completionQuantity="1" isForCompensation="false">
  <bpmn:incoming>EAIID_DB634C6F_17FC_445e_BFC0_859332A9DF22</bpmn:incoming>
  <bpmn:outgoing>EAIID_E66372CD_60F6_4df2_922B_42965CB333DC</bpmn:outgoing>
</bpmn:task>

<bpmn:exclusiveGateway
id="EAID_D9F3621C_93D5_4601_9B39_E768CD769863" name="grid undetected" gatewayDirection="Unspecified">
  <bpmn:incoming>EAIID_D9F3621C_93D5_4601_9B39_E768CD769863</bpmn:incoming>
  <bpmn:outgoing>EAIID_84515F2F_664F_4abf_B97E_3D227C43A3A7</bpmn:outgoing>
</bpmn:exclusiveGateway>

<bpmn:sequenceFlow
id="EAID_D9F3621C_93D5_4601_9B39_E768CD769863"
sourceRef="EAIID_E10BF67C_FC51_478e_AAF6_F09EA5D1C16F"
targetRef="EAIID_B50D26C7_DFA6_4332_A85B_0CCDE70FCC06"/>

<bpmn:endEvent id="EAIID_84515F2F_664F_4abf_B97E_3D227C43A3A7" name="grid undetected" />

<bpmn:sequenceFlow
id="EAIID_EC67CF99_29AD_417e_BD85_512C254364F0"
errorRef="EAIID_2C88E9CA_1F27_407c_8FAB_EDEFB5AE9D17"/>
<bpmn:manualTask id="EAID_4C9D82A1_A597_4a5b_B586_20F2BF7C56F4" name="Grid Handler Inspection" startQuantity="1" completionQuantity="1" isForCompensation="false">
  <bpmn:incoming>EAID_E2421F5C_FAD3_44e8_A197_8C119C7EF6F9</bpmn:incoming>
  <bpmn:outgoing>EAID_1A489C70_D3C5_4cf5_B334_5E87559D4151</bpmn:outgoing>
</bpmn:manualTask>

<bpmn:sequenceFlow id="EAID_E2421F5C_FAD3_44e8_A197_8C119C7EF6F9" sourceRef="EAID_2F1114C7_A880_41c1_B678_DBDD19FD2913" targetRef="EAID_4C9D82A1_A597_4a5b_B586_20F2BF7C56F4"/>

<bpmn:exclusiveGateway id="EAID_455DA206_80EA_420C_A26F_36BE8A5D8237" name="fix GH" gatewayDirection="Unspecified">
  <bpmn:incoming>EAID_1A489C70_D3C5_4cf5_B334_5E87559D4151</bpmn:incoming>
  <bpmn:outgoing>EAID_95A6206B_253E_420a_B94C_A2DC21734BEC</bpmn:outgoing>
  <bpmn:outgoing>EAID_34406160_1C09_40b2_A4BB_5DBAC8AFB000</bpmn:outgoing>
</bpmn:exclusiveGateway>

<bpmn:sequenceFlow id="EAID_95A6206B_253E_420a_B94C_A2DC21734BEC" sourceRef="EAID_4C9D82A1_A597_4a5b_B586_20F2BF7C56F4" targetRef="EAID_455DA206_80EA_420C_A26F_36BE8A5D8237"/>

<bpmn:endEvent id="EAID_8C6984DE_4784_4485_A6D6_EFA70D163025" name="Grid handler Error">
  <bpmn:incoming>EAID_B20E6AB9_DB81_4a5a_B5E0_AC1E6B88C820</bpmn:incoming>
  <bpmn:incoming>EAID_34406160_1C09_40b2_A4BB_5DBAC8AFB000</bpmn:incoming>
</bpmn:endEvent>

<bpmn:sequenceFlow id="EAID_34406160_1C09_40b2_A4BB_5DBAC8AFB000" sourceRef="EAID_4C9D82A1_A597_4a5b_B586_20F2BF7C56F4" targetRef="EAID_455DA206_80EA_420C_A26F_36BE8A5D8237"/>

<bpmn:endEvent id="EAID_D1271573_7611_43bf_9FF9_5AF12152043F" name="Vacuum Error">
  <bpmn:incoming>EAID_F6A8081C_4BF7_407A_AA0E_28E10E6A3CF3</bpmn:incoming>
</bpmn:endEvent>

<bpmn:task id="EAID_C63923EE_2A4B_4957_87AA_671421170B30" name="Adjust Vacuum" startQuantity="1" completionQuantity="1" isForCompensation="false">
  <bpmn:incoming>EAID_6A7683BA_F970_4956_B622_75EAA32C678</bpmn:incoming>
</bpmn:task>

<bpmn:sequenceFlow id="EAID_E27EC84_5A0E_4005_86FC_AED475F54D82" sourceRef="EAID_6A7683BA_F970_4956_B622_75EAA32C678" targetRef="EAID_C63923EE_2A4B_4957_87AA_671421170B30"/>

<bpmn:exclusiveGateway id="EAID_8191F341_E224_47ff_BE4E_3A2D89B8CFF" name="vacuum ok" gatewayDirection="Unspecified">
  <bpmn:outgoing>EAID_6A7683BA_F970_4956_B622_75EAA32C678</bpmn:outgoing>
  <bpmn:outgoing>EAID_2AAFAF4B_2867_40f7_8A0C_5ADD2E55A848</bpmn:outgoing>
</bpmn:exclusiveGateway>
<bpmn:incoming>EAID_2AAFAF4B_2867_40f7_8B0C_5ADD2E55A848</bpmn:incoming>

<bpmn:outgoing>EAID_F6A8081C_4BF7_407a_AAFE_28E1E06A3C3F</bpmn:outgoing>

<bpmn:outgoing>EAID_A4A2CCB8_00E4_40c7_9E66_A70A6363A9AD</bpmn:outgoing>

</bpmn:exclusiveGateway>

<bpmn:sourceRef id="EAID_44A2CCB8_00E4_40c7_9E66_A70A6363A9AD">EAID_8191F341_E224_47ff_BE4E_3A2B8DB9BCFF</bpmn:sourceRef>

<bpmn:targetRef id="EAID_7373A066_6042_4f85_AE5E_D7DC4BE647BA">EAID_D1271573_7611_43bf_9FF9_5AF12152043F</bpmn:targetRef>

<bpmn:sourceRef id="EAID_F6A8081C_4BF7_407a_AAFE_28E1E06A3C3F">EAID_8191F341_E224_47ff_BE4E_3A2B8DB9BCFF</bpmn:sourceRef>

<bpmn:targetRef id="EAID_D1271573_7611_43bf_9FF9_5AF12152043F">EAID_C63923EE_2A4B_4957_87AA_671421170B30</bpmn:targetRef>

</bpmn:sequenceFlow>

<bpmn:gatewayDirection>Unspecified</bpmn:gatewayDirection>

<bpmn:sourceRef id="EAID_2AAFAF4B_2867_40f7_8B0C_5ADD2E55A848" name="delay ">EAID_8191F341_E224_47ff_BE4E_3A2B8DB9BCFF</bpmn:sourceRef>

<bpmn:targetRef id="EAID_D1271573_7611_43bf_9FF9_5AF12152043F">EAID_8191F341_E224_47ff_BE4E_3A2B8DB9BCFF</bpmn:targetRef>

</bpmn:exclusiveGateway>

<bpmn:sourceRef id="EAID_C487A6F9_050A_4d1a_AEEA_9C3D1AC00812">EAID_2886B22C_F13C_4eff_9976_7CBA01C5414D</bpmn:sourceRef>

<bpmn:targetRef id="EAID_6F6B680_0B85_4566_BF1B_39B814E8450A">EAID_4F18D941_3BBF_44c4_A0A4_3BE8826D915C</bpmn:targetRef>

</bpmn:sequenceFlow>

<bpmn:sourceRef id="EAID_7B7DFD0C_3018_46c1_8FC9_490BA35D226D">EAID_44A2CCB8_00E4_40c7_9E66_A70A6363A9AD</bpmn:sourceRef>

<bpmn:targetRef id="EAID_889BAA63_58FD_4c2c_A9CF_B28BEC4A8155">EAID_F6A8081C_4BF7_407a_AAFE_28E1E06A3C3F</bpmn:targetRef>

</bpmn:sequenceFlow>
<bpmn:sequenceFlow id="EAID_6FFBE680_0B85_4566_BF1B_39B814E4850A">
    <bpmn:sourceRef>EAID_57B821A9_81B4_4F36_81D1_9A92821A3EDB</bpmn:sourceRef>
    <bpmn:targetRef>EAID_7B7DFDDC_3018_46C1_8FC9_490BA35D226D</bpmn:targetRef>
</bpmn:sequenceFlow>
<bpsim:Property name="t_metrology" type="double">
    <bpsim:ExpressionParameter value="getProperty('t_metrology_uc_1')"/>
</bpsim:Property>

<bpsim:Property name="t_inverted_helios" type="double">
    <bpsim:FloatingParameter value="75"/>
</bpsim:Property>

<bpsim:Property name="t_tranport_foup_to_tem" type="double">
    <bpsim:FloatingParameter value="0"/>
</bpsim:Property>

<bpsim:Property name="t_pluck_5_sample_temlink" type="double">
    <bpsim:FloatingParameter value="15"/>
</bpsim:Property>

<bpsim:Property name="t_transfer_for_pluck" type="double">
    <bpsim:FloatingParameter value="5"/>
</bpsim:Property>

<bpsim:Property name="t_transport_grid_to_tem" type="double">
    <bpsim:FloatingParameter value="5"/>
</bpsim:Property>

<bpsim:Property name="t_transfer_sample_to_holder" type="double">
</bpsim:Property>
<bpsim:Property name="n_offline_images" type="int">
  <bpsim:ExpressionParameter value="getProperty('n_lamella_per_job')*getProperty('n_features_per_lamella')" />
</bpsim:Property>

<bpsim:Property name="t_offline_tem_stem_eds" type="double">
  <bpsim:ExpressionParameter value="getProperty('t_offline_tem_ft')+getProperty('t_offline_stem_ft')+getProperty('t_offline_eds_ft')" />
</bpsim:Property>

<bpsim:Property name="t_offline_metrology" type="double">
  <bpsim:FloatingParameter value="0" />
</bpsim:Property>

<bpsim:Property name="t_unload_wafer_temlink" type="double">
  <bpsim:FloatingParameter value="3" />
</bpsim:Property>

<bpsim:Property name="t_pluck_sample_temlink" type="double">
  <bpsim:FloatingParameter value="3" />
</bpsim:Property>

<bpsim:Property name="t_unload_wafer_temlink" type="double">
  <bpsim:FloatingParameter value="1" />
</bpsim:Property>

<bpsim:Property name="t_unload_grids_temlink" type="double">
  <bpsim:FloatingParameter value="4" />
</bpsim:Property>

<bpsim:Property name="t_load_wafer_helios" type="double">
  <bpsim:FloatingParameter value="4.5" />
</bpsim:Property>
<bpsim:Property name="t_load_job_helios" type="double">
    <bpsim:FloatParameter value="0"/>
</bpsim:Property>

<bpsim:Property name="t_create_chunk_helios" type="double">
    <bpsim:FloatParameter value="30"/>
</bpsim:Property>

<bpsim:Property name="t_chunk_lift_out_helios" type="double">
    <bpsim:FloatParameter value="15"/>
</bpsim:Property>

<bpsim:Property name="t_final_thinning_helios" type="double">
    <bpsim:FloatParameter value="22"/>
</bpsim:Property>

<bpsim:Property name="t_unload_wafer_helios" type="double">
    <bpsim:ExpressionParameter value="4"/>
</bpsim:Property>

<bpsim:Property name="t_unload_tem_holder" type="double">
    <bpsim:FloatParameter value="2"/>
</bpsim:Property>

<bpsim:Property name="t_unload_grids_from_holder" type="double">
    <bpsim:FloatParameter value="4"/>
</bpsim:Property>

<bpsim:Property name="t_pluck_sample" type="double">
    <bpsim:ExpressionParameter value="getProperty('t_load_wafer_temlink')+getProperty('n_lamella_per_job')*getProperty('t_pluck_sample_temlink')+getProperty('t_unload_wafer_temlink')+getProperty('t_unload_grids_temlink')"/>
</bpsim:Property>

<bpsim:Property name="t_prep_lamella_exsolve" type="double">
    <bpsim:ExpressionParameter value="getProperty('t_load_wafer_exsolve')+getProperty('t_load_prep_job_exsolve')+getProperty('n_lamella_per_job')*getProperty('t_create_final_lamella_exsolve')+getProperty('t_unload_wafer_exsolve')"/>
</bpsim:Property>

<bpsim:Property name="t_inverted_process_helios" type="double">
    <bpsim:ExpressionParameter value="getProperty('t_load_wafer_helios')+getProperty('t_load_job_helios')+getProperty('t_create_chunk_helios')+getProperty('t_chunk_lift_out_helios')+getProperty('t_final_thinning_helios')+getProperty('t_unload_wafer_helios')+getProperty('t_unload_grids_temlink')"/>
</bpsim:Property>
<bpsim:Property name="manual" type="int">
  <bpsim:ExpressionParameter value="1"/>
</bpsim:Property>

<bpsim:Property name="automatic" type="int">
  <bpsim:ExpressionParameter value="2"/>
</bpsim:Property>

<bpsim:Property name="sample_transfer_to_holder" type="int">
  <bpsim:ExpressionParameter value="getProperty('manual')"/>
</bpsim:Property>

<bpsim:Property name="t_tem_prep" type="double">
  <bpsim:ExpressionParameter value="30"/>
</bpsim:Property>

<bpsim:Property name="t_load_tem_job_temlink_file" type="double">
  <bpsim:FloatingParameter value="3"/>
</bpsim:Property>

<bpsim:Property name="t_load_tem_job_manual" type="double">
  <bpsim:ExpressionParameter value="20"/>
</bpsim:Property>

<bpsim:Property name="t_load_tem_job_metrios" type="double">
  <bpsim:ExpressionParameter value="getProperty('t_load_tem_job_temlink_file')"/>
</bpsim:Property>

<bpsim:ElementParameters elementRef="EAID_275CB643_15FB_499d_A800_F7D07B23A978">
  <bpsim:ControlParameters>
    <bpsim:Condition value="getProperty('prep_method')=getProperty('Inverted_H')"/>
  </bpsim:ControlParameters>
</bpsim:ElementParameters>

<bpsim:ElementParameters elementRef="EAID_954E1720_3AB0_40a7_AE04_EF2C5DC9096A">
  <bpsim:ControlParameters>
    <bpsim:Condition value="getProperty('transport_type')=getProperty('manual_transport')"/>
  </bpsim:ControlParameters>
</bpsim:ElementParameters>
<bpsim:ControlParameters>
  <bpsim:ElementParameters>
    <bpsim:ControlParameters>
      <bpsim:Probability>
        <bpsim:FloatingParameter value="0"/>
        <bpsim:Probability>
      </bpsim:ControlParameters>
      <bpsim:ElementParameters>
        <bpsim:ElementParameters>
          <bpsim:Calendar id="269511078111736@localhost" name="TEM Prep">BEGIN:VCALENDAR
            BEGIN:VEVENT
            DTSTAMP:20190626T115110
            UID:269511078111736@localhost
            DTSTART:20190626T060000
            DURATION:P0DT0H30M0S
            RRULE:FREQ=DAILY;INTERVAL=1
            END:VEVENT
            PRODID:Enterprise Architect 14.1.1427
            VERSION:2.0
            END:VCALENDAR</bpsim:Calendar>
          <bpsim:Calendar id="26952923411736@localhost" name="ShiftBreak1">BEGIN:VCALENDAR
            BEGIN:VEVENT
            DTSTAMP:20190626T115209
            UID:26952923411736@localhost
            DTSTART:20190626T110000
            DURATION:P0DT2H0M0S
            RRULE:FREQ=DAILY;INTERVAL=1
            END:VEVENT
            PRODID:Enterprise Architect 14.1.1427
            VERSION:2.0
            END:VCALENDAR</bpsim:Calendar>
          <bpsim:Calendar id="269524766811736@localhost" name="ShiftBreak2">BEGIN:VCALENDAR
            BEGIN:VEVENT
            DTSTAMP:20190626T115247
            UID:269524766811736@localhost
            DTSTART:20190626T230000
            DURATION:P0DT2H0M0S
            RRULE:FREQ=DAILY;INTERVAL=1
            END:VEVENT
            PRODID:Enterprise Architect 14.1.1427
            VERSION:2.0
            END:VCALENDAR</bpsim:Calendar>
        </bpsim:ElementParameters>
      </bpsim:ElementParameters>
    </bpsim:ControlParameters>
  </bpsim:ElementParameters>
</bpsim:ControlParameters>
B. Sample Analysis Deployment Demo BPMN

```xml
<?xml version="1.0" encoding="UTF-8"?>
  <bpnm:process id="SampleAnalysisProcess" name="SampleAnalysis" isExecutable="true" camunda:taskPriority="1">
    <bpnm:startEvent id="StartEvent_030egaa" name="start analysis" camunda:initiator="demo">
      <bpnm:outgoing>SequenceFlow_04a3tvw</bpnm:outgoing>
    </bpnm:startEvent>
    <bpnm:sequenceFlow id="SequenceFlow_04a3tvw" sourceRef="StartEvent_030egaa" targetRef="transfer_sample" />
    <bpnm:sequenceFlow id="SequenceFlow_023eiz7" sourceRef="transfer_sample" targetRef="load_holder" />
    <bpnm:serviceTask id="RunToolReadiness" name="Run Tool Readiness" camunda:type="external" camunda:topic="chk_tool_readiness" camunda:taskPriority="1">
      <bpnm:extensionElements>
        <camunda:inputOutput>
          <camunda:outputParameter name="Alignemnts" />
        </camunda:inputOutput>
      </bpnm:extensionElements>
    </bpnm:serviceTask>
    <bpnm:endEvent id="end_analysis" name="Analysis Complete">
      <bpnm:incoming>SequenceFlow_12s2z47</bpnm:incoming>
      <bpnm:terminateEventDefinition />
    </bpnm:endEvent>
    <bpnm:userTask id="load_holder" name="Load Holder in TEM" camunda:assignee="demo">
      <bpnm:extensionElements>
        <camunda:formData>
          <camunda:formField id="holder_loaded" label="Holder is Loaded" type="boolean" defaultValue="false"/>
        </camunda:formData>
      </bpnm:extensionElements>
    </bpnm:userTask>
    <bpnm:userTask id="transfer_sample" name="Transfer Sample to Holder" camunda:assignee="demo">
      <bpnm:extensionElements>
        <camunda:formData>
          <camunda:formField id="grid_id" label="Grid ID" type="string" defaultValue="None"/>
          <camunda:formField id="grid_type" label="Grid Type" type="enum">
            <camunda:value id="Value_3mm" name="10mm Grid"/>
          </camunda:formField>
        </camunda:formData>
      </bpnm:extensionElements>
    </bpnm:userTask>
  </bpnm:process>
</bpnm:definitions>
```
C. Metrios Tool Readiness Worker (NodeJs)

// based on https://github.com/camunda/camunda-external-task-client-js
const { Client, logger } = require('camunda-external-task-client-js');
var request = require('request');
// configuration for the Client:
// - 'baseUrl': url to the Process Engine
// - 'logger': utility to automatically log important events
// - 'asyncResponseTimeout': Long polling timeout (then a new request is issued)
const tool_readiness_api = 'http://localhost:5000/api'
const camunda_server_endpoint = 'http://10.113.140.145:8080'
const config = { baseUrl: camunda_server_endpoint + '/engine-rest', use: logger };
const { Variables } = require("camunda-external-task-client-js");
// create a Client instance with custom configuration
const client = new Client(config);
const processVariables = new Variables();

// subscribe to the topic: 'run_met'
client.subscribe('chk_tool_readiness', async function (task, taskService) {

    console.log('process_id: ' + task.processInstanceId)
    console.log('calling tool readiness server....');

    request(tool_readiness_api + '/Alignments', function (error, response, body){

        console.log('statusCode:', response && response.statusCode); // Print the response status code if a response was received
        console.log('body:', body);
        if (error) {
            console.log('Error..\n', error);
            processVariables.set("Alignments", null);
        }
        if (body) {
            console.log(body.toString());
            var alignments = JSON.parse(body)
            console.log('returning alignments', alignments);
            processVariables.set("Alignments", alignments.value);
        }
    });
    await taskService.complete(task, processVariables); // Complete the task
});
D. Metrios Auto Recipe Runner Worker (NodeJS)

// based on https://github.com/camunda/camunda-external-task-client-js
const { Client, logger } = require('camunda-external-task-client-js');
// more information https://docs.camunda.org/get-started/quick-start/service-task/#b-using-javascript-nodejs

var request = require('request');
var exec = require('child_process').execFile;

// configuration for the Client:
// - 'baseUrl': url to the Process Engine
// - 'logger': utility to automatically log important events
// - 'asyncResponseTimeout': long polling timeout (then a new request is issued)
const camunda_server_endpoint = 'http://10.113.140.145:8080'
const config = {
  baseUrl: camunda_server_endpoint + '/engine-rest',
  use: logger
};

const Variables = require("camunda-external-task-client-js");

const client = new Client(config);
const processVariables = new Variables();

// subscribe to the topic: 'metrology'
client.subscribe('metrology', async function (task, taskService) {
  // Get a process variable
  const recipe_file = task.variables.get('recipe_file');

  console.log('process_id: '${task.processInstanceId}''
  console.log('starting auto recipe runner: Recipe file:', recipe_file);
  console.log("Start AutoRecipeRunner");
  exec('AutoRecipeRunner', [recipe_file], function (err, data) {
      if (err) {
        console.log("Error Received..\n", err);
        processVariables.set("RecipeRunnerResponse", data);
        taskService.handleBpmnError(task, "Recipe_Failed_Error", "Error Running Recipe", processVariables);
      }
      else {
        console.log("Data Received..\n", data.toString());
        processVariables.set("RecipeRunnerResponse", data);
        taskService.complete(task, processVariables);
      }
  });
});
Where innovation starts