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Efficiency and Collaboration in Hardware Development: A Lean Approach

Case Study

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ABSTRACT :

Companies strive towards perfection in their product development processes and want to stay as competitive as possible. In order to achieve that objective, emphasis needs to be put on streamlining the process. Therefore, this thesis explores the Lean methodology from a product development perspective and showcases the effectiveness of the value stream mapping (VSM) and design structure matrix (DSM). The research is executed at a company specialising in energy and marine power solutions and is outlined as a case study. Several research angles have been utilised, which enabled the recognition of diversity in the collected data and information. The methodology is divided into two primary elements: 1) analysing a case project from a component functionality and managerial perspective, and 2) executing a value stream analysis of the hardware development process, which is utilised to develop automation components for complex power solutions. The qualitative research focuses on achieving a holistic understanding of a hardware development process (HWDP) through VSM and DSM. Quantitative data can mainly be seen in the case project analysis, where the output is formed on historical data from an application lifecycle management system and Internal documentation platform. In line with the methodology, the thesis aimed to answer the following research questions: RQ1: How can the process be streamlined by identifying inefficiencies and proposing improvements? RQ2: How can cooperation and collaboration be improved to reduce overall development lead time?

The results of the thesis are categorised based on the research methodology's two primary elements. The project analysis and current state findings have identified the challenges related to outsourcing, communication, collaboration, and technological knowledge gaps. A cross-functional VSM allowed for capturing the information flow between the departments and identifying the wastes and bottlenecks in the process. A value assessment resulted in 47 VA, 16 RNVA, and 8 NVA activities. The NVA activities were analysed, and improvement suggestions were generated, focusing on stakeholder communication, supplier relationships, testing processes, change management, release meetings, and field testing. The DSM enabled the visualisation of dependencies between tasks and structural changes with partitioning. Based on simulations comparing the structural changes between the two DSMs, a 50 % decrease in lead time was identified. However, the implementation feasibility of the new structure is unclear, and further evaluation must be carried out in collaboration with the stakeholders. The thesis uncovered five managerial implications related to holistic process overview, effective outsourcing, improved in-house expertise, robust project planning and scheduling, and continuous improvement. This comprehensive efficiency analysis of the HWDP can be considered a success as it has pinpointed the crucial aspects that can be utilised to achieve an optimal future state of the process.

KEYWORDS: Lean, Process Improvement, Waste Reduction Value stream mapping, Design Structure Matrix, Hardware Development

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Abbreviations

ALM	Application Lifecycle Management
ART	Agile Release Train
DSM	Design Structure Matrix
HW	Hardware
HWDP	Hardware Development Process
MVP	Minimum Viable Product
NVA	Non-Value-Added
PD	Product Development
RNVA	Required-Non-Value-Added
SW	Software
SAFe	Scaled Agile Framework
TRS	Technical Requirement Specification
VA	Value-Added
VSM	Value Stream Mapping

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1 Introduction

Product development — a challenging field to take on — but surprisingly, every organisation views it as a key strategy for outperforming the competitors (Tyagi et al., 2015, p. 202). Improving PD processes to be as optimal as possible is the crucial element in gaining a competitive edge. The goal is to prioritise value creation as the foundation by focusing on the product's design and functionality, enabling effective innovation through developing and utilising new technology (Synnes & Welo, 2022, p. 626). The lean methodology provides a framework for improving PD processes. However, a complete comprehension of how lean differs between manufacturing and engineering environments must be achieved beforehand. (Reinertsen & Shaeffer, 2005, p. 57). The focal point lies in process standardisation, making transparency possible with visualisations, distributing project information quickly, and eliminating waste to enable continuous improvement (Stechert & Balzerkiewitz, 2020, p. 764).

In order to enable the strategies of the lean methodology and successfully improve a process, specific tools can be utilised. Value stream mapping (VSM) has become increasingly recognised as a tool for capturing internal and external process details. It allows for comprehensive visualisations of the workflow, including the material and information flow, and considers the timeline, which surrounds details internally in the company and to external stakeholders (Seth et al., 2017, p. 398). Additionally, the design structure matrix (DSM) allows for visualising complex PD flows by highlighting the relationships and interactions in the process (Eppinger & Browning, 2019, p. 133). Together, these tools provide a holistic understanding of a process, enabling effective identification of issues and bottlenecks and offering crucial improvement suggestions.

1.1 Research Purpose

This research is performed for a technology company specialising in producing complex energy and marine power solutions. In order to complete these complex solutions, several components need to be developed, one of which is the extensive automation system, whose primary purpose is to enable fluent control and optimal performance of the solutions. While the software projects are running smoothly, issues have been seen in HW-related projects involving control electronics and instrumentation components. These issues are mainly related to the development lead times and inefficient cooperation and communication between the involved departments in the hardware development process. Thus, this thesis project aims to evaluate the current hardware development process (HWDP) for automation components and identify its inefficiencies using lean engineering tools. In this case, the focus is on Value Stream Mapping (VSM) and Design Structure Matrix (DSM). The thesis output will be a comprehensive analysis of the current process. Based on the analysis, the thesis will propose improvement suggestions to streamline and improve the HWDP.

To guide the thesis, two research questions were developed based on the identified background at the case company. The thesis will be formed around the following research questions:

RQ1: *How can the process be streamlined by identifying inefficiencies and proposing improvements?*

RQ2: *How can cooperation and collaboration be improved to reduce overall development lead time?*

1.2 Research objectives

To fulfil the purpose of this research, the following objectives need to be completed:

- 1. Produce a comprehensive literature framework:** Study the fundamentals of lean engineering and how it can be utilised in product development processes. Focus on understanding how value stream mapping (VSM) and design structure matrix are utilised to streamline activities in processes and how cross-functional communication and collaboration are established.
- 2. Study the current value stream at the case company:** Capture the task and activity of the current HWDP at the case company. Identify the major stakeholders of the process, both internal and external. Collect and analyse data from a specific HW development project executed by the current process. Utilise application lifecycle management (ALM) systems and internal documentation as the base for the data.
- 3. The current state of the value stream:** Create a current state VSM of the HWDP through a current state workshop at the case company. Use the case project data as complementary information during the workshop.
- 4. Map out the critical problem areas:** Analyse the VSM with the process's primary stakeholders (End Users), identify the problem areas and suggest improvement suggestions. If the mapped process is complex and needs better visualisation of the iteration loops and dependencies, utilise the DSM tool.
- 5. Future state value stream map:** Visualise the improvement suggestion and the overall lead time reduction.

A detailed diagram of the master's thesis process can be seen in Figure 1. It was created to increase the accessibility of the research objectives, understand how they are inter-related and keep track of the current research phase of the author

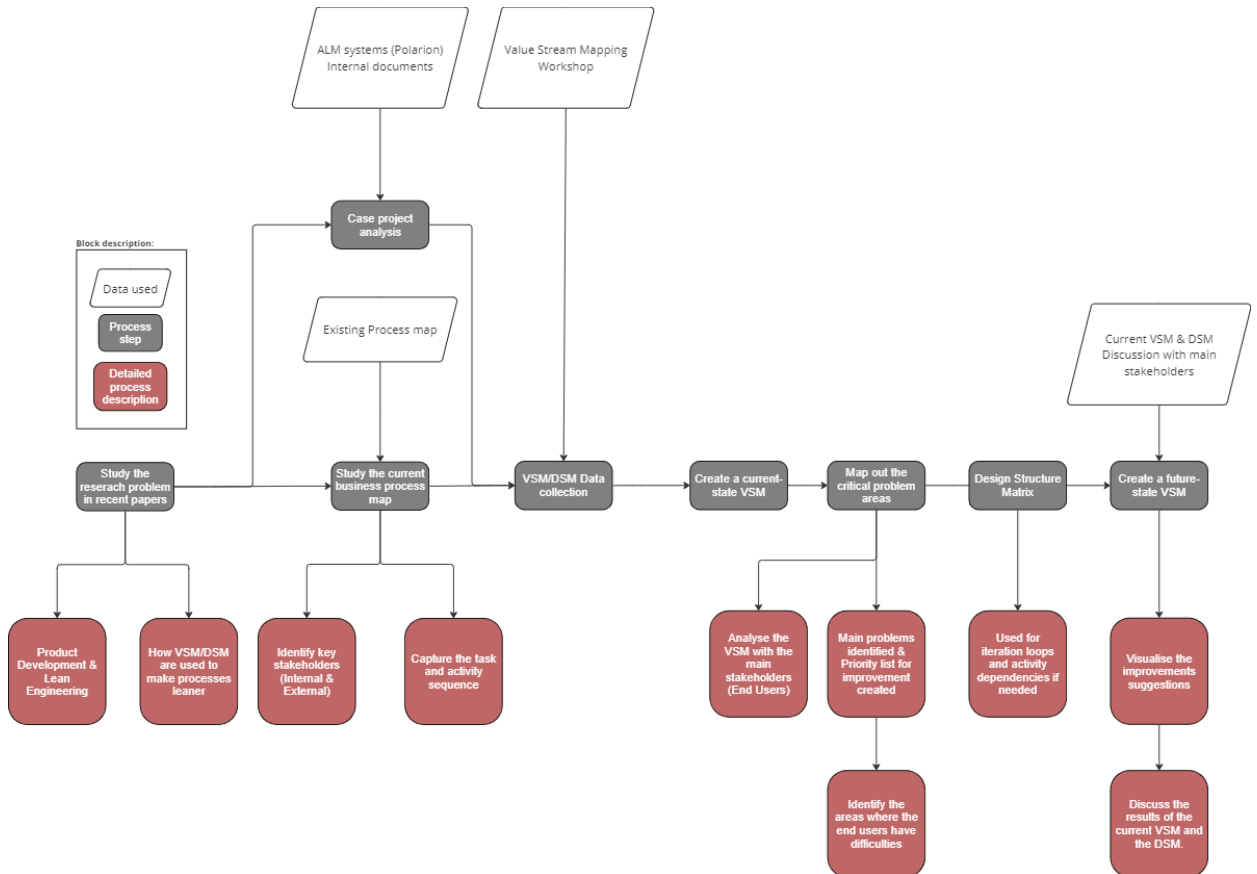


Figure 1. A detailed diagram of the master's thesis process

1.3 Research delimitations

The thesis focuses on analysing the case company's hardware development process (HWDP), which is utilised to develop new and competitive automation components that enhance the case company's competitive position in the energy and marine markets. The research is dedicated to analysing the HWDP and a specific case project, which can be considered a somewhat problematic project due to its many challenges regarding lack of product knowledge and project planning. The primary purpose is to improve the process through lean engineering, with value stream mapping and design structure matrix as the sole focus. The following delimitations outline the research of the thesis:

1. **Hardware component – case project analysis:** The research specifically analyses a puzzling and drawn-out HW development project that has encountered many challenges. The main emphasis of the project analysis is to determine how the

project has been managed and where the bottlenecks have occurred. Furthermore, the engineering and technical parts of the component will also be studied; these include the design, functionality, and implementation of the component, but will be limited to only investigating as much as needed to get out the most crucial parts regarding opportunities for process improvements.

2. **Process improvement:** The research's main focus is identifying inefficiencies and improving the overall efficiency of the process. Additionally, the focus will be on achieving a holistic understanding of the process by focusing on the process itself and related activities such as communication, collaboration, and decision-making between different departments.
3. **Value stream definition:** The analysed value stream is in the field of product development and includes all the steps on a high level, from concept development, system-level design, detail design, testing and validation until ramp-up.
4. **Data collection and analysis:** The study uses several methods, including historical data collection on the case project and a value stream mapping workshop on the HWDP. The case project will provide a deep analysis of how the current process is utilised with quantitative and qualitative data. The value stream mapping workshop will mainly provide qualitative data.

2 Lean engineering

The theoretical framework presented in this thesis contains a comprehensive literature review of the subject: Lean Engineering. The review is based on academic articles, books, and reports. The literature review explores the nature of Lean engineering and is explored from a product development (PD) point of view, focusing on process improvement and how value stream mapping (VSM) can be utilised in combination with design structure matrix (DSM) to reduce waste in a process and achieve continuous improvement.

2.1 The Origins of Lean

Novel methodologies arise from situations where old theories are no longer applicable; this was undoubtedly accurate for Lean, which emerged at the right time to aid in increasing industrial growth. In order to properly comprehend the roots of lean manufacturing, one must first investigate 1880s craft production and the shift to mass production around 1915, when craft production found challenges that it could not overcome. In the 1920s, there was a breakthrough with the so-called mass production systems. The increased utilisation of these systems came with negative and positive outcomes; however, this was a learning curve at the time that shaped advanced industrial thinking. The term lean production found its roots in the 1950s and was adopted by the Japanese company Toyota, which was the first company in the world to fully utilise the power lean production systems in the 1960s (Womack et al., 1990, p. 19).

2.2 Lean methodology key concept

The concept of lean engineering revolves around the elimination of *muda*, which is a Japanese term for “waste” in business engineering processes. Any activity that consumes resources without producing something of value can be defined as *muda* (Womack & Jones, 2003, p. 15). Value is defined based on what the customer decides it is and what is essential for them and is prepared to invest in, e.g., the customer specifies what is

required for a product, and the supplier creates it. In reality, this is not as simple as it sounds, especially regarding complex HW product development (Oppenheim, 2011, pp. 14–15).

To eliminate waste, Womack and Jones (2003) propose a *lean thinking* concept that provides a way to output more for the customers through minimised use of human effort, resources, time and space. This is possible due to the following strategies defined in *lean thinking*:

- A method for defining the value
- Optimal sequencing of value-generating activities
- Uninterrupted and effective execution of the activities

Lastly, a common solution in general process reengineering methodologies is eliminating job opportunities. Lean thinking, on the other hand, is driven to enable waste-to-value transformation through quick feedback loops on the efforts, ultimately providing new job opportunities as opposed to eliminating them (Womack & Jones, 2003, p. 15).

2.3 Lean principles

Six lean principles have been developed in order to fully utilise the procedure of generating value without waste: value, value stream, flow, pull, perfection, and respect for people (Figure 2). The last-mentioned, respect for people, does not belong to the original lean principles but has become more common during later years; thus, it will also be discussed. The importance of each will be described based on the works of Womack & Jones (2003) and Oppenheim (2011).

The first principle – Value

The value can only be defined by the customer, which is either internal or external; thus, the first principle is dedicated to understanding and defining customer value. Value in the lean methodology is only essential when it relates to a specific product or service and fulfils the customer's price and time requirements. Therefore, the customer's requirements need to be accurately understood and correctly implemented in the product

or service in order to make it according to the lean thinking methodology, avoiding rework to all costs (Oppenheim, 2011, p. 17; Womack & Jones, 2003, p. 16)

The second principle – Value stream

This principle consists of understanding and mapping the value stream of end-to-end processes and activities involved in achieving a successful product or service. It entails mapping end-to-end connected tasks, decision/review/approval nodes, and the information and relationship flow between these elements to create value for the customer. The mapping process focuses on eliminating non-value-added activities and allows for a smooth flow for value-added activities by avoiding rework, backflow, and stopping (Oppenheim, 2011, pp. 17–18; Womack & Jones, 2003, p. 19).

The third principle – Flow

Continuous flow is critical in an engineering process to achieve a streamlined enterprise where the work progresses through value-adding activities and processes without rework, backflow or stopping. To optimise the flow, work should be organised in batches. Some prerequisites include strong value creation, good corporate preparedness, and satisfactory planning of the lean program (Oppenheim, 2011, p. 20; Womack & Jones, 2003, p. 23).

The fourth principle – Pull

The fourth principle emphasises the concept of pulling a product or service instead of pushing it on the customer. First, there must be a specific need from an internal or external customer in the process in order to execute a task. Second, the task should be executed at the right time, i.e., when the customer requires the task's output. To effectively utilise the pull principle, the performer of the task should be in close cooperation with the customer to enable effective communication, work coordination, and task deliverables. If this is not sufficient enough, there might be obsolescence due too early task execution and scheduling failures if the task is done too late (Oppenheim, 2011, p. 21; Womack & Jones, 2003, p. 24).

The fifth principle – Perfection

The fifth principle can be defined as how well the four previously mentioned principles are performed. The purpose is to improve an organisation's activities and processes continuously. According to Womack and Jones (2003), the most critical element for achieving perfection is transparency, i.e., making all wastes, defects, and inefficiencies visible in the organisation and prioritising to eliminate the most extensive ones. To fully utilise the concept of perfection, one needs to understand the difference in optimising a specific task or a whole process. The overall value proposition establishes whether the output of a given task is sufficient. From the perspective of an engineering process, these need to be continuously improved to stay competitive in the market at all times (Oppenheim, 2011, pp. 21–22; Womack & Jones, 2003, pp. 25–26).

The sixth principle – Respect for people

Interestingly, the last principle, Respect for people, is a reasonably new principle within the lean methodology and does not belong to the original ones. Within a Lean business, respect for people is the key to success. This principle encourages people to uncover issues and imperfections, discuss fundamental causes and corrective measures, and brainstorm effective solutions to minimise risks of problems occurring. The following elements are needed to achieve this setting:

- A culture of mutual respect and trust
- Transparent and honest communication
- Cooperative relationships between stakeholders (Oppenheim, 2011, p. 22).

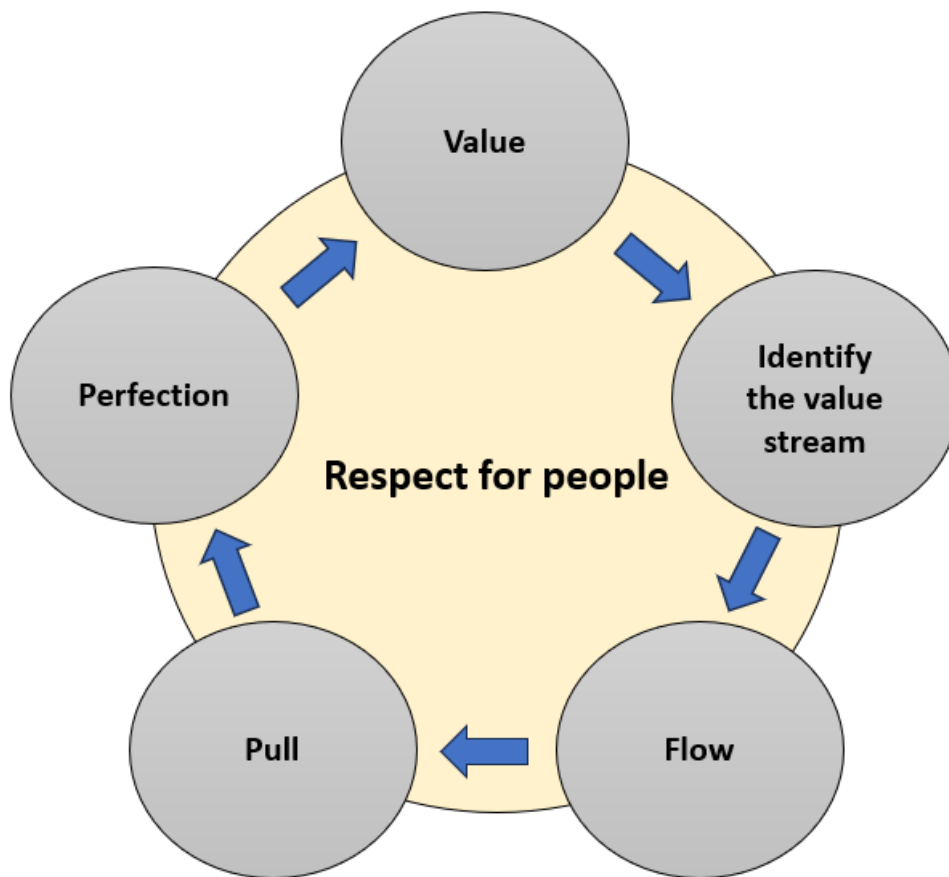


Figure 2. The six lean principles (Oppenheim, 2011, pp. 17–22; Womack & Jones, 2003, pp. 16–26)

2.4 Applying lean to product development

The field of lean product development is expanding rapidly due to the competition and the desire of companies to develop products and systems more quickly, efficiently, and at lower costs. Furthermore, the creativity existing in engineering is also a strong driving factor due to its tenacious problem solvers (Oppenheim, 2011, p. 25). According to Stechert and Balzerkiewitz (2020), numerous manufacturing companies have effectively implemented lean thinking into their organisation. This is because the methodology has been more thoroughly researched and applied in the manufacturing field for an extended period, naturally making it more successful. However, the authors further

mention that product development organisations pose difficulties for lean implementation due to the following:

- A wide variety of diverse and non-repetitive tasks
- Extensive collaboration and communication between departments and external partners in the value stream (Stechert & Balzerkiewitz, 2020, p. 764).

To address these difficulties, the general difference between lean product development and manufacturing needs to be defined. Additionally, one must understand how the lean principles are applied in the field of lean product development.

In general, the difference between lean product development and manufacturing is that lean product development consists of defining a set amount of requirements that transform into a physical product, whereas lean manufacturing consists of physical parts or raw materials that flow through a production system (Oehmen & Rebentisch, 2010, p. 7). According to Reinertsen and Shaeffer (2005), engineering and manufacturing have certain similarities; however, there is still a significant difference between them. Producing a physical product through manufacturing is a repetitive, sequential, and constrained process, whilst, in engineering, the process is non-repetitive, non-sequential, and unconstrained, generating logical information (Reinertsen & Shaeffer, 2005, p. 51).

To better grasp the differences between manufacturing and engineering, McManus (2005) has defined a table on how the application of the lean principles, excluding the respect for people principle, differs between these two fields (Table 1). In conclusion, engineering is concerned with adjusting to new goals and prioritising information and knowledge, whereas manufacturing is concerned with clear, defined goals and material flow. Engineering strives for efficiency through planned iterations, but manufacturing strives for a production flow driven by takt time. Lastly, engineering perfection enables enterprise improvement, while manufacturing perfection achieves error-free, repeatable processes.

Table 1. Difference between lean principles in engineering and manufacturing (Adapted from H. McManus et al., 2005 p.8)

<i>Lean principle</i>	<i>Engineering</i>	<i>Manufacturing</i>
Value	Emergent goals and adapts as the process unfolds	Clear goals, visible at each process step
Value stream	Focuses on information and knowledge	Focuses on parts and material
Flow	Efficient planned iterations	Iterations considered waste
Pull	Driven by the needs of the enterprise	Driven by takt time (customer demand)
Perfection	Enables enterprise improvement	It aims for a repeatable process without errors

Finally, Reinertsen and Shaeffer (2005) state that caution is needed when implementing lean principles into an engineering environment. It has been seen that engineering and manufacturing are completely different when it comes to adding value. E.g., risk-taking within the engineering field is crucial, whilst in manufacturing, it does not add any value. In manufacturing, variability is considered waste, but it can be the essence of value-added activities in engineering. Although engineering has its own character, there are still an extensive amount of application where lean can be applied (p. 57)

2.5 Types of Waste and Identification

Waste elimination was defined as the fundamentals of the lean concept; however, to eliminate waste, it must be identified first (Oppenheim, 2011, p. 15). To begin with, activities involved in an engineering process can be categorised into three types:

- **Value-Added (VA) activities** – Generates value by enhancing the information or material transformation, or reducing the uncertainty in a process. Furthermore, they should be iterated as little as possible and the customer should be willing to pay for these activities.

- **Required-Non-Value-Added (RNVA) activities** – Do not generate any value but are required and cannot be eliminated due to requirements set by, e.g., a contract, legislation or existing technology.
- **Non-Value-Added (NVA) activities** – Consume time and resources and do not generate any value but can be eliminated or reworked.

NVA activities can be directly translated into waste. According to Pepe et al. (2011), it is crucial to know the types of waste within lean for successfully analysing the process, identifying issues and bottlenecks, and suggesting potential improvement suggestions (Pepe et al., 2011, p. 4). It needs to be noted that the wastes found in manufacturing are not the same as in engineering processes, as discovered in the previous chapter; manufacturing is mainly based on a physical flow, whereas engineering is more dedicated to a logical information flow. The following table (Table 2) defines the types of waste and provides real-life examples of what these could be within engineering processes.

Table 2. The types of waste in lean engineering adapted from the works of (McManus, 2005, pp. 58–59; Oehmen & Rebentisch, 2010, p. 9; Pepe et al., 2011, pp. 4–5)

Waste type	Definition	Examples
Waiting	Idle time or delays due to un-available information.	<ul style="list-style-type: none"> • Waiting for information to be received and information waiting to be utilised. • Waiting for long lead time activities to finish and waiting due to unrealistic schedules.
Excessive processing	Processing information beyond the specified requirement	<ul style="list-style-type: none"> • Components and systems are overengineered. • Fragmented reports and an excessive number of approvals for information release.
Over production	Overproducing or producing ahead of the following process requirement	<ul style="list-style-type: none"> • Providing information too early or too detailed. • A lack of understanding the participants' needs resulting in a

		tendency to send all information to everyone.
Inventory	Unused or work-in-progress information.	<ul style="list-style-type: none"> • Interruptions in the work lead to the need for saving the information. • Saving outdate/obsolete/just-in-case information
People	Underutilisation or overutilisation of human resources.	<ul style="list-style-type: none"> • The manager engages in stress activities to compensate for the lack of human resources instead of managing the team. • Having people work on tasks that could be automated.
Unnecessary motion	Unnecessary motion of people, information, or resources during the process.	<ul style="list-style-type: none"> • Excessive meetings/discussions/emails not leading to any valuable outcome. • Excessive hand-offs instead of maintaining continuous ownership.
Transportation	Transferring data/information from one location to another (between people, organisations or systems).	<ul style="list-style-type: none"> • Duplicating and pasting identical information to several places. • Data or information is handled by several individuals before reaching the end user.
Defects	Any error, mistake, or flaw occurring in the process requires rework.	<ul style="list-style-type: none"> • Making mistakes in component and architecture design. • Providing erroneous information internally/externally

2.6 Value stream mapping

Value stream mapping can focus on manufacturing (Factory value stream mapping) or engineering (product development value stream mapping). Since the thesis focuses on an R&D organisation, the VSM will be studied from the engineering point of view. According to McManus (2005), there is only one common aspect of value stream mapping that engineering and manufacturing share; they both benefit from the process

improvement aspect. However, this alone is not enough to achieve a fully lean enterprise (McManus, 2005, p. 19). Value stream mapping can be defined as a process mapping method that analyses how the value enters, flows through, and is delivered to the customer (either internal or external) in the process. Additionally, it investigates how information and data impact the overall workflow. The process can be viewed from both a logical and physical flow standpoint. (Pyzdek & Keller, 2010, p. 323).

McManus (2005) has created a comprehensive guideline on how to successfully apply value stream mapping (VSM) to PD processes (p. 9). Although the guideline is thoroughly made, other sources will also be used when building up the VSM framework for PD processes.

2.6.1 Preparations

According to McManus (2005), VSM improvement can be executed as kaizen workshops (p 21). These workshops consist of cross-functional teams, including experts from different areas whose primary goal is to solve problems and participate in lean process improvement (Oakland, 2014, p. 351). A mapping tool is chosen before or during the workshop, and a template is created. The process to be improved is selected based on a pre-defined problem or a higher-level value stream map (McManus, 2005, p. 21).

In order to execute a VSM analysis and improvement of a process, the following elements need to be defined:

1. The process
2. Key stakeholders
3. The mapping team
4. The scope
5. The value (McManus, 2005, p. 21).

Defining the process consists of capturing internal and external tasks; this can be done by performing interviews with the involved participants in the process (Pepe et al., 2011,

p. 3). Another way is acquiring historical project information through a Gantt chart or analysing a currently existing process map (Oppenheim, 2011, p. 36). Knowing who the key stakeholders are is heavily related to defining the process and the mapping team. The key stakeholders in a process consist of the participants, users, customers (internal or external), suppliers, and others (McManus, 2005, p. 21). It is crucial to use a broad range of stakeholders to achieve a holistic understanding of the process (Barnhart, 2013, p. 83). To succeed in implementing a VSM, it is crucial to have a committed mapping team with clearly defined roles and responsibilities.

Additionally, all team members should be involved in lean concept training to successfully achieve the objectives of a VSM application (Serrano Lasa et al., 2008, p. 50). The scope should be clearly defined to ensure the highest possible efficiency in the VSM. This can be done by:

- Having the team define critical elements of the value stream.
- Bounding the process to include a strict beginning and ending point.
- Identifying the product that the process uses.
- Identifying inputs, outputs, constraints, and customers (internal or external) (McManus, 2005, p. 24).

Furthermore, a higher-level VSM can be created as an initial starting point to better scope the most crucial bottlenecks. By doing this, the areas where the improvements will have the most considerable effect on the lead times can be identified.

Understanding how each task in a process contributes towards achieving a more streamlined process is critical. Although value is continuously created, it is not realised until the process output is produced. Trying to measure it can be rather tricky in practice since human estimations can cause errors and inaccuracies (McManus, 2005, pp. 31–32). Therefore, the key value aspects should be selected by the team before the current state mapping begins. As one gains more experience and insight into the process and its inefficiencies, these values can be further updated to match the task contributions (p.33).

In the work of Chase (2001), a comprehensive task contribution list has been developed, including the following value attributes:

1. **Functional performance of the end product** – Activities that assist in defining the function or the form of the product.
2. **Definition of the process of delivering the product** – Activities that contribute to delivering the product to the customer.
3. **Reducing risk and uncertainty** – Activities that aim to decrease the potential risks and uncertainty in performance, cost, or schedule.
4. **Forming the final output** – Activities that aim to form the final documentation provided to the customer.
5. **Facilitating communication** – Activities that aim to increase communication and collaboration efficiency between departments.
6. **Enabling other tasks to start** – Activities that pinpoint the critical dependencies to achieve a smooth process flow.
7. **Emphasising cost and/or schedule** - Activities that contribute to reducing the cost or labour of the product.
8. **Learning or resource enhancement** – Activities that aim to bring forward the essential process knowledge, skill improvements, and resource development within departments.
9. **Improving employee job satisfaction** – Activities that aim to improve employee job satisfaction by increasing the employee to execute similar tasks.
10. **Other** - Activities that contribute to other areas than the above-mentioned ones, e.g., work environment, regulatory, or environmental.

Finally, a relevant visualisation tool that can be used to summarise the elements mentioned above and better understand the values stream is a SIPOC (supplier, inputs, process, outputs, customer) diagram (Oppenheim, 2011, p. 167). The SIPOC is utilised to define business processes that are the key to successfully completing specific organisational objectives (Oakland, 2014, p. 18). The following questions are answered and visualised in the SIPOC:

1. Who is the primary stakeholder in the process?
2. What value and output does it generate?
3. Who is the process owner?
4. What inputs are provided?
5. What resources are used?
6. What are the value-creating steps?
7. Does the subprocesses have clear start and end point?

Cao et al. (2015) state that the SIPOC diagram's five components interact and are connected. The tool can be utilised for any company, showing a series of activities across different departments in a business process. Moreover, it can support balancing the information flow and generating performance indicators, making the company effectively achieve their objectives (Cao et al., 2015, p. 4104). A SIPOC diagram is illustrated in Figure 3 and is adapted from the work of Cao et al. (2015, p. 4110), Oakland (2014, p. 13), and Pyzdek and Keller (2010, p. 202). The purpose and the objectives have also been added to the SIPOC diagram since it will be used in the context of VSM implementation and improvement. By doing this, the diagram becomes more aligned with the goals of the VSM, assisting in practical implementation.

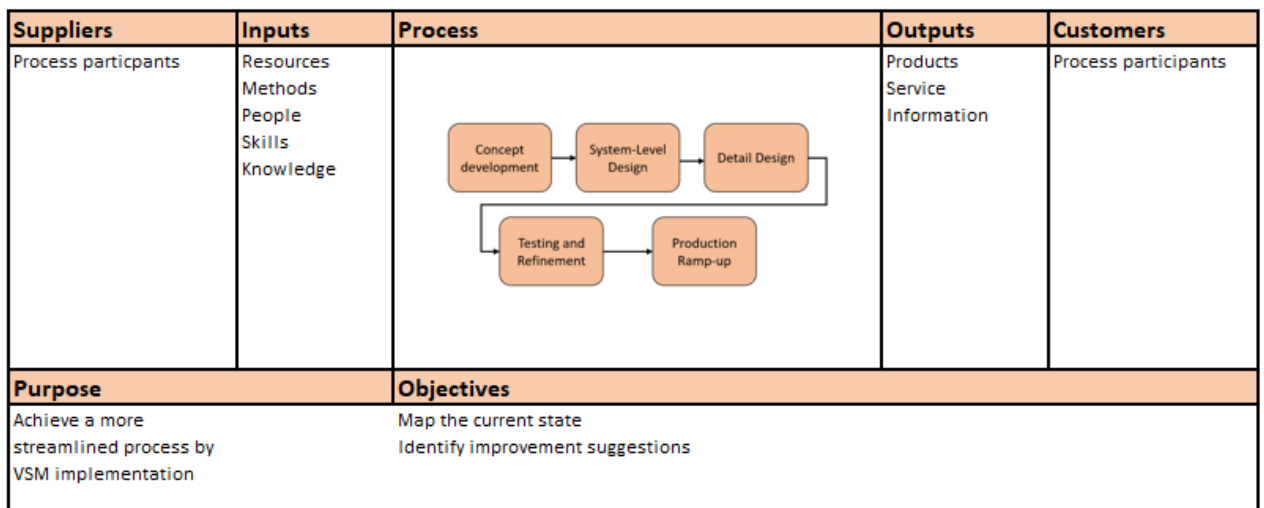


Figure 3. SIPOC diagram (Cao et al., 2015, p. 4110; Oakland, 2014, p. 13; Pyzdek & Keller, 2010, p. 202)

2.6.2 Current state

The current state map can be defined as a non-streamlined graphical representation, including performance data on the activities of the current product development plan that serves as a starting point for identifying and eliminating waste (Oppenheim, 2011, p. 35). It is crucial to thoroughly grasp the current state before identifying waste and suggesting improvements (McManus, 2005, p. 37). The main focus of mapping the current state is to achieve a holistic understanding of challenges in the process by presenting objective, uncomplicated data from a wide range of stakeholders. According to Barnhart (2013), the following aspects should be included when identifying these challenges:

- Where and when do the challenges occur?
- In what form does it occur, and how often?
- To whom does it occur, and how often?
- What is known about the problem from theory and within the company?
- What process steps and dependencies surround the problem? (Barnhart, 2013, p. 81)


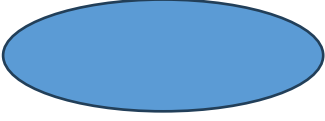
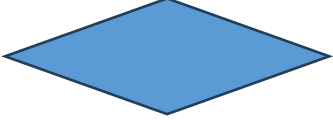




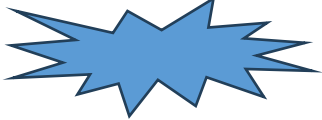
The mapping process itself can be divided into three steps:

1. Organising the process steps (tasks) and information flow.
2. Gathering performance data on the activities and information flow
3. Assessing how value is produced (McManus, 2005, p. 37).

Organising the process steps (tasks) and information flow

Before the current state can be created, it needs to be decided on how detailed the process steps and information flow should be. It is vital to find a balance between a high-level breakdown and a detailed breakdown of a process. McManus (2005) states that between 10 to 30 tasks is a sufficient breakdown, providing traceability and enough detail. Furthermore, if the process is complex, more tasks may be appropriate to visualise the process correctly. When the process detail decision has been made, the tasks and information flow can be mapped out, establishing the current state's topology. Different process mapping symbols should be utilised to better understand the meaning of different activities in the process (p. 40-41).

Table 3. Mapping symbols (Adapted from McManus, 2005, p. 41)

Shape	Used as
	<p style="text-align: center;">Action Task</p> <p>Represents a task requiring specific action</p>
	<p style="text-align: center;">Review Task</p> <p>Represents an evaluation of a task</p>
	<p style="text-align: center;">Decision Task</p> <p>Indicating a decision point in the process</p>
	<p style="text-align: center;">External Factor</p> <p>Represents an external task impacting the process</p>
	<p style="text-align: center;">Inventory</p> <p>Represents waiting or queues</p>
	<p style="text-align: center;">Major Information Flow</p> <p>Represents the major flow in the value stream</p>
	<p style="text-align: center;">Minor Information Flow</p> <p>Represents the minor flow, such as rework or iterations</p>
	<p style="text-align: center;">Attention burst</p> <p>Draws attention to a problem in the process</p>

Pyzdek and Keller (2010) state that a common way of mapping out a current state is with a so-called spaghetti or entangled chart, as it will be called in this thesis. The entangled chart typically represents a whole product development process and visualises how the product flows through the value stream from concept development until production ramp-up. The reason it is entangled is that it often visualises complex processes, including iterations and information transfers back and forth between different people and places. To the left in Figure 4, a mapped current state is visualised. In this process, all the steps are mapped out as they are, considering all the waste and iterations. An optimal process can be seen to the right, where the Lean principles have been implemented, and the wastes and iterations have been successfully eliminated (p. 326). Considering the entangled way of mapping, it can be further enhanced by utilising the cross-functional format by implementing department/stakeholder lanes when mapping out the tasks. This helps visualise the number of tasks a specific role has during the process (Oakland, 2014, pp. 215–216; Pyzdek & Keller, 2010, p. 195).

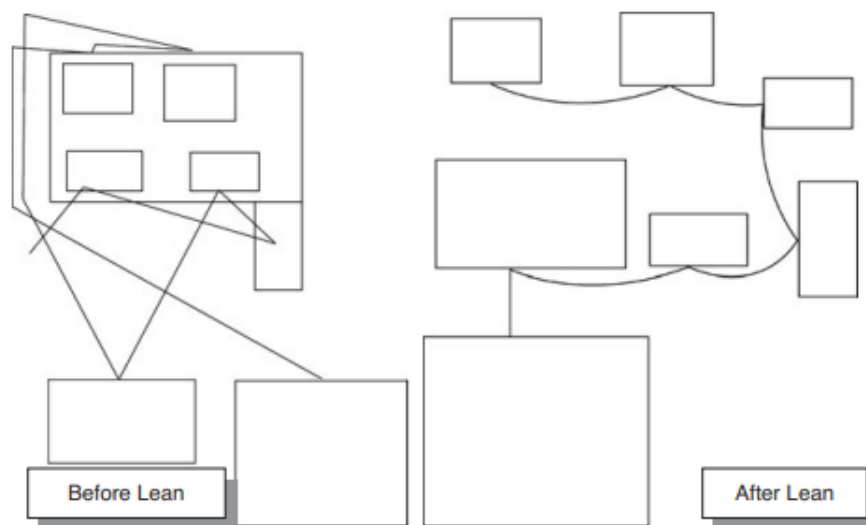


Figure 4. Entangled process (before lean) – Smooth process (after lean)(Pyzdek & Keller, 2010, p. 326).

Gathering performance data on the activities and information flow

It is essential to successfully gather the correct performance data on the activities and information flow to achieve a comprehensive analysis of the value stream (Oppenheim, 2011, p. 35). The data type should be determined based on the purpose, scope, and goals of the VSM application. It is crucial to utilise the knowledge and experience of the participants of the mapping team when it comes to identifying data sources and understanding complex data. It is also important to normalise the data from different sources and to normalise it into a typical work effort, including minimum and maximum defined efforts. When the data is implemented into the value stream map, only the most necessary data that provides insight into the process should be utilised. A sufficient way of visualising time-related data is with a timeline that represents cycle times with the consideration of parallel tasks. It must be noted that depending on the level of the VSM analysis, different types of data metrics and visualisation should be considered. I.e., the data representation should be tailored to fit the purpose and nature of VSM analysis (McManus, 2005, p. 44).

Lastly, to fully comprehend the performance data collection stage, McManus (2005) has defined a thorough list including different types of data metrics:

- Cycle time: the time (clock or calendar time) it takes to perform an instance of an activity.
- In Process time: the time (hours or days) of continuous work required to complete an activity.
- Lead time: the period between when the task occurs until it is finished.
- Costs (fixed or non-recurring): the needed resources for a task to be executed.
- Capacity: the amount of jobs that a specified process can do.
- Utilisation: the amount of the actual usage of the capacity.
- Availability: the availability of resources (in percentage).
- Failure rate: the percentage of task failure rate.
- Rework rate: the amount a task needs to be iterated.
- Downstream task satisfaction: the quality of task outputs.

- Waiting and inventory: the time a single job has to wait or the number of jobs in a queue (McManus, 2005, p. 46).

Assessing how value is produced

Pepe et al. (2011) state that identifying the most critical areas in the process is a way of assessing the values produced. To identify critical areas for improvement, the VSM should be analysed and discussed with the key stakeholders. The goal is to identify the areas where the process participants (key stakeholders) have the most challenging tasks. The results of this identification can be utilised to create a priority list, including improvement suggestions for the critical areas in the process (p. 7). Together with identifying the most critical areas and generating a priority list on the improvements, the creation of a minimum viable product (MVP) can be implemented. In traditional product development, going from concept development until production ramp-up is often a lengthy process aiming for product perfection. The objective of the MVP is to start the learning process as quickly as possible, not to finish it. E.g., an MVP intends to address more than technical or product design issues compared to a prototype or concept test. Its objective is to evaluate key business assumptions supporting lean implementation (Ries, 2011, pp. 93–94).

Furthermore, the value can be assessed by tagging the tasks as VA, RNVA, or NVA. It needs to be noted that more detailed map times reveal NVA tasks more quickly than high-level ones. This is because NVA tasks are often hidden within VA tasks. Therefore, it is critical to assess how tasks provide value, e.g., how they contribute towards defining the process and product or lowering the risks to make the definitions more valuable. A value assessment can also be executed on the information flow between tasks. By highlighting where the value-added tasks and information flows exist on the map, it supports creating a future state VSM, aligning with the MVP's objective of evaluating key business assumptions (McManus, 2005, p. 49).

2.6.3 Future state

According to Rother and Shook (2018), the future state map can be defined as a streamlined, optimised process that has undergone waste identification and elimination, designed to materialise quickly and resulting in concrete improvements within a short period (Rother & Shook, 2018, p. 57). The future state should focus on the following elements:

- First, analyse and rank the improvement suggestions based on their impact and effort while also identifying markers for detailed improvements requiring further detailed work.
- Second, streamline the process and eliminate unnecessary iterative flows to achieve a precise and transparent information flow. Clarify who delivers what information, to whom, and in what format by defining clear expectations for information supply. Information should be reformatted if it benefits downstream tasks in a cost-effective manner.
- Third, balance the workload and the resource utilisation to avoid bottlenecks in specific departments and to be able to keep up with specified task durations. Try to minimise task variation and remove external constraints that slow down the process.
- Fourth, try to standardise processes and implement new technology enabling automated tasks and reviews while also managing uncertainty with the least amount of effort and ensuring effective iteration by managing reviews correctly.
- Fifth, implement key performance indicators that can be monitored and measured during future projects (McManus, 2005, p. 71; Pepe et al., 2011, p. 9).

In order to realise the goals of the future state map, several tactical actions must be incorporated. First, it is crucial to have a clear and transparent information flow, where expectations for who supplies what information, to whom, and in which format is defined. Second, a balance between the workload and resources must be defined to complete the tasks within a specified time. Task variation external constraints should be removed.

2.7 Design structure matrix

The DSM can be defined as a network modelling tool that visualises a system's elements and how they interact, i.e., representing a system's architecture or the designed structure. This modelling tool has proven highly effective in engineering and management process improvement. Eppinger and Browning (2019) have concluded that there are four different types of DSM:

- **Product Architecture DSM** – Used for identifying and analysing the relationships between different components within a product or system.
- **Organisation Architecture DSM** – Used for visualising the communication and collaboration dependencies between a company's departments or teams.
- **Process Architecture DSM** – Used for capturing the relationship and dependencies between tasks and activities in a process.
- **Multidomain Architecture MDM** – Used for combining the above-mentioned DSM types, creating a comprehensive visualisation of the developed product, involved people, and processes utilised (Eppinger & Browning, 2019, pp. 1–2).

2.7.1 DSM definition

Since the thesis analyses the current state of a hardware development process, the process architecture DSM will be the main focus of DSM literature. The DSM can be defined as a square matrix with X amount of rows and columns where each task is presented in a list format. Specifically, each task's row visualises its inputs, while its column displays its output. The information flow of the process is shown through markings in the cells of the matrix (Ulrich & Eppinger, 2016, p. 400). As mentioned, the process architecture design structure matrix is a tool for visualising and analysing task dependencies and information flow in a process. This tool allows for identifying serial, parallel, and iterative flows, where these flows can be re-modelled or manipulated. E.g., in Figure 5, if task A provides information to task B, a dot is placed in the cell in column A, row B. If a marking is above the diagonal, it represents information flowing from a later task to an earlier, i.e., an iterative process. A perfect flow is when the information flows from an earlier

task to a later one; visualising this in the DSM results in the markings being under the diagonal (Karniel & Reich, 2011, p. 38).

In order to fully understand the flows within the DSM, one must also investigate the different types of DSM activity interactions visualised in Figure 4 consisting of:

- **Sequential activities:** These activities are done in a specific order and are dependent on the previous activity being completed. In some cases, sequential activities can be overlapped by starting the downstream activity before the upstream activity.
- **Parallel activities:** Parallel activities are independent from each other, meaning that they can be executed simultaneously. However, two parallel activities can be dependent on the same resources, which then results in interaction between the two parallel activities.
- **Coupled activities:** Generates iterations because of the nature of these activities requiring inputs from one or more downstream activities. These activities are common within engineering processes due to uncertainty and risks in development-related tasks, such as design, analysis, testing, and validation.
- **Conditional activities:** These activities can be defined as decision points in the DSM and should be visualised with another symbol. I.e., depending on the outcome of the upstream task, it can take different routes in the DSM. (Eppinger & Browning, 2019, pp. 133–135).

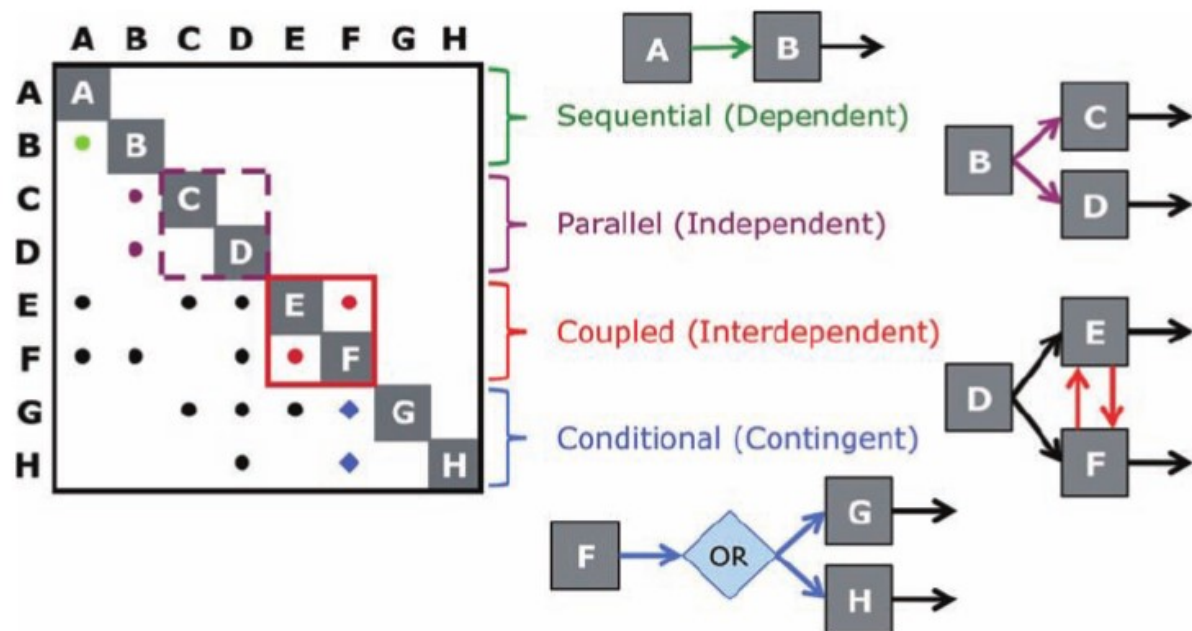


Figure 5. DSM activity interactions (Eppinger & Browning, 2019, p. 134)

2.7.2 DSM algorithms

Finally, different DSM algorithms will be discussed. Karniel and Reich (2011) have defined three types of DSM re-modelling algorithms: Partitioning, Clustering, and Sequencing. These algorithms are illustrated in Figure 6. The partitioning algorithm reorders the rows and columns to eliminate or minimise the iterative loops. This is done by bringing the feedback marks under the diagonal or as close as possible to the diagonal. The main objective of partitioning is to minimise the number of iterations in a process; having fewer iterations ultimately results in a more effective process. However, Karniel and Reich state that it is unlikely that only the partitioning algorithm is enough to achieve an optimal process; thus, the remaining coupled activities need further re-modelling with the sequencing algorithm, which includes both partitioning and tearing. Tearing is not an algorithm by itself; it is a manually operated procedure that eliminates feedback marks based on knowledge of activity relationships. The clustering algorithm is mainly utilised within the Product and Organisation architecture DSMs, where it is used to identify entangled component relationships. Lastly, the sequencing algorithm combines

partitioning with manual tearing, allowing for the elimination of those left-over iterative loops to get a more optimal process. In the sequencing example in Figure 6, the E to A and G to A feedback marks could be eliminated, and then the partitioning algorithm could be utilised (Karniel & Reich, 2011, pp. 42–43).

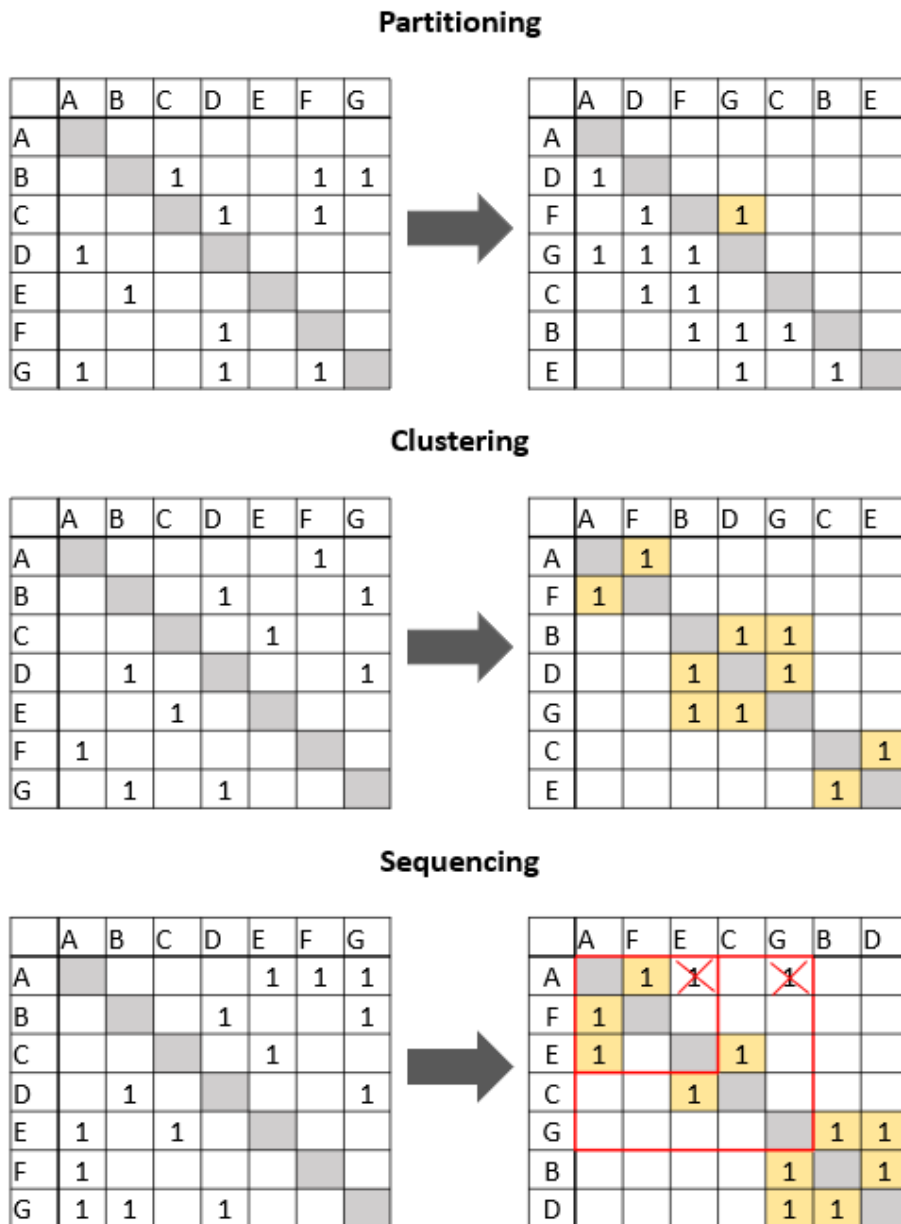


Figure 6. DSM algorithms (Adapted from Karniel & Reich, 2011, p. 42-43).

3 Research Methodology

This chapter presents how the research have been executed and what tools and methods have been used during the procedure. First, the case study approach is discussed and how the approach has been utilised. Second, the data collection methods and analysis are explained. Third, the research validity and reliability are elaborated on. All these elements together create a thorough research methodology.

3.1 Case study

Simons (2009) indicates that depending on the type of circumstance, the definition of a case study varies (p.19). Simons has studied prior works regarding the definition variation and concludes that “what they all have in common is a commitment to studying a situation or phenomenon in its ‘real life’ context, to understanding complexity, and to defining case study other than by methods (qualitative or otherwise)”. In many instances, the case study relates to a specific company, project, or system. (Simons, 2009, pp. 21–22).

The thesis analyses an end-to-end product development process used within hardware automation component projects within the R&D sector of a technology company. Additionally, a specific case project is analysed to acquire deep insight into how the current process has been utilised. The project is a typical R&D-based project for the case company, where the output of the project is a customised product utilised to complete and enhance a more significant and complex system.

3.2 Data collection and analysis

Three main data collection elements besides the literature review were utilised in this thesis (Table 4): An application lifecycle management system, a document management system, and a VSM workshop. The two first mentioned were mainly related to the case project analysis. The analysed data could be utilised as presentation material during the

workshop as real-life examples to spark exciting and vital discussions. The VSM workshop was the main contributor to analysing and identifying improvements to the current HWDP at the case company. Lastly, a DSM software tool was used for dependency visualisation, partitioning, and simulations.

3.2.1 Application lifecycle management system

The application lifecycle management (ALM) system was utilised to collect historical data on the case project. The ALM system is a tool in which relevant project data, tasks, and activities are managed and monitored. It provides functions for categorising and filtering the relevant tasks and activities for a specific project and enables exports to Excel for further data analysis and visualisation. Historical data from the project timeline was collected from the start of the project up until the present day, providing an extensive perspective on the project's progress. Using ALM as a data collection tool allowed for a structured way of working, where the project's milestones, decisions, and changes could be thoroughly analysed. The most relevant data could be extracted from the system and visualised, which made it possible to identify patterns or trends in the progression of the project.

3.2.2 Internal documents

A document management system was utilised as a central hub to gather all of the project's relevant files and documents. This tool allowed for effective filtering and ease of access to documents and files for the case project. The documents used were mainly related to understanding how the project has progressed since the beginning and consisted of a task list, weekly follow-up meeting notes, revision traceability instructions, and a project schedule. The most important documents were the two latest mentioned. The revision traceability instructions allowed for understanding how the component's serial number could be used to identify which HW revision it was. This came in handy during the construction of the project HW revision timeline. The project schedule,

visualised as a Gantt chart in PowerPoint, consisted of several revisions of how the project had been planned during 2019 – 2021.

3.2.3 VSM Workshop

The workshop data collection method has been highly significant because of its essence of gathering all the relevant process participants and stakeholders in the same location, resulting in sophisticated and vital debates regarding the way of working in the current HWDP. The purpose of the workshop can be divided into two main objectives:

- Analyse and improve the current HWDP at the case company.
- Demonstrate the effectiveness of the VSM tool in order to increase process efficiencies and eliminate waste.

The workshop participants consisted of individuals with different roles in the HWDP, where the participants included were from the following departments: design and development, testing and validation, and sourcing. I.e., various experts from different departments were included, resulting in a cross-functional team providing valuable data for the HWDP and the thesis. The thesis author has functioned as the facilitator, I.e., kept the discussions ongoing, managed the VSM preparation phase, and was primarily responsible for the workshop documentation. The mapping process itself was documented virtually in a visual collaboration platform called Miro. The first workshop was held face-to-face as a kick-off meeting to build relationships, have better communication, and faster decision-making. During the first workshop, the purpose and goals of the workshop data collection strategy were presented, and the VSM methodology was explained. Furthermore, the workshop consisted of mapping the current state of the HWDP, including identification and documentation of the tasks and sub-processes and the information flows and dependencies. The second and third workshops were held online and were devoted to analysing the mapped current state, identifying waste, and suggesting opportunities for improvement for the identified wastes. Additionally, potential risks and challenges related to the improvement suggestions were elaborated.

During the workshops, various background information was observed and looked upon to provide context and to better understand the current situation of the HWDP. The following materials were utilised:

- An existing flowchart of the HWDP
- The thesis author's Excel data collection sheet consisting of work item data from the analysed case project
- A Gantt chart of the case project
- A SIPOC Diagram

To get an extensive overview of the current situation of the HWDP, insights and data were not restricted to the analysed case project. It was encouraged to provide information that was seen as critical from any development projects within the automation department.

3.2.4 DSM simulation tool

A commercially available research tool from dsmweb was utilised for DSM partitioning and probability simulation. This tool was developed by Prof. Steven Eppinger's student from MIT and consists of an Excel macro to be utilised for general DSM operations, such as partitioning, tearing, banding, and simulation. The current state mapped during the workshop was entered into the DSM tool in a list format. a DSM was generated from the list, and it was then possible to add dependencies between the tasks. The tool was utilised to partition the current state. Based on the structural differences, a probability simulation was then done on the non-partitioned and partitioned DSM to verify how much the lead time could potentially be decreased.

Table 4. Data collection overview

Method	Type	Analysis	Notes
Literature Review	Qualitative	Content analysis	The literature review summarises the crucial theory regarding lean engineering and value stream mapping from scientific articles, reports, and books.
Workshops	Qualitative	Content analysis	The current value stream was mapped and analysed in three workshop sessions.
ALM System	Quantitative	Trend analysis	Data from the ALM system was exported from a specific case project and analysed from a project performance perspective.
Internal documents	Qualitative	Content analysis	Documents regarding the case project's planning and scheduling were analysed.

3.3 Research reliability and validity

The terms reliability and validity are mainly intended for quantitative use; however, in pretty much all qualitative research, both are heavily utilised (Golafshani, 2003, pp. 601–602). According to Golfshani (2003), reliability can be defined as the degree to which the results of a study are consistent over time and include a comprehensive presentation of the population under investigation. Moreover, the results can be considered reliable if the findings can be reproduced with another research method (p.598). Golfshani further mentions that validity can be defined as the degree to which the research measures what it is supposed to do. Increasing the research validity measurement can be done by defining precise research questions that pinpoint the investigated issue in the thesis. These specified questions can be answered by looking through the work of others or by performing tests or practical experiments (p.599).

The case project of the thesis analyses quantitative and qualitative data, whereas the workshop is completely based on qualitative data. In order to increase the reliability and validity of the thesis, the triangulation technique was utilised. Rose and Johnson (2020) mention that in order to achieve an accurate description and presentation of an outlined research, the triangulation technique allows for recognising the diversity in the collected information by expanding the research perspective to be approached from many angles with different methods (Rose & Johnson, 2020, p. 10). In view of the thesis, it can be said that the research approach is broad due to its nature of investigating the research issues with the help of an individual case project analysis together with a collaborative workshop. The case project provided the thesis with historical facts on how the project proceeded, whereas the workshop included individuals with various expertise and background knowledge.

4 Results and discussion

The results are divided into two main parts: a case project analysis and a value stream mapping workshop of the HWDP. The case project has been analysed from two perspectives: a component functionality view and a managerial perspective. This analysis includes an assessment of the rework rate, generated defects, and the project timeline. This enabled for identifying what issues have occurred and where during the project timeline. The outcome from the project analysis was also used as presentation material before the workshop started to provide real-life examples. The workshop, its preparation phase, and its findings are then discussed and presented. Lastly, a DSM analysis is performed and elaborated on, the possibility of performing a future state VSM is brought up, and a cross-functional diagram of the HWDP is presented.

4.1 The case project

On the subject of the case company, one of its core competencies is the development of marine and energy power solutions. As part of these complex systems, many components need to be developed to achieve a fully functioning system. One of which is the extensive automation system, whose main purpose is to enable fluent control and optimal performance of the solutions. The ongoing case project can be categorised as a hardware research and development (R&D) project following the outlined HWDP guideline in Appendix 1. The project is an internal development project entailed to enable new technology within the automation system and strengthen the position of the company's marine and energy power solutions. The guideline is an internally developed process used for hardware development projects within the company.

The case project was analysed through an internal Application Lifecycle Management (ALM) system and an internal document management platform. Since the main objective is to allocate inefficiencies that have happened in the past time of the project, the analysis will be executed by focusing on the HW development timeline of the project both from a component functionality view and a management view.

4.1.1 ALM system

The ALM system provided the author with a complete introduction to the project through an information page in the ALM system. Within this critical information page, a key project storyline detail was identified: the component's concept development was totally handled by an external supplier before it was relocated to the case company. This presented challenges since there was a lack of in-house expertise on the component; thus, there might have been insufficient knowledge transfer between the supplier and the case company. Additionally, it was found that the work methodology within the development department was changed from traditional project management to agile and specifically SAFe (Scaled Agile Framework) during the project timeline, resulting in a learning curve related to this new way of working.

The ALM system was also utilised to collect historical data on the case project. Within the system, categorising and filtering relevant activities related to the project was possible. The ones utilised in this analysis will be described below:

- **HW Revision** – The HW revision defines the version of the HW component and is built upon a unique alphanumeric code indicating specific configurations and specifications. It helps to categorise the modifications and defects to the component in which they occurred, improving the traceability.
- **Modification** – The modification includes improvements and changes within a new HW revision. They often address known issues identified in the previous HW revision and other potential improvements based on feedback and technical progress.
- **Defect** – A defect is an issue or failure found in the component that negatively affects the functionality or performance. Defects can occur as either an in-house defect or an in-service defect. The first mentioned is related to the development, including the design, manufacturing, and validation phase, while the second is related to issues generated on customers' systems.

4.1.2 Hardware revision timeline

A comprehensive HW revision timeline was created in Excel and can be seen in Appendix 2. The timeline contains all the production dates of the different HW revisions, acting as milestones on the timeline. To better understand how the project has proceeded, the timeline also contains defects, modifications, and the first planned full release of the component. The HW revisions and the modifications can be seen above the timeline, while the defects are visualised below the timeline. The modifications are linked directly to the HW revision in which it is applied. The defects are visualised as periods with the discovery date as the start point and the fixed date as the endpoint. Some additional information was added to the title of the defects, showing if they are still in progress or not valid. Overall, the generated HW revision timeline shows that the case project has been ongoing for an extensive time. There have been several defects and revisions throughout the project that have resulted in it not being possible to follow the original plans of the project. As the project has progressed, it is evident that a large amount of HW revisions has extended the length of the project significantly; however, the extensive amount of revisions has most likely been seen as necessary to ensure the quality of the full release component. To increase accessibility and the efficiency of the analysis, the following charts were visualised:

- An analysis of HW revision amounts and lead times between the different revisions (Figure 7).
- A breakdown of defects and modifications linked to their respective HW revision (Figure 8).
- A defect trend chart represents the number of defects discovered over time, which enables identifying patterns of when defects appear during development (Figure 9).
- A defect fix time chart visualising the number of defects and their fix time as lead time. (Figure 10)

The full release of the component was postponed multiple times, resulting in not successfully meeting the project schedule. The majority of the modifications have been gathered as a large batch in HW revision 6.2. This might be due to the 3rd planned full release that was supposed to take place after the releases of the 6.2 revision. Figure 7 shows the amount of HW revisions in the project and the lead time between them. An interesting finding is that the HW revision 6.2, consisting of the large modification batch from the HW timeline, has a relatively small wait time from the previous revision. This indicates that multiple revision development has been ongoing simultaneously, e.g., different, more minor SW-related features and/or larger HW-related features. So, in this case, it is perhaps necessary to consider the time between 6.1 and 6.2 since the 6.0.1 revision only contains more minor changes. Overall, it can be stated that the component has been reworked many times, leading to a long project timeline. Reworking a component often contributes towards more administrative work due to the increased amount of documentation needed and the obligation to keep the stakeholders informed on the new revision.

Figure 8 shows the defect findings, resolutions, and modifications across the HW revisions. HW 1 experienced a higher number of defects; however, several did not require an HW upgrade. I.e., the defect was inexact or could be fixed through administrative work. It can also be seen that the number of modifications in the later HW revisions was higher compared to the rest. This indicates that the fixed defects resulted in modifications to the component that increased its durability and ensured its compliance with various factors within the complex system. Furthermore, the defects reported have continuously decreased as the HW revisions advance. It must be noted that the data represented in the chart are the defects and modifications that could be directly linked to a specific HW revision.

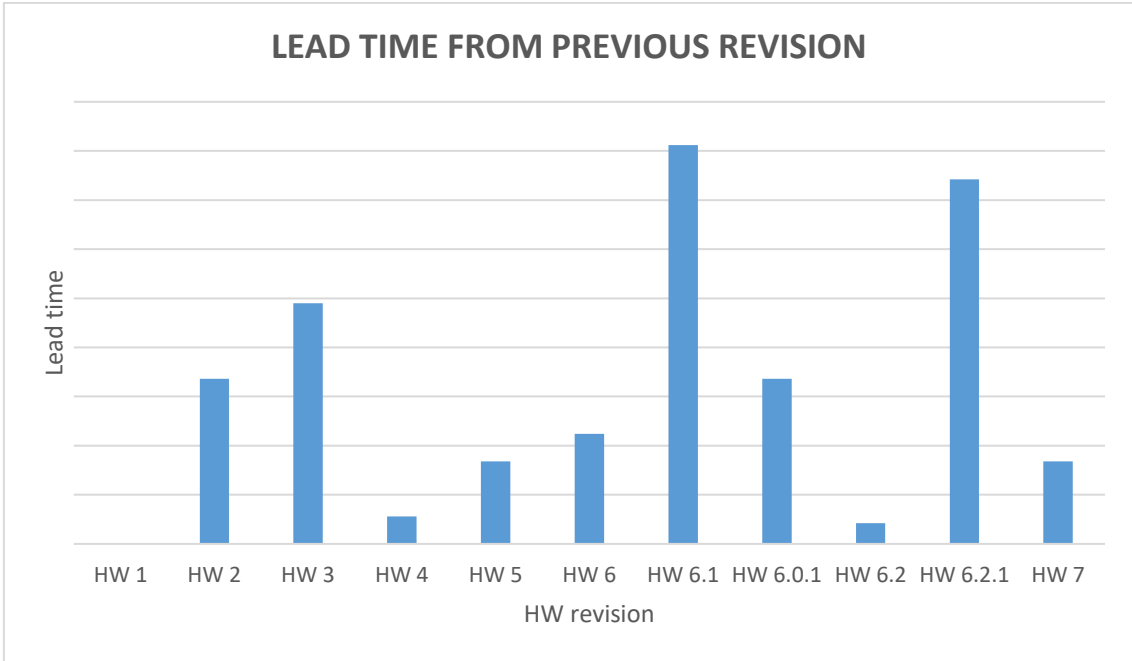


Figure 7. HW revision amounts and lead times

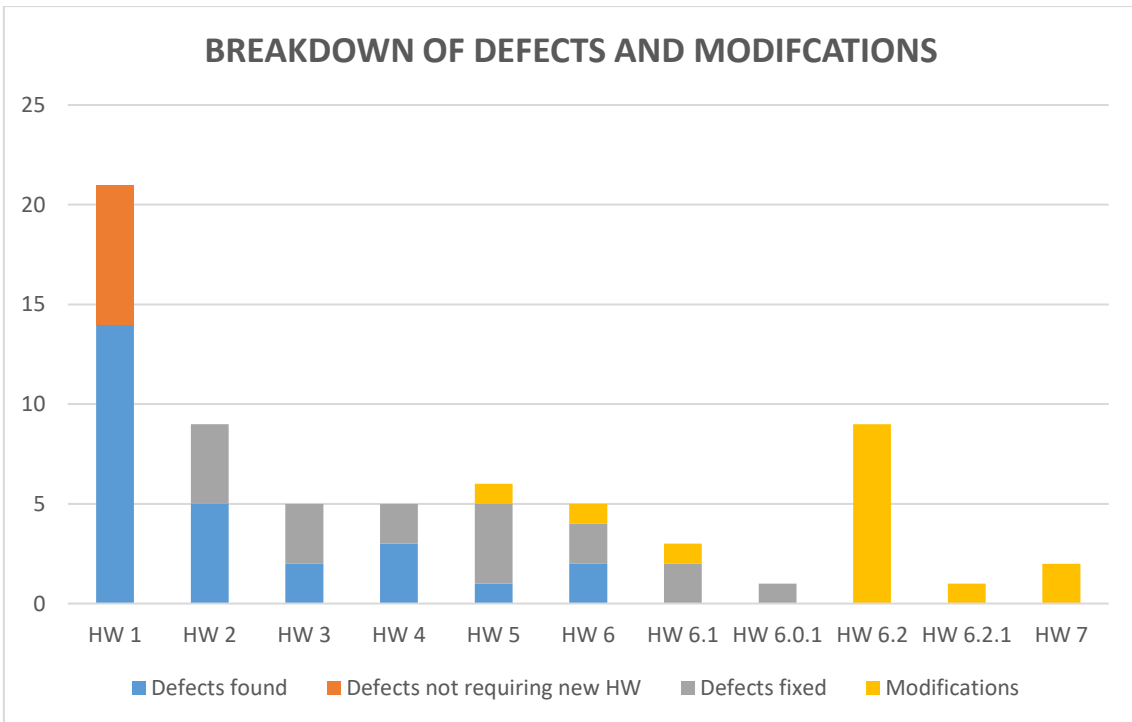


Figure 8. Breakdown of defects and modifications based on HW revisions

Figure 9 visualises the number of defects discovered over time. Most of the defects were discovered in the beginning phase of the project during the first released HW revisions, which was also seen in the breakdown of defects and modifications. However, there have also been a few discoveries during the project's later stages, which have contributed to the lengthy project execution. Figure 10 visualises all the reported defects and their fix time as lead time in chronological order from the most considerable wait times to the smallest. Overall, most of the defects have been fixed within a set amount of time. Three of the reported defects stick out and have a much larger fix time/in-progress time compared to the others. This adds some indication towards where the extensive project length might have come from. To get some deeper background information, it was decided to investigate further, gathering data on the lengthy defects. Furthermore, the analysis will also consider the in-service defects since they often result in more extensive issues requiring complex decisions. By analysing the most extensive and crucial defects, including both those that emerged from the development (in-house defects) and those that emerged after the deployment (in-service defects), the following observations were seen:

- During the project's ramp-up, failures at the supplier side started showing that the product did not fulfil the specified requirements. This might relate to the manufacturing process quality on the supplier side being slightly deficient.
- There have been issues with the different capabilities of the component, which have affected the product's performance and compliance with the more extensive system. This might be due to insufficient knowledge regarding how the product should work within the extensive system, both at the case company and the supplier.
- The analysis indicates that the product was put too early on the field, since several failures have been generated from the customer's systems. An important lesson learned would be to push towards not releasing a product if it is not fully validated.

