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Adopting Virtual Reality into the New Product Development Process

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Life is a challenge – you either take it head on, enjoying the ups and enduring the downs, or runaway and learn nothing, potentially regretting the lost experience. My adventure thus far has, to say the least, been an uphill challenge. I have many people in my life that I would like to give my deepest gratitude towards for helping me get to where I am today. To my supervisors, Anna Granlund, Mats Ahlskog and Jessica Bruch, for continuously challenging me and thus expanding my thinking. To Viktorija Badasjane and Natalie Agerskans, for all the discussions, laughing, crying, brainstorming, and getting through writers block – to Helena Blackbright and the rest my MDU colleagues for supportive talks and holding me up when I was sinking – to all of my Volvo colleagues and mentors, Joakim Carlborg, Ulrich Faß, Anna Ericson Öberg, Matilda Lagerkvist and many more, for welcoming me and supporting me through this endless book writing– to my loving husband Nathan Zimmerman, for your endless support through this chapter of our lives together, and to our fur babies, Björn and Sigrid, for reminding me that life has far more pillars of meaning that should also be enjoyed.

Barrett Michael Sauter
Västerås, Sweden
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Abstract

While Virtual Reality (VR) is recognized as a promising technology for design reviews, virtual prototyping and cross-functional collaboration, many manufacturing companies struggle to move beyond pilots and isolated use. A process on the adoption of VR is lacking, stemming from organizational know-how, process changes, and technology integration into existing systems. Prior research often treats these people, process and technology dimensions separately and offers limited insight into how adoption unfolds in practice over time. Therefore, the purpose of this thesis is to facilitate the adoption of VR technology into the New Product Development (NPD) process by holistically considering the dimensions of people, process, and technology. The research is based on two retrospective multiple case studies in two large manufacturing companies in the automotive and heavy vehicle industries. Empirical data was collected through a survey, semi-structured interviews, internal documents, observations and informal discussions. This resulted in the study of VR adoption at multiple organizational levels (e.g. strategic, tactical, and operational) explored among three appended papers and this thesis.

The findings show that challenges related to VR adoption primarily concern misalignments between people, process and technology across strategic, tactical and operational levels. Identified challenges include a lack of clear ownership and roles, dependence on key users, lack of time to prepare VR and standardized ways of working, unstructured VR use in the NPD process, cumbersome workflow surrounding VR software, and demanding VR preparation and data handling. To address these challenges, the thesis identifies seven mitigations, including establishing dedicated facilitators and key user roles, securing management commitment, establishing ownership of Virtual Reality work, strengthening vertical alignment, reducing data complexity and planning VR adoption as a staged, long-term maturity process.

Overall, the thesis contributes a holistic, process-oriented, multi-organizational level understanding of VR adoption in NPD processes and provides empirically driven guidance on how to design and steer VR adoption towards sustained, value-adding use in manufacturing. Additionally, this thesis makes theoretical contributions by investigating VR adoption through a multi-organizational understanding of people, process, and technology dimensions, thereby uncovering new challenges and mitigations. A VR adoption process is also identified, bridging the gap between initial adoption and mature adoption and a roadmap for VR adoption is presented, compiling a combination of vital VR adoption variables, which had been previously presented as standalone in literature.

Sammanfattning

Virtuell verklighet (Eng: VR) är idag erkänt som en lovande teknik för designgranskningar, virtuell prototypframtagning och tvärfunktionellt samarbete i tillverkningsindustrin. Trots detta upplever många tillverkningsföretag utmaningar att, utöver i pilotprojekt och isolerad användning, utnyttja VR. En process för VR-införande saknas, vilket härrör från organisatorisk kunskap, processförändringar och teknikintegration i befintliga system. Tidigare forskning inom VR har hitintills oftast behandlat aspekterna kring människan, process och teknik separat och erbjuder därför begränsad insikt i hur införande utvecklas i praktiken över tid. Därför är syftet med denna avhandling att underlätta införandet av VR i produktutvecklingsprocessen genom dimensionerna: människan, processer och teknologi. Avhandling är baserad på två retrospektiva fallstudier genomförda på två stora tillverkningsföretag inom fordonsindustri. Empirisk data samlades in genom en enkät, semistrukturerade intervjuer, interna dokument, observationer och informella diskussioner. Detta resulterade i en studie av implementering av VR på flera organisatoriska nivåer (t. ex. Stategisk, taktisk och operativ) som utforskades bland tre bifogade artiklar och denna avhandling.

Resultat visar sig att de samtliga utmaningar vid VR införande främst gäller skillnader i bristfälligt samspel mellan människor, processer och teknik på strategiska, taktiska och operativa nivåer. Följande utmaningar vid införandet av VR identifierades: brist på tydligt ägarskap, brist på tydliga roller, personberoende knutet till nyckelanvändare, brist på tid att förbereda sig för VR och standardiserade arbetssätt, icke standardiserade arbetssätt i produktutvecklingsprocessen, krångligt arbetsflöde kring VR-programvara, krävande förberedelsearbete samt omfattande datahantering. För att hantera dessa utmaningar identifierade denna avhandling sju åthärder: etablera dedikerade facilatorer och viktiga nyckelanvändarroller, säkra ledningens engagemang, etablera ägarskap för VR-arbete, stärka den vertikala anpassningen, minska datakomplexiteten och etablering av en etappvis och långsiktig mognadsprocess för införande av VR.