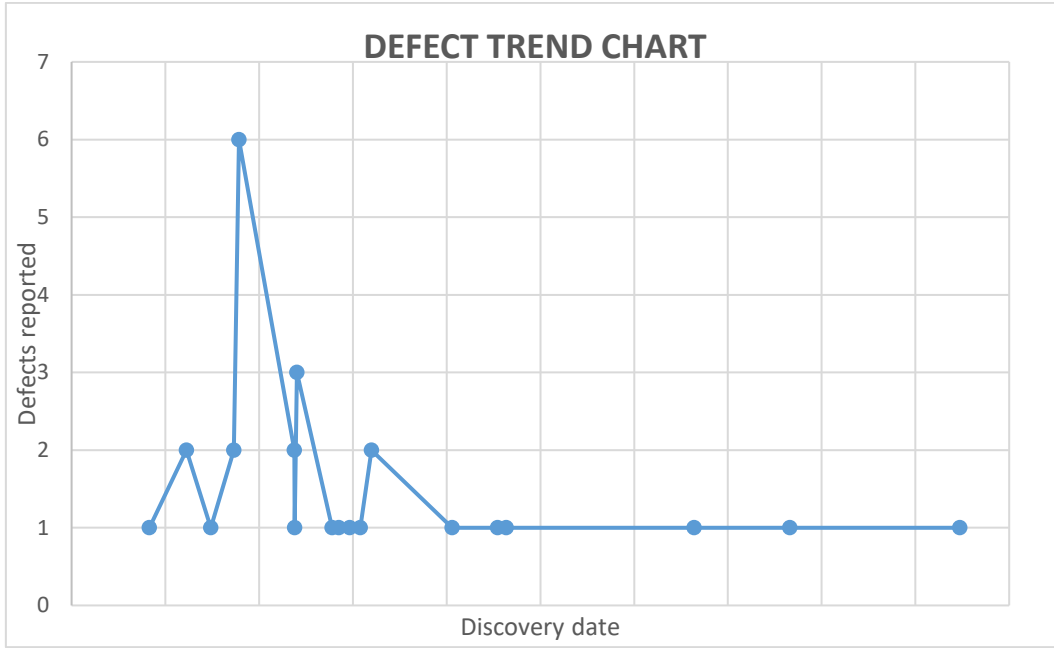


Figure 9. Defect trend chart

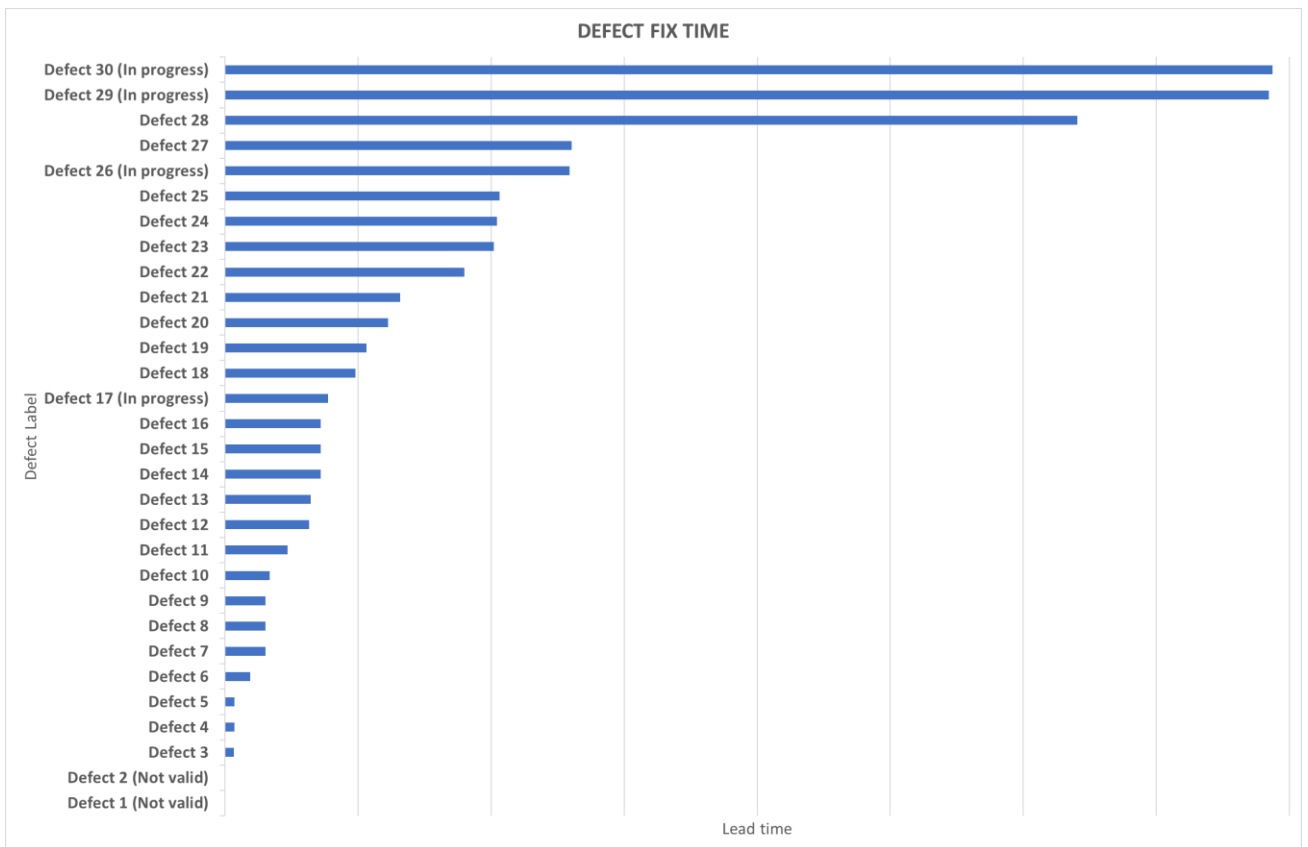


Figure 10. Defect fix time

4.1.3 Existing project schedule

An existing project schedule was found in the document management system, illustrated in a Gantt-type format. The chart included the tasks of both the case company and the supplier. The chart had been created in PowerPoint, resulting in the accessibility somewhat decreasing due to the space limitation on a single slide.

After observing the Gantt chart, it was found that the tool was implemented in the later stages of the project, which indicates that no project schedule has been created, or at least, no visualisation tools such as a Gantt chart have been created in the beginning. The chart reveals that many tasks have been postponed, resulting in project changes and further project schedule updates. Regarding progress monitoring, it can be seen that the progress of the scheduled work has not been fulfilled since many of the tasks have been postponed, resulting in changes and further updates to the project schedule. With postponing the tasks, both the limited and full development release of the component have been pushed forward, leading to the internal customers being unable to fulfil their plans with the component. No clear dependencies structure can be identified, such as finish to start, start to start, finish to finish, or start to finish dependencies. This makes it relatively hard to identify relationships between the tasks and activities.

4.1.4 Time data collection

An attempt was made to collect the grand total amount of the documented hours on the project; however, without any success. This data would have been beneficial during the later part of the results, which focuses on improving the HWDP. Normally, the project's hours are documented on a single investment element specified for the project. In this case, the project's documented hours have been spread out on five different elements, where three of them are general investment elements, and two are project-specific. Unfortunately, it was not possible to filter out the hours documented on the case project. This results in not being able to gain any insight into the level of effort required to complete the project, how efficient the project was, or how much the project cost.

4.1.5 Project analysis summary

The project analysis has shown that there have been many difficulties with the project and that it has been ongoing for an extensive amount of time. One of the first observations was that the concept development and first designs of the component were completely handled by an external supplier before it was moved to the case company. This posed difficulties since there was a lack of in-house expertise on the component, and there was a possibility that the knowledge transition between the supplier and case company was inadequate. Another general finding was that the departmental work methodology was changed from traditional project management to SAFe, resulting in a new way of working.

Based on the timeline analysis and the existing project schedule, it can be seen that many tasks and activities have been postponed multiple times, and these difficulties have made the project's length very extensive. Since the execution of the project has been so long due to all the technical difficulties, it has become evident that project planning and scheduling are essential at the start of a project. Therefore, to increase the effectiveness of future projects, a scheduling tool, such as the Gantt chart, is highly recommended to minimise the risk of delays and waiting to occur. The work methodology transition also needs to be considered here. Hence, the SAFe framework and its roadmap and iterative planning could include a dependencies structure and critical path to better keep the project on schedule.

The analysis indicates that more focus needs to be put on the project in terms of understanding the requirements. Especially the scope of the projects needs to be defined, both internally and at the supplier. Since many related projects within this hardware development sector are complex, the technical knowledge of the product to be developed needs to be on a top-tier level to understand how the requirements of the product are defined. Since the automation components are developed to be used in a more complex system, adopting a holistic approach towards the development is crucial. This involves

not only understanding the standalone functionality of the component but also grasping how these components operate within the broader scope of the complex system. If there is a lack of this knowledge, consultation should be considered in order to minimise the risk of misunderstandings and possible rework of the component. Reworking a component always contributes towards more documentation and requirements in informing stakeholders that new revisions are coming. Therefore, the amount of revision should be limited to a certain amount.

The analysis of the extensive defects also showed insufficient knowledge regarding how the product works within the extensive system. During the project's ramp-up, failures at the supplier side started showing that the product did not fulfil the specified requirements. Additionally, the analysis indicates that the product was put too early in-service on the field, since several failures have been generated from the customer's systems. An important lesson learned would be to push towards not releasing a product if it is not fully validated.

4.2 Workshop preparations

Preparation of a workshop is crucial in order to make the workshop execution phase as effective as possible. In this case, the preparations are mainly built upon defining crucial elements around mapping the process's current state. First, the process to be mapped was defined. Second, the stakeholders of the process were defined, and a mapping team was selected consisting of people with a variety of expertise and responsibilities. Third, the scope and critical value aspects were chosen to specify the focus of the mapping process. Fourth, to summarise all of these elements, a SIPOC chart was created to increase the accessibility of the elements and understanding of them. Finally, a virtual mapping template was created, and the process mapping symbols to be used were defined.

4.2.1 Define the HWDP

The current hardware development process defined at the case company can be seen in Appendix 1. The HWDP is a flow chart diagram containing a major information flow with smaller feedback and iteration loops. The diagram visualises the whole HWDP process from concept development until ramp-up. The diagram utilises several flow chart symbols such as start/end, process/task, decision, and document symbols. It can be seen that there has been an emphasis on defining the document outputs for the involved activities. Several departments are involved in the HWDP as well as the suppliers, and it can be stated that there is no clear definition of who does what in this diagram.

4.2.2 Define the team

The mapping team was defined before the workshop was executed. To get a cross-functional representation of the process, people with a variety of expertise and responsibilities were included in the mapping team. The team was mainly defined based on the people involved in the case project and other crucial stakeholders closely involved in the HWDP. The team composition was based on internal documentation of the assignees of the case project tasks and an ART (Agile Release Train) team composition chart in the ALM system. The majority of the defined individuals participated in all of the workshops and consisted of the following roles:

- Product Owner, HW development
- Scrum master / Developer, HW development
- 2 x Experts, HW development
- 2 x Senior Experts, HW development
- Application Engineer, HW development
- Line Manager, Testing & Validation
- Supplier Development Engineer, Sourcing

4.2.3 Scope and value definition

The scope of the HWDP consists of five phases: concept development, system-level design, supplier selection and cooperation, testing and validation, and the ramp-up phase. The main goal was to achieve a higher-level map where the activities and information flows are clearly visualised. The activities and information flow between the departments were analysed to identify improvement suggestions and increase the overall process efficiency. The reason for only mapping the current state into a higher level is to provide a more extensive overview of the process and increase the understanding of how communication and collaboration between specific departments should be done.

Furthermore, the critical value aspects were selected based on what the tasks in the existing HWDP contribute to. These consist of the following:

- Reduction of risks and uncertainties – Activities that aim to decrease the potential risks within the HWDP
- Facilitating communication – Activities that aim to increase communication and collaboration efficiency between departments.
- Enabling other tasks to start – Activities that Aim to pinpoint the critical dependencies within the HWDP to achieve a smooth process flow
- Learning or resource improvement – Activities that aim to bring forward the essential process knowledge, skill improvements, and resource development within the R&D.
- A Definition of processes to deliver the product – Activities that contribute to defining the released product to the ramp-up phase within the company.

4.2.4 SIPOC diagram

A SIPOC (Suppliers, Inputs, Process, Outputs, Customers) diagram was created before the workshop, which summarises the key parameters mentioned above. The SIPOC diagram was used as presentation material when introducing the purpose and goals of the workshop. The SIPOC was utilised to give a comprehensive overview of the process being

mapped and analysed. When observing the SIPOC diagram (Figure 11), it can be distinguished the types of people and information that are needed to map the current state of the HWDP. Additionally, it specifies the outputs and who is gaining something from it. Lastly, the SIPOC was used as a guideline for the participants in the workshops.

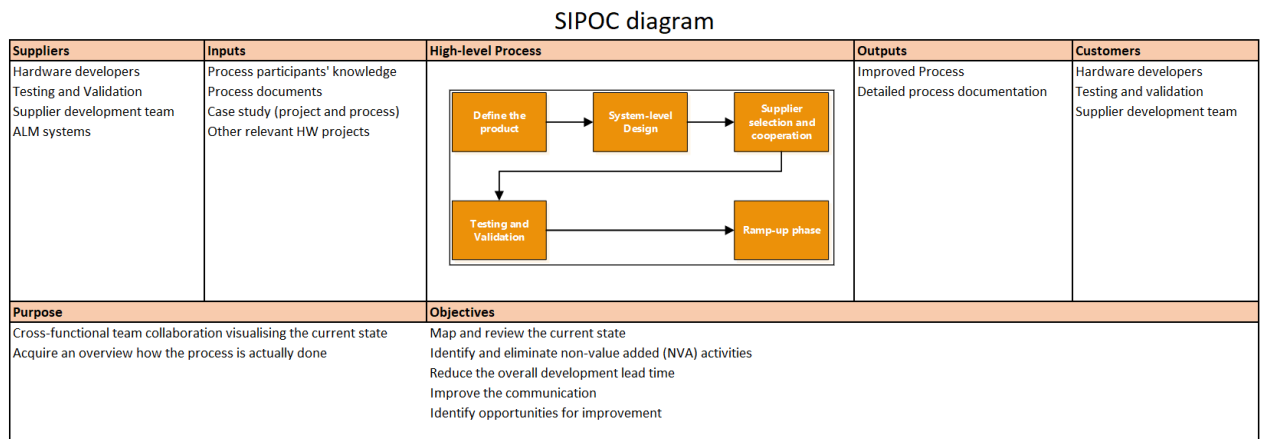


Figure 11. SIPOC diagram

4.2.5 VSM template and mapping symbols

A VSM template was created virtually (Figure 12) as part of the VSM workshop. The template was created in a cross-functional diagram style consisting of four lanes, where the lanes were dedicated to the specified stakeholder departments stated in Chapter 4.2.1. This type of template style was chosen to present the entire process flow visually and to easily be able to capture all of the tasks, sub-processes, information flows, and dependencies between the different departments. This results in a structured framework for outlining the process's current state, enabling a thorough comprehension of how value is created and delivered across the different departments.

Furthermore, some distinct mapping symbols were also created to increase the map's accessibility (Figure 13). In this case, the symbols used represent the following process aspects:

- **Activity (Square)** – This symbol represents an activity, task, or process step in the VSM and includes a short description of it.

- **Review/Decision/Approval (Diamond)** – This symbol represents a review, decision or approval within the process. E.g., it indicates whether an action is ready to proceed in the process or if it has to take another path based on some criteria.
- **Flow of information (Arrow)** – This symbol represents the information flow between the process's steps, including the flow of physical items, data, or communication.
- **Delay (Triangle)** – This symbol represents delays and waiting in the process. It is used to indicate where the waiting occurs and can support in locating areas where improvement is needed in the process.

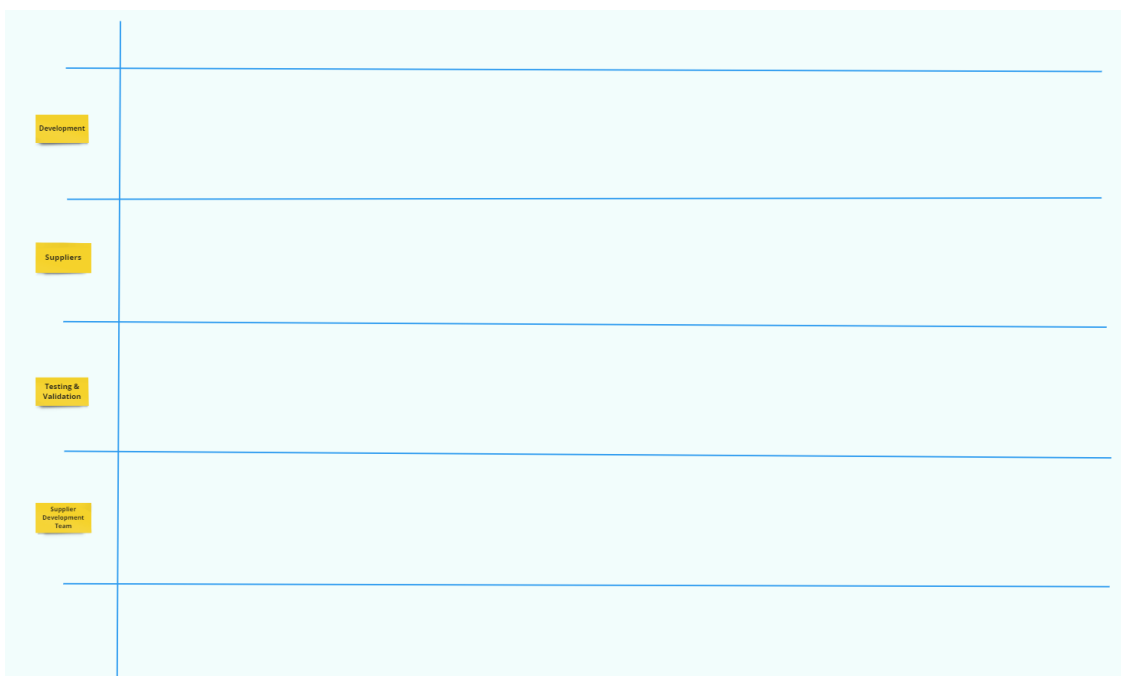


Figure 12. VSM template consisting of the specified stakeholder lanes

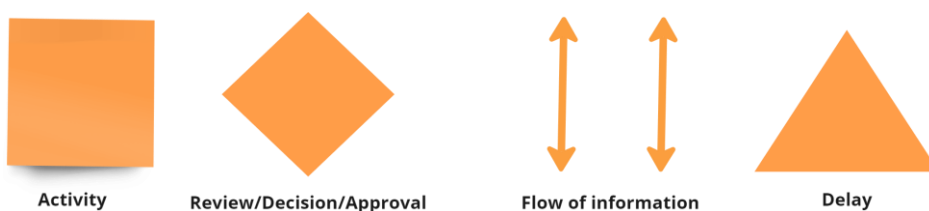


Figure 13. Mapping symbols

4.3 Workshop execution

The workshops have resulted in an extensive overview of the current value stream of the HWDP, consisting of the physical process, the information flow and dependencies between the different tasks and activities, and the visualisation of the value-added and non-value-added tasks.

4.3.1 Pre-workshop brainstorming

At the beginning of the workshop, it was found out that the specified template to be used during the current mapping session was insufficient, according to the workshop participants. At this stage, the template included four different departments: development, suppliers, testing & validation, and the supplier development team. It can be acknowledged that these departments are the ones that were defined when executing the preparative work before the workshop. This resulted in discussions regarding who should be added to the mapping template. After the discussions, the template had shifted quite heavily, with an increased amount of lanes. The final template consisted of the following stakeholder lanes:

- Upper management
- Product owner (part of the HW development team)
- HW Developer / Expert
- Technical Services
- Suppliers
- Testing & Validation
- Supplier Development Team
- Supply Management
- ELMEC (Electromechanical)

It was decided to split the development team into a product owner lane and a developer/expert lane, the reason being to distinguish between management-related activities and engineering-related activities. Additionally, these two lanes consisted of the most amount of tasks. A stakeholder map was created to better grasp the stakeholders'

contribution to the HWDP (Figure 14) afterwards. The stakeholder map is organised into three major sections:

- **Core team:** The core team includes the HW development (HW developer / Expert and Product Owner), Testing & Validation, and Suppliers. These departments are the key decision-makers in the project, ensuring that the project is completed on time.
- **Involved:** The involved consists of the Supplier Development Team and Supply Management. These departments are not part of the core team but work closely with them, attending regular meetings where the core team is gathered and provides input or helps to move work forward.
- **Informed:** The informed comprises Senior/Upper management, Technical Services, and ELMEC. These departments mainly want to stay up-to-date with project progression and provide feedback/consultation when necessary.

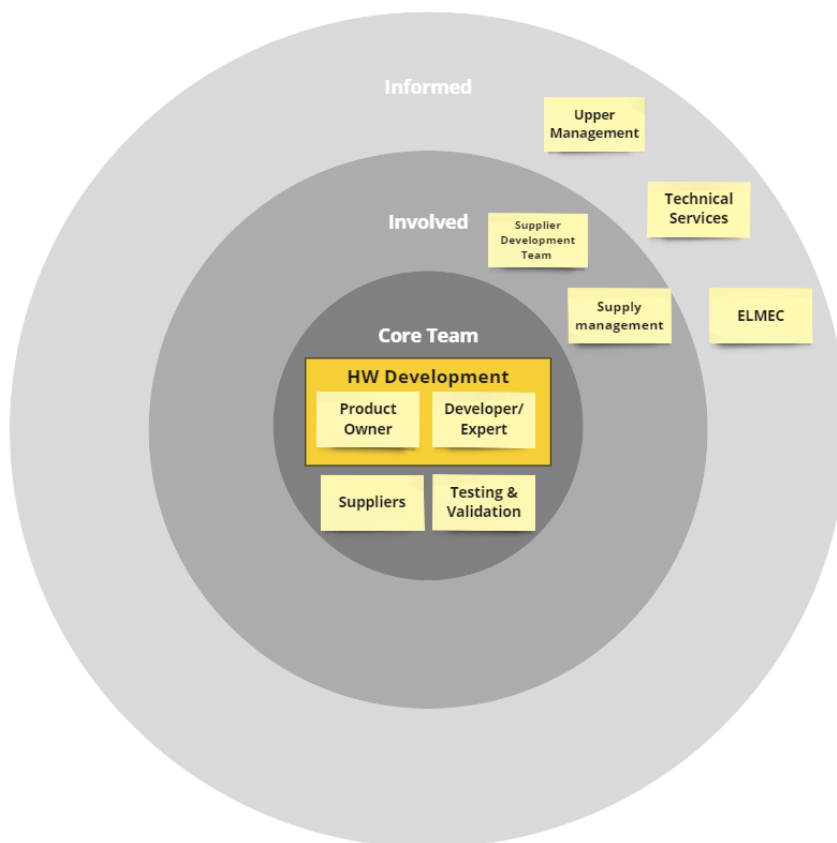


Figure 14. Stakeholder map

4.3.2 Current state mapping

During the current state VSM workshop, the current situation of the HWDP was mapped in the produced VSM template. The procedure for mapping the activities and information flows was facilitated by the thesis author. The existing process flow chart of the HWDP (Appendix 1) was the main guideline during the mapping phase. All participants had access to the virtual mapping board and contributed via there. The main approach during the mapping workshops was to follow the existing process flow chart of the HWDP one task at a time and then elaborate on the critical information flows and dependencies related to that task. After the mapping stage, all of the activities were gone through and tagged as Value Added (VA), Non-Value-Added (NVA), or Required Non-Value-Added (R-NVA). This classification phase was done to achieve a categorised value stream displaying how each activity contributes to the process. The activities were tagged from a process perspective, i.e., how they benefit/counteract the process. The activities were tagged in teams where the teams of the different departments tagged their own tasks. Since not a participant from all of the stakeholder lanes was present, the whole group defined these tasks. After activity tagging, they were reviewed and either accepted or declined to have the correct tag. Those tasks that caused conflicts were further discussed.

4.4 Current state findings and analysis

The findings and analysis chapter focuses on the information flow, task value assessment, and issue identification of the current state of the HWDP. Furthermore, improvement suggestions are discussed and listed.

4.4.1 Information flow

The produced current state VSM can be seen in Appendix 3. By observing the current state map, it can be seen that the main focus is set on mapping out the activities of the HW development team, suppliers, and testing & validation; thus, their tasks are perhaps

more detailed than the other lanes. The main reason that these tasks are more detailed is due to their high impact in achieving an efficient process and complete product.

However, the other stakeholder lanes play an equally important role because their sub-processes create dependencies for the main development activities. I.e., due to the complexity of all the entangled dependencies and information flow, the cooperation and communication must flow smoothly and need to be clearly visualised between the departments in order to achieve a lean process. Iterations can be identified, but it is difficult to define how extensive and crucial these are; therefore, it was decided to investigate these issues more deeply with the help of a DSM (Chapter 4.6).

The mapping symbols used during the workshop were limited to the information flow arrow, activity, and review/decision/approval symbols. No delay symbols were utilised to decrease the number of symbols mapped, resulting in better accessibility when analysing the current state map. However, delays were later discussed and documented in the sense of where they occur in the process.

4.4.2 Outsourcing

The outsourcing of the HWDP was a subject that was heavily discussed during the workshop since it is a significant factor in the development and as it was defined to be an area requiring improvements regarding communication and collaboration. Since the case company's HW development is often related to longer projects, there are often many iterations if technological problems occur. Projects are occasionally put on hold internally, mainly due to internal priorities, poor management planning, resource constraints or strategic or business-related changes. When the project is on hold, the suppliers also shift their focus towards other customers. Moreover, when the project is started again, there is a risk that the same individuals from the supplier side cannot be involved due to their new commitment and priorities towards other customers. New people must be included in the project, and there have to be new learning curves established, resulting in slow start-ups and delays.

Another issue is the misunderstanding of component requirements. With outsourcing, the suppliers must fully understand what is being developed and what the specified requirements are meant for. The requirements must be opened up and explored deeply to avoid looping with contacting and discussing what the purpose of the requirements is. It was noticeable that when selecting new suppliers, it is essential to focus on communication and collaboration skills, technologically related knowledge, and project management expertise. The way of working needs to be clear, and there needs to be a robust communication structure with the suppliers.

4.4.3 Value assessment

The amount of VA, NVA, and RNVA activities in the HWDP is visualised in Figure 15. In total, there are 47 VA, 16 RNVA, and 8 NVA activities. To further improve the HWDP, the value assessment chapter will focus on bringing up the NVA activities and discussing the major issues related to them. The goal of addressing the major issues related to NVA activities is to identify opportunities for process enhancement. This is done by further elaborating on the information and data from the workshop. Table 5 lists the NVA tasks and categorises them according to the type of waste. It can be seen that the majority of the NVA tasks are categorised as waiting (five tasks), followed by excessive processing (two tasks), and defects (one task). It was found in the literature review that the most common waste is waiting; this can also be concluded from this waste categorisation. The next step will be to list the issues and improvement suggestions in detail. Furthermore, to improve the accessibility of actually being able to implement the improvement suggestions, a summary of the issues and improvement suggestions in the NVA can be seen in Appendix 4.

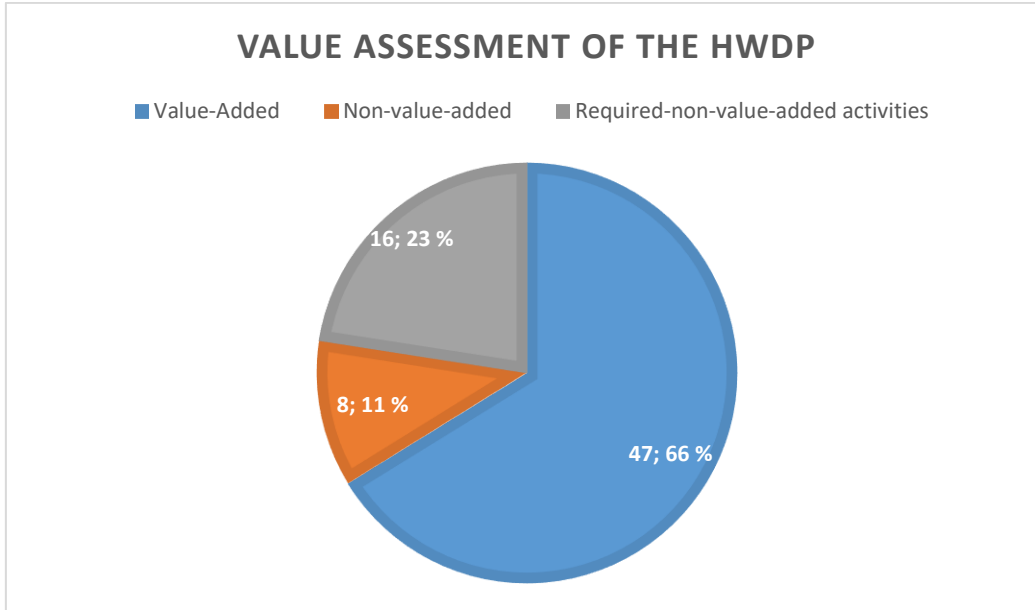


Figure 15. Value assessment of the HWDP

Table 5. NVA task categorisation

<i>Task name</i>	<i>Task type</i>	<i>Waste type</i>
<i>Scope review with stakeholders</i>	Review	Waiting
<i>Does order and contract exist</i>	Approval	Waiting
<i>Review test cases</i>	Review	Waiting
<i>Update test specification</i>	Activity	Excessive Processing
<i>TRs update</i>	Activity	Excessive Processing
<i>Review the change content of the TRs</i>	Review	Waiting
<i>Release meeting with stakeholders</i>	Review/Decision	Waiting
<i>Field test</i>	Activity	Defects

Scope review with stakeholders

The scope review is considered to be executed wrongly during the HWDP. In some cases, there have been scope creeps during projects, which have led to challenges in managing the project correctly. The stakeholders of the projects have shown that they do not fully grasp all the related requirements to the product and how they relate to the project's scope. Additionally, it is sometimes challenging to involve the correct stakeholders if the topic is complex and to integrate all of their requirements. As this NVA activity was defined as a review meeting, it has been seen that the stakeholders have not prepared

enough before the meeting to completely get engaged in the discussions and resolve potential issues and difficulties. This results in iterating the meeting due to stakeholders having to attain more profound knowledge regarding the product's scope.

The issues were addressed through several improvement suggestions. First, the possibility of implementing automated reviews was discussed. It could perform certain verifications such as document completeness, consistency, and compliance checks. This would allow for continuous updates of the project scope by ensuring that the necessary elements are included. Secondly, push the stakeholders to read up on the concept and requirement of a product and start tracking how well-prepared the stakeholders are. Thirdly, a stakeholder map visualising the expertise areas of the stakeholders should be mapped out to better know whom to contact for which issue.

Does order and contract exist?

This review task is related to the supplier selection process and the creation of the framework agreement, which is a type of contract. The contract on its own is value-added; however, the contract establishment often generates long lead times (up to nine months). Based on this issue, the case company might end up obtaining competence from an inadequate supplier, resulting in unfulfilled product requirements.

Based on these remarks, the supplier selection process needs to be of higher quality to understand the core competence of the suppliers in scope. This includes executing more detailed evaluations and site visits to gain hands-on experience with the supplier's competence. Furthermore, project management knowledge needs to be emphasised and confirmed that it is at the highest level to ensure that the projects are managed as efficiently as possible to minimise the potential risks.

Review test cases – Update test specification

The review test cases and update test specification activities will be described jointly. It was noticed that there is no outlined procedure for test case creation, and currently, the

validation of a product is done jointly by the developers and testers, making it hard to work systematically since the developers are not always trained in writing comprehensive test reports. This issue causes confusion and delays during the process due to excessive processing. Additionally, there are no strategies to avoid re-testing of a test case. This sub-process should be opened up, mapped out precisely, and analysed for inefficiencies. Furthermore, training materials regarding test report writing should be investigated.

Update TRS – Review and negotiate the change content

The loop of updating the TRS and then reviewing and negotiating the change content generates excessive processing and waiting. It was noticed that this is related to tracking how often the TRS is being updated during the project. Currently, there is no quick distribution of the updated content to the stakeholders. The review and negotiate change content is partly the same issue. E.g., if the TRS is updated, the contract needs to be re-negotiated, and if the product needs an exception even though the requirements are accepted, a new TRS document is needed. Based on this, it was concluded that the main issue is related to not having a sufficient traceability system while also not having a sufficient TRS created when the contract is signed with the supplier.

There needs to be more effort put into the TRS creation process so that it is complete when the contract is signed with the supplier. A set amount of allowed iterations could be specified in the process. Furthermore, A proper change action follow-up system should be implemented, which automatically distributes the source of the change and information to the stakeholders. This would allow for faster action points to be decided. E.g., a system could be implemented that alarms when a requirement has been updated, and it would show an overview of which test case that has to be updated.

Release meeting with stakeholders

During the investigation of the release meeting activity, it was noted that there is insufficient closed-loop feedback during the project timeline, i.e., the correct stakeholders

are not updated correctly about the critical events and milestones of the project. Furthermore, when it is time for the product release meeting, there are still a lot of opinions and questions in it. This results in unnecessary iterations of the release meeting. The primary purpose of the meeting is to synchronise between all stakeholders and agree that the product can be released.

To solve these issues, there were suggestions of creating a thorough list of the correct stakeholders, which indicates their impact and significance during the project timeline, and these need to be informed if there are critical changes and events that occur during the project. Furthermore, this goes well with the improvements listed in the previous activity analysis, pinpointing that a proper change action follow-up system should be implemented. In this case, the system could be utilised to resolve questions and concerns before the release meeting.

Field test

Lastly, there is the field test activity. This activity takes up much time; the product must collect a significant amount of operating hours before getting fully released. There are issues seen with establishing the contract of allowing a not fully released product to start running on a customer's systems. This often takes much time, as it requires locating the correct customer willing to be responsible for implementing the not fully released product. Overall, this activity is rather crucial and cannot be done in other ways at the moment. However, there was discussion that there might be a potential to research into more improved environmental tests that could replace/shorten this extensive test and bring out the potential risks and defects as accurately as the field test. This would result in a considerable efficiency improvement in the process.

4.5 Design Structure Matrix

A DSM was generated based on the mapped current state from the VSM workshop (Appendix 5), collecting all stages from concept development to ramp-up. A partitioned version of the DSM can be seen in Appendix 6. The DSMs visualise the dependencies and relationships between the activities in the HWDP and will aid in the operation of knowing if a particular decision or task could be made earlier in the process. A total of 71 tasks are listed within the DSM, which can be considered a hefty amount. To better be able to analyse the DSM:

- The listed tasks were coloured-coded to distinguish which department/role performs which task (Table 6).
- The most extensive feedback loops were marked with a grey symmetrical square within the DSM to identify them better.

Table 6. DSM task colour-coding

Colour Coding:

Upper Management / Stakeholders
Product Owner
Developer/Expert
Technical Services
Suppliers
Testing & Validation
Supplier Development Team
Supply Management
ELMEC

4.5.1 DSM analysis

By observing the generated DSM, it can be seen that there are several extensive feedback loops, where the largest ones occur in the middle of the process. These feedback loops result in unnecessary rework within the HWDP, causing long project execution times. The colour coding shows that close collaboration and communication between departments are needed at the beginning of the process. However, the colour coding also indicates that there might be some collaboration and communication issues since

the testing & validation department and suppliers are included somewhat later in the process compared to the other departments. The workload distribution between departments could be considered somewhat imbalanced since most tasks are dedicated to HW development, suppliers, and testing & validation. Moreover, this could result in bottlenecks within the process, causing delays and wait time issues.

The DSM was partitioned to get the feedback loops as close to the diagonal as possible. There is a clear difference between the original DSM and the sequenced one, as it can be seen that the most extensive feedback loops have been eliminated and turned into smaller continuous loops in the middle of the DSM. So, with the new DSM, there are more feedback loops, but they are more compressed than in the non-partitioned DSM, and most of them are one-step loops. It was also identified that the smaller loops in the middle of the DSM would be hard to execute in the defined order. Therefore, it is difficult to tell if the re-ordering can be implemented as a new way of working in the HWDP. However, both the unpartitioned and partitioned DSM can be used as guidelines in a future state mapping workshop, optimising the information flow within the process to streamline information exchanges, eliminate redundant flows, and reduce dependencies.

4.5.2 DSM simulation

A task transition probability simulation was executed on the non-partitioned and partitioned DSM. The simulation was done to compare the structural differences between the two DSMs. The simulation input was based on in-process time assumptions on the listed tasks in the DSM. The assumptions consisted of a minimum, likely, and maximum assumption of in-process time. Furthermore, the task transition probability was defined as 80 % on all tasks under the diagonal and the rework probability to 20 % on all the tasks above the diagonal. Two tests consisting of 100 simulations were run to get a sufficient result. The exact simulation input was used in both tests. Figure 16 and 17 visualises the simulation results. This result suggests that there would be a 50 % decrease in lead time. It is evident that the structural differences between the two DSMs' simulation outputs play a fundamental role. However, a 50 % lead time decrease can be considered

rather optimistic since achieving such a large decrease in lead time demands fully grasping the process and understanding the availability of resources and actual implementation of the partitioned process. Furthermore, it is essential to consider that the stability and quality of the process might be reduced if the efficiency of a process is heavily increased.

Due to the limitation of the data used only consisting of assumptions, the findings cannot be fully relied on and should be evaluated with caution. The result is also not a final output of the lead time reduction but rather some initial indicators of how much it can be decreased in theory. Therefore, it would be important to run a similar simulation with more gathered data on the actual in-process times and task transition and rework probabilities. This data could be estimated, e.g., by experts in the process or by historical data documented on the tasks.

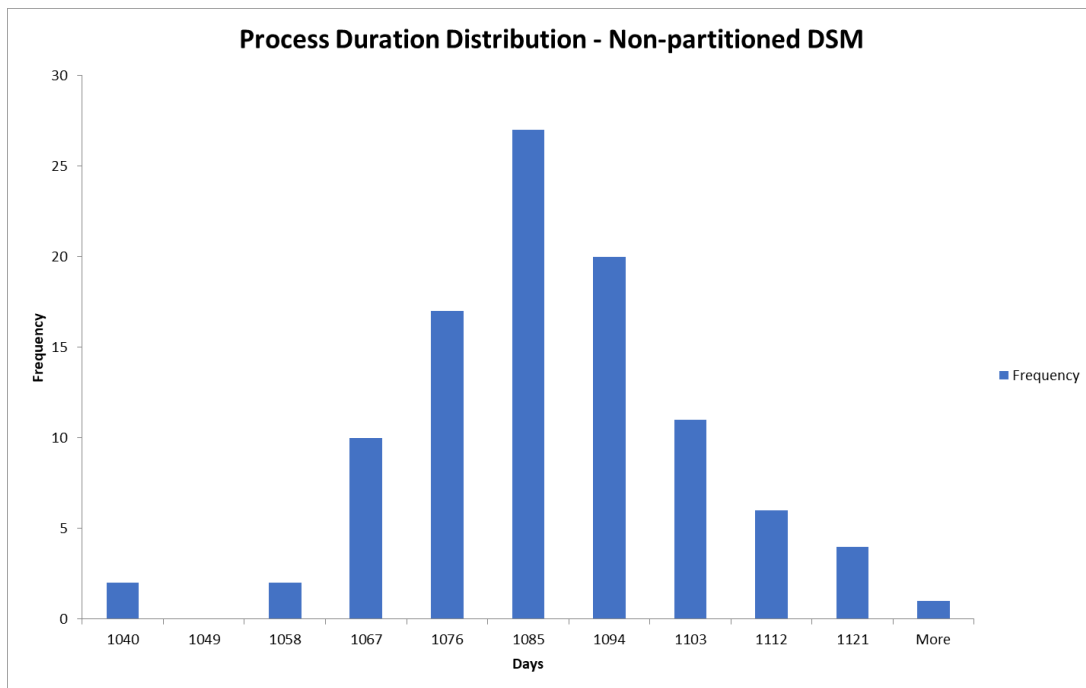


Figure 16. Simulation results – Non-partitioned DSM

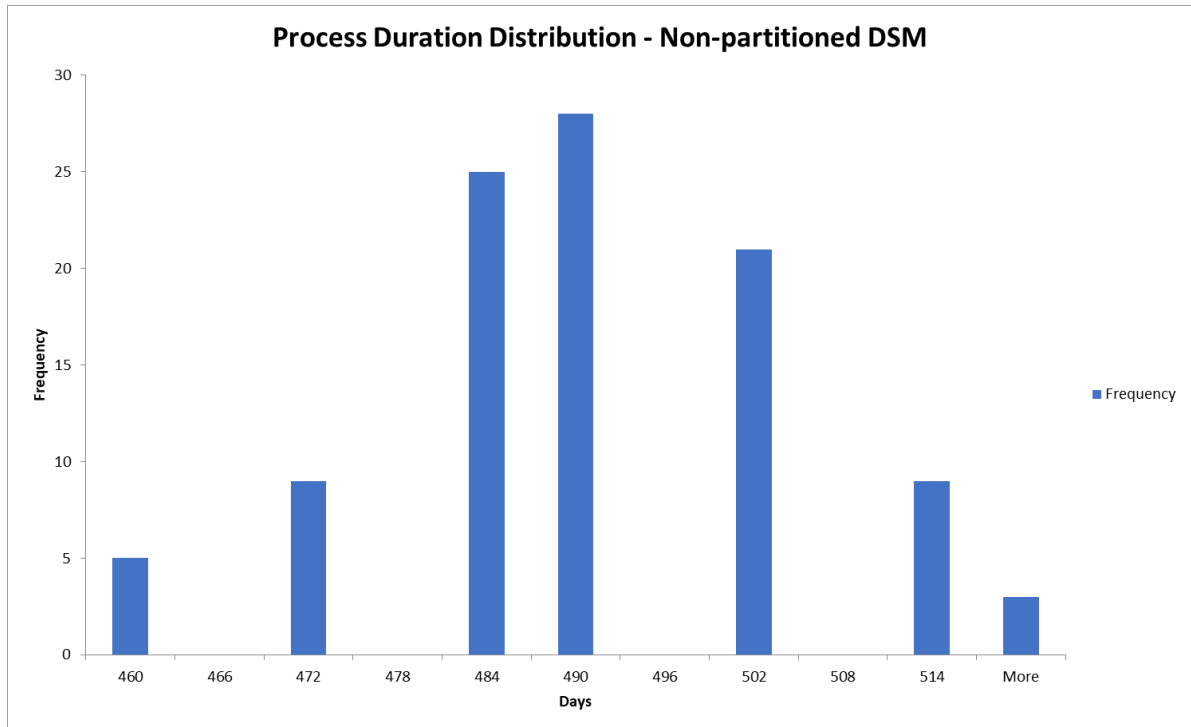


Figure 17. Simulation results – Partitioned DSM

4.6 Future state VSM

Unfortunately, there was no official future state VSM workshop due to the time limit of the thesis; thus, a new process of the HWDP will not be proposed, including any of the identified findings. However, a cross-functional flowchart based on the current state map was created. This topic is elaborated more in chapter 4.7.

The recommended next step would be to arrange a future state VSM workshop, where the case project, VSM and DSM findings would be discussed and analysed with the main stakeholders. In the workshop, the main goal would be to:

- First, rank the improvement suggestions based on their impact and effort
- Second, try to streamline the process and eliminate iterative flows by adding or deleting tasks.
- Third, balance the workload and the resource utilisation to avoid bottlenecks in specific departments.

- Fourth, try to standardise processes and implement new technology enabling automated tasks and reviews.
- Fifth, implement key performance indicators which can be monitored and measured during future projects.

4.7 Novel Cross-functional diagram of the HWDP

Since there was not enough time to execute the future state mapping workshop, a new process flowchart of the HWDP was created in a cross-functional style (Appendix 7). However, creating the process flow chart did not consider the analysed findings or the partitioned DSM. It mainly illustrates the current state of the HWDP in a more streamlined format to avoid all of the entangled information flows. The process flow chart was made for all individuals involved in HWDP to better understand the whole picture of all the steps within the current process. The chart is mainly utilised by the core team, except the suppliers. When visualising the process in this style, it becomes more apparent which department executes which activity and the dependencies between activities and departments. By implementing a routine of following the cross-functional flowchart, communication and collaboration could potentially be increased. Furthermore, the new process flowchart is an excellent tool to use as background material when executing the future state mapping workshop.

5 Conclusions

Through the utilisation of lean tools, this thesis aimed to produce a comprehensive analysis to enhance the current state of the HWDP at the case company. The lean methodology and its implementation in engineering were conceptualised as fundamentally important when translating the results and discussions into a product development context, contributing to overall process improvement. The thesis was formed around two decisive research questions, which aimed to seek answers to how the process can be streamlined by identifying inefficiencies and proposing improvements and how cooperation and collaboration could be improved to reduce overall development lead time.

The empirical findings need to be categorised into two foundational elements: analysing a puzzling and drawn-out HW development project from a managerial and functional perspective combined with acquiring a holistic view of the HWDP by focusing on its related elements, consisting of communication, collaboration, and decision-making between different departments through the VSM and DSM tools. By utilising the case study methodology, it allowed for acquiring data from a real-life context. The research is mainly a qualitative study; however, many different research angles have been utilised, which enabled the recognition of diversity in the collected data and information. Quantitative data can mainly be seen in the case project analysis, where the output is formed on historical data from an ALM system and Internal documentation platform. Moreover, not only looking at the process itself but also including an analysis of a project carried out through it allowed for a comprehensive evaluation, providing insight into how the process functions in theory and has been put into practice.

The project analysis highlights the key points showing where and how the bottlenecks and implications have occurred. The analysis has pinpointed several challenges that have led to difficulties regarding the project's progression, resulting in an extended project timeline. Initially, the project was almost fully outsourced since both the concept development and first designs were done at the supplier, leading to a lack of in-house expertise and potential knowledge gaps when the project was transitioned to the case

company. The findings are related to outsourcing activities, internal scheduling, communication, and collaboration. The project's timeline was greatly extended because of several delays; thus, emphasising project planning and scheduling is crucial to facilitate effective project execution, reducing delays and managing dependencies. A clear technology knowledge gap has been identified, resulting in extensive rework and delay of the component development. Since projects within the hardware development sector are often rather complex, they require a broad range of expertise. Therefore, more focus needs to be put into understanding the project requirements internally and with the suppliers, ensuring that a holistic understanding of the component is achieved, not only understanding the standalone functionality of the component but also grasping how it is integrated and utilised in the more extensive system.

Mapping out the current state of the HWDP was a critical contribution toward identifying waste inefficiencies and improving communication and collaboration. The approach involved going through the current state on a higher level with the main stakeholders and identifying VA, NVA, and RNVA activities, which contributed to assessing the activities' impact on the process. Firstly, a general observation from the current state mapping session was that outsourcing was a hotly debated topic. Since there is a significant need for outsourcing, a strong communication structure with the suppliers is crucial to execute projects effectively. In order to achieve this, the supplier selection process should consider the following aspects: communication and collaboration skills, technologically related knowledge, and project management expertise. Furthermore, the product's requirements to be developed must be clearly defined to avoid misunderstandings and looping conversations regarding the requirement definitions with the supplier. Secondly, the current state analysis provided a value assessment of the mapped tasks, resulting in 47 VA, 16 RNVA, and 8 NVA activities. The NVA activities were categorised based on their task type and waste type providing a detailed description. These activities were further elaborated on by outlining their crucial issues and focusing on providing detailed improvement suggestions to them. The focus was on improving stakeholder communication and engagement, supplier relationships, testing processes, change management,

release meetings, and field testing. All the improvement suggestions contribute towards achieving a streamlined process and enhancing cooperation and collaboration to reduce development lead time.

The cross-functional current state VSM effectively captured the dependencies and information flow between the departments. In some parts of the map, the amount of information flowing between the groups was heavily entangled when analysing the map. Ultimately, it became evident that another tool was needed to sort out this mess: the DSM. Utilising the process architecture DSM enabled powerful visualisation of the process's relationship between tasks and activities. Utilising the partitioning algorithm on the DSM allowed for structurally changing the process by minimising the iterative loops. Two simulations were run to see how much the lead time may be reduced based on the structural changes between the non-partitioned and partitioned DSMs. When the simulation results were compared, the partitioned DSM showed a 50% reduction in lead time. This indicates that minimising the large iterative loops decreases the lead time effectively. Unfortunately, the possibility of fully implementing the new structure cannot be answered since the re-ordering is only based on an algorithm instead of careful evaluation by the stakeholders. Furthermore, since there was no collection of time data on the tasks and activities, the DSM simulations had to be executed through assumptions, putting limitations on the simulation results in terms of reliability; however, the results could still be utilised as initial indicators of how the lead time could be decreased in theory.

Since the current state was only mapped to a higher level, sub-processes within the HWDP could be opened up and explored further for NVA activities. On the other hand, mapping the current state to a higher level provided a more extensive overview, resulting in an increased understanding of how communication and collaboration could be improved. Converting the mapped current state into a cross-functional process flowchart enables a more transparent and holistic approach towards working together in future projects by placing the related tasks and activities in their specified department lane.

Based on the analysis, there are several managerial implications to consider:

- Holistic Process Overview – managers should focus on enhancing communication, collaboration, and decision-making across the different departments involved in the HWDP. Effective communication is vital, and a transparent flow of information between departments reduces inefficiency and aligns the teams toward the same goal.
- Effective outsourcing – the suppliers should be carefully selected based on their technical expertise, managerial skills, and communication and collaboration competence. A clear internal and external understanding of product requirements is crucial to prevent misunderstanding and enhance project execution.
- In-house expertise development – a broad range of expertise needs to be developed to achieve a comprehensive understanding of the components and their integration into the more complex system. This includes having a thorough understanding of the project requirements both internally and with the suppliers.
- Effective project planning and scheduling – emphasis should be placed on effective project planning, scheduling, and managing dependencies in alignment with the SAFe framework to meet the project timeline.
- Continuous improvement – strive for continuous improvement by encouraging teams to evaluate the process, identifying wastes, and proposing improvements.

It can be concluded that the thesis has effectively answered the two identified research questions. The research question “How can the process be streamlined by identifying inefficiencies and proposing improvements?” is addressed through the case project analysis and current state findings by highlighting challenges related to outsourcing, communication, technology knowledge gaps, and project planning and scheduling. By using VSM and DSM, it has been possible to effectively capture the process's current state, visualising all the wastes and bottlenecks. Improvement suggestions have been identified from the value assessment, including an analysis of VA, NVA, and RNVA activities. The second research question, “How can cooperation and collaboration be improved to reduce overall development lead time?” was answered by highlighting the importance

of communication and collaboration in the HWDP. By implementing the VSM and DSM together with the analysis, it has become evident that there is a need for better communication between the involved departments, including the suppliers. All the identified improvement suggestions contribute towards achieving improved cooperation and collaboration to reduce the overall lead time, and additionally, utilising the partitioning algorithm allowed for structural changes in the process where the iterative loops were minimised. This adjustment can potentially decrease the overall lead time by 50 %.

Undoubtedly, this extensive investigation of the specified hardware development process can be considered a successful outcome as it has provided a comprehensive overview by highlighting the essential aspects that contribute to a more streamlined and enhanced process. Even though the implementation phase could not be executed, the thesis's output still produces a critical value that hopefully could be utilised in attaining an optimal future state of the process. Ultimately, as one of the earliest statements in the thesis claims, to secure a competitive advantage in product development, one must strive to achieve perfection in the process.

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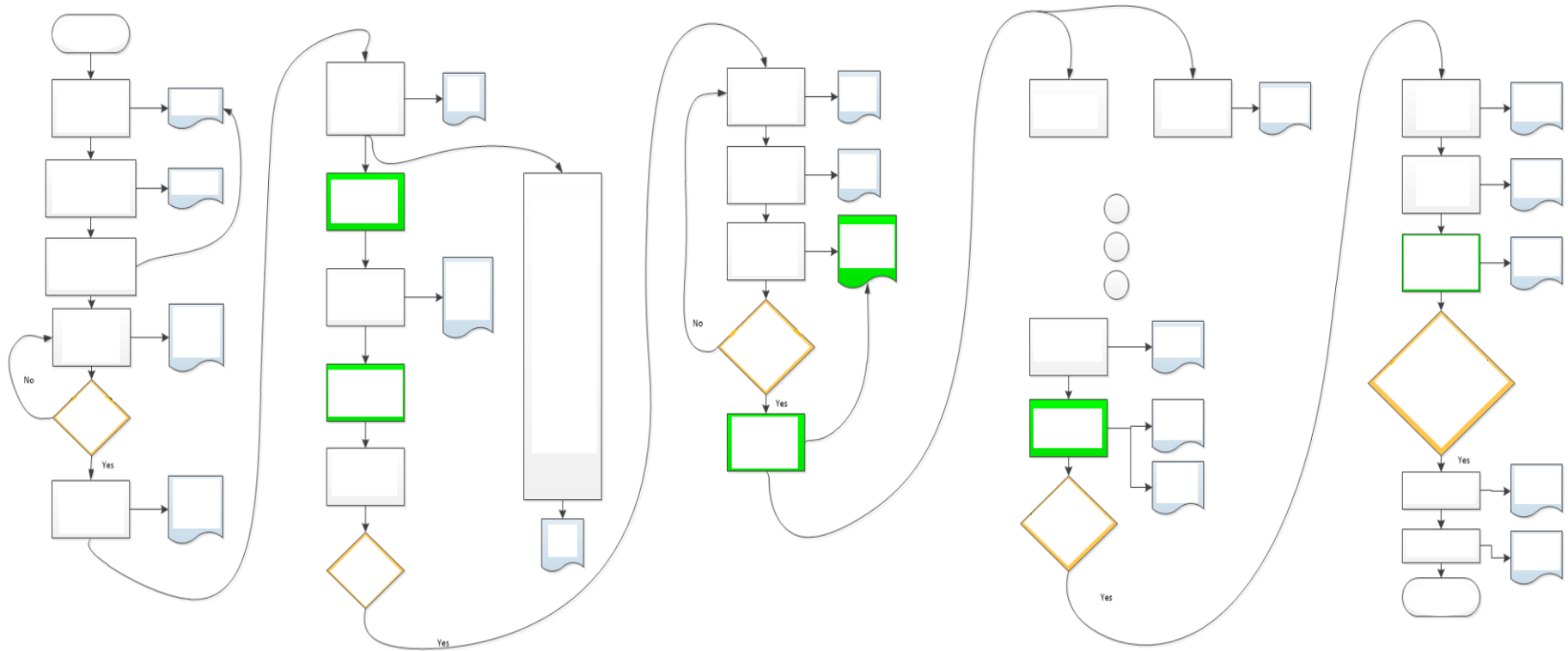
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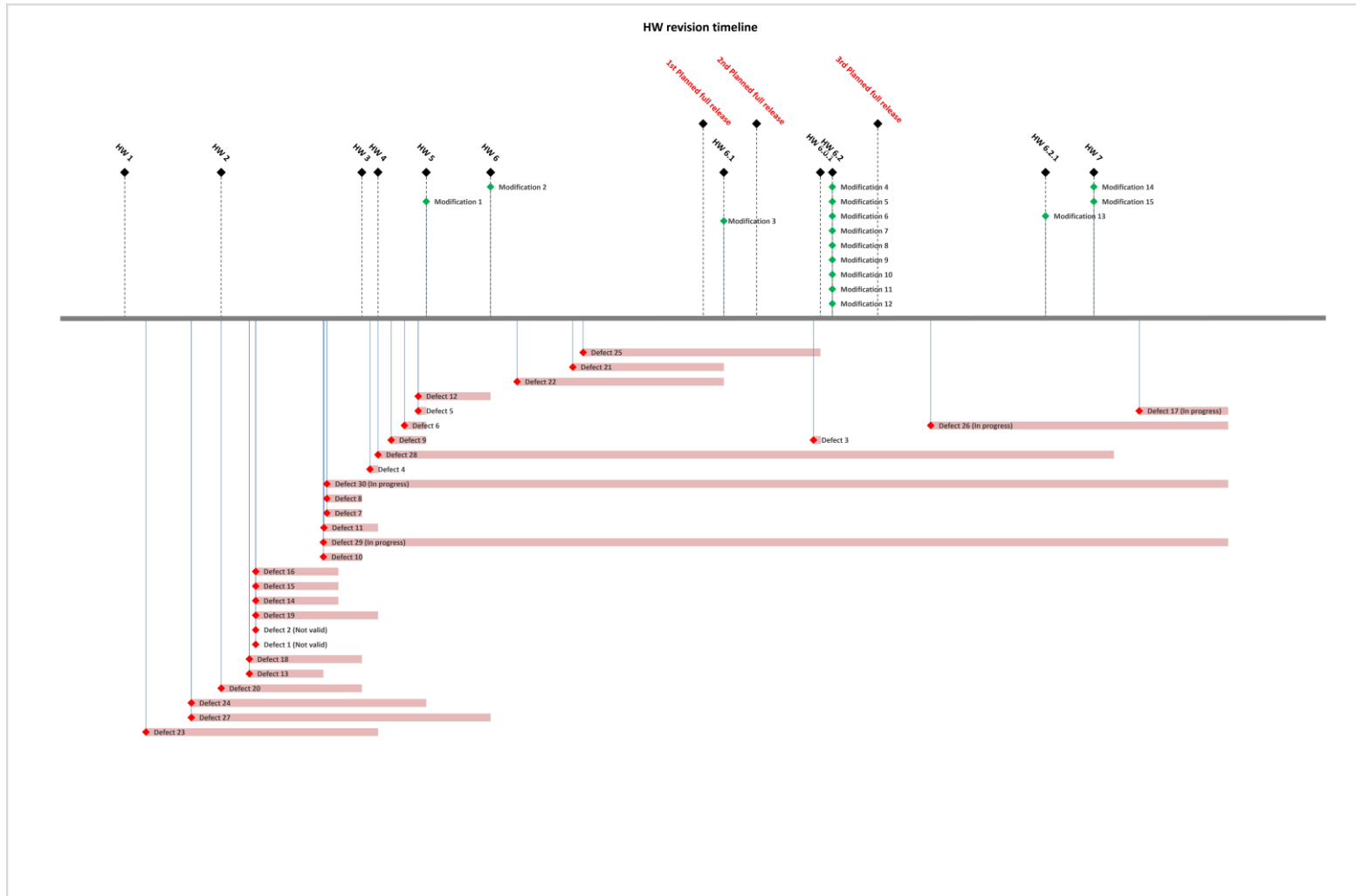
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Appendices

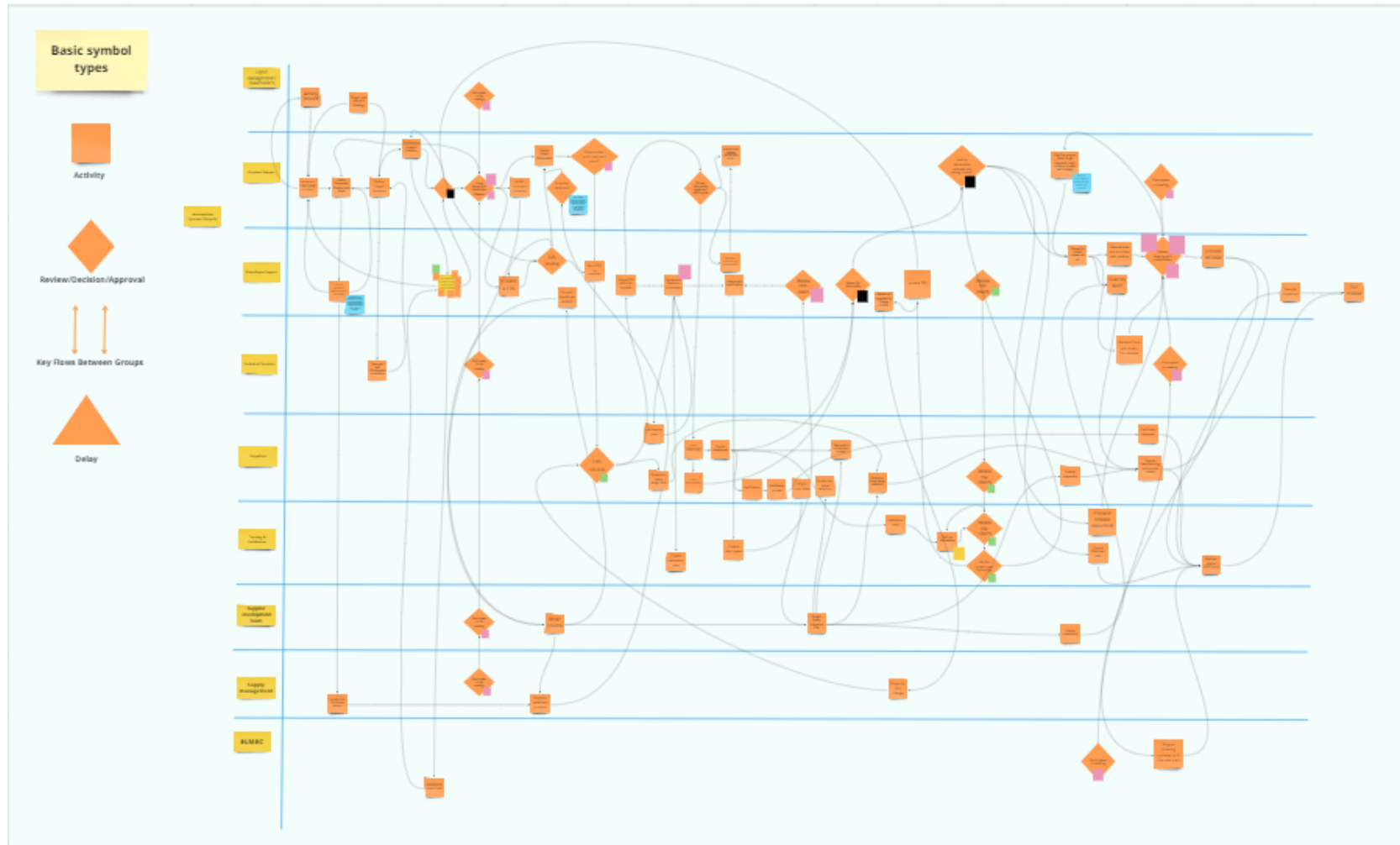
Appendix 1. Existing hardware development process



Appendix 2. Hardware revision timeline of the case project



Appendix 3. Current state value stream map

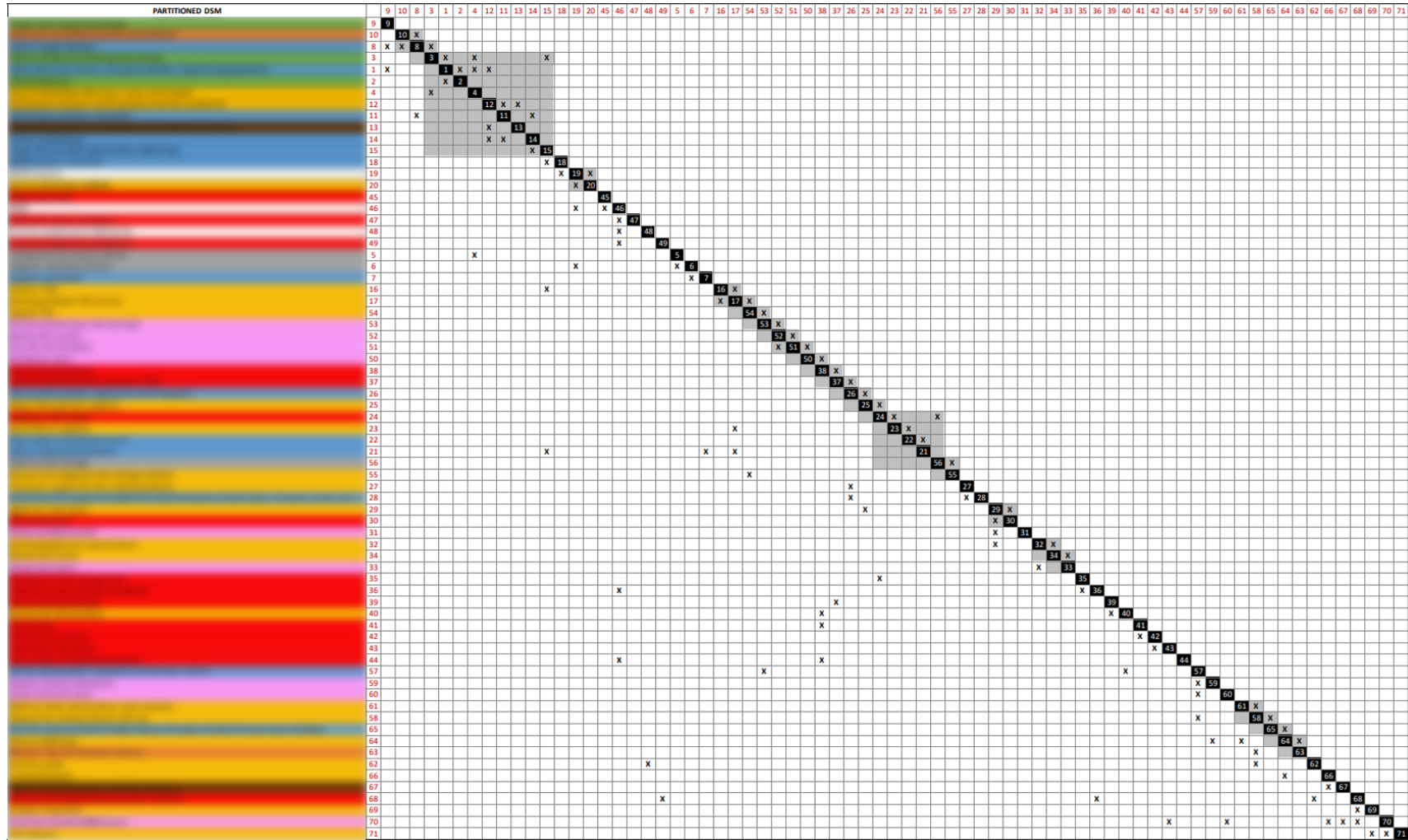


Appendix 4. Summary of non-value added issues and improvement suggestions

Activity Name	Issues	Improvements
Scope review with stakeholders	<ul style="list-style-type: none"> - Scope creep during projects leading to challenges in project management. - Stakeholders not fully grasping project requirements and scope. - Difficulty involving correct stakeholders for complex topics. - Stakeholders not adequately prepared for review meetings, resulting in iteration. 	<ul style="list-style-type: none"> - Implement automated reviews for continuous updates of project scope. - Push stakeholders to read up on product concepts and requirements. - Create a stakeholder map which visualises their core expertise.
Does order and contract exist?	<ul style="list-style-type: none"> - Long lead times (up to nine months) in establishing supplier contracts, potentially leading to obtaining services from inadequate suppliers. 	<ul style="list-style-type: none"> - Execute more detailed evaluations and site visits to understand suppliers' core competence. - Emphasise project management knowledge on the supplier and ensure high-level management to minimise project risk effectively.
Review test cases – Update test specification	<ul style="list-style-type: none"> - No outlined procedure for test case creation, causing confusion and delays. - No strategies to avoid re-testing of a test case 	<ul style="list-style-type: none"> - Open up and map out a precise process for test case creation. - Analyse the process for inefficiencies and make necessary improvements.
Update TRS – Review and negotiate change content	<ul style="list-style-type: none"> - Generates excessive processing and waiting due to updating the TRS multiple times during the project. 	<ul style="list-style-type: none"> - Specify a set amount of allowed iterations for TRS updates. - Implement a change action follow-up system to distribute change information to stakeholders

	<ul style="list-style-type: none"> - No quick distribution of updated TRS content to stakeholders, leading to contract renegotiation and a new TRS document. 	<p>automatically.</p> <ul style="list-style-type: none"> - Implement a system to alarm when a requirement is updated and identify which test cases need to be updated.
Release meeting with stakeholders	<ul style="list-style-type: none"> - Insufficient closed-loop feedback during the project timeline, leading to stakeholders not being updated about critical events and milestones. - Unnecessary iterations of the release meeting due to opinions and questions not being addressed beforehand. 	<ul style="list-style-type: none"> - Create a thorough list of correct stakeholders indicating their impact and significance during the project. These need to be informed about critical changes and events. - Implement a proper change action follow-up system to address and resolve questions and concerns before the release meeting.
Field test	<ul style="list-style-type: none"> - Field test activity takes much time, requiring 3000 hours of operation before full release. - Challenges in establishing contracts for not fully released products running on a customer's system 	<ul style="list-style-type: none"> - Research into improved environmental tests that can replace/shorten the extensive field test while still bringing out potential risks and defects as accurately as the field test

Appendix 6. Partitioned DSM



Appendix 7. Novel cross-functional flowchart of the HWDP