Sammantaget bidrar avhandlingen med en flernivå- och processorienterad förståelse av införande av VR i produktutvecklingsprocessen samt ger empiriskt driven vägledning för hur VR initiativ kan utformas och styras mot en hållbar och värdeskapande användning inom tillverkningsindustrin. Dessutom bidrar denna avhandling med teoretiska bidrag genom att undersöka införande av VR genom ett människa-, process- och teknikperspektiv, och därigenom avslöja nya utmaningar och begränsningar. En VR-

införandesprocess identifieras också, som överbryggar klyftan mellan initial införande och mogen införande, och en färdplan för VR-införandesprocessen presenteras, some sammanställer en kombination av viktiga VR-införandesvariabler, vilka tidigare presenteras som fristående i litteraturen.

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. Sauter, B., Granlund, A., Ahlskog, M., Bruch, J. & Badasjane, V. (2023). Integrating XR technologies in the product realization process: Current approaches and challenges. In *26th EurOMA conference EurOMA23, 3-5 July 2023. Leuven, Belgium.*

Contribution: Sauter wrote the paper, with input from all authors. Sauter conducted the literature review, data collection and data analysis. All authors contributed to the study's conception, design, reviewing and editing. Sauter was the corresponding author and presented the conference paper.

II. Sauter, B., Granlund, A., Badasjane, V. Ahlskog, M. & Bruch, J. (2024). *What not to do: VR implementation teams and the barriers that inhibit them*. In J. Andersson, S. Joshi, L. Malmsköld & F. Hanning (Eds.), *Sustainable production through advanced manufacturing, intelligent automation and work integrated learning,* Vol. 52, pp.453-463. IOS Press.

Contribution: Sauter wrote the paper with input from all authors. Sauter conducted the literature review, data collection and data analysis. All authors contributed to the study's conception and design. Granlund and Ahlskog contributed to writing, reviewing and editing. Sauter was the corresponding author and presented the conference paper.

III. Sauter, B., Ahlskog, M., Granlund, A. & Bruch, J. (XXXX). Achieving Adoption of Virtual Reality in the New Product Development Process: Key decisions and implementation activities. *[Submitted]*.

Contribution: Sauter conducted the literature review, data collection, data analysis. Sauter wrote the paper with input from all authors. All authors contributed to the study's conception, design, reviewing and editing.

Additional publications by the author, not included in the thesis.

Ahlskog, M., Badasjane, V., Granlund, A., Bruch, J., Sauter, B. (2022). *Differing Views of the Meaning of Digital Transformation in Manufacturing Industry*. In H.C. Ng Amos, A. Syberfeldt, D. Högberg & M. Holm (Eds.), *SPS2022,* Vol. 21, pp. 331-340. IOS Press.

Ahlskog, M., Granlund, A., Badasjane, V., Bruch, J., Sauter, B. (2023). Approaching digital transformation in the manufacturing industry- challenges and differing views. *International Journal of Manufacturing Research*, 18(4), pp. 415-433.

Badasjane, V., Granlund, A., Ahlskog, M., Bruch, J., Sauter, B. (2023). Adapting the organizational structure for coordinating the digital transformation. In *26th EurOMA Conference. 3-5 July, 2023. Leuven, Belgium.*

Ahlskog, M., Granlund, A., Badasjane, V., Sauter, B. (2024). *Paradoxes in the Digital Transformation of Production Systems*. In J. Andersson, S. Joshi, L. Malmsköld & F. Hanning (Eds.), *Sustainable production through advanced manufacturing, intelligent automation and work integrated learning,* Vol. 52, pp. 244-255. IOS Press.

Badasjane, V., Ahlskog, M., Granlund, A., Bruch, J., Sauter, B. (2025). Navigating through uncertainties: coordinating digital transformation in international manufacturing networks. *Journal of Manufacturing Technology Management*, 36(9), pp. 1-18.

Contents

Abbreviations

DFMA	Design for Manufacturing and Assembly
DOI	Diffusion of Innovation
NPD	New Product Development
TTM	Time to Market
VR	Virtual Reality

1 Introduction

This section presents the research background, the problem statement, the research purpose and research questions, and the scope of this thesis.

1.1 Background

Customer demands are changing in today's manufacturing market, evolving toward convenience and digital interactions while increasingly emphasizing environmental changes, to name a few (Lundin & Kindström, 2023; McKinsey, 2021; Steward et al., 2019). To remain competitive, manufacturing companies must reduce time-to-market (TTM) for new products, which requires adapting the new product development (NPD) process to shorten the time from design to market while maintaining product quality (Lyu et al., 2022; Wu et al., 2020). A common approach includes integrated product development (Kang et al., 2022). However, the need to continue to decrease TTM brings new challenges to manufacturing companies. Virtual reality (VR) may be one technology bringing new opportunities to the forefront that manufacturers can harness to continue their strategic approaches toward decreased TTM (Freitas et al., 2022; Soori et al., 2024). VR-related research has steadily increased across multiple areas, such as automotive, engineering, construction, and heavy machinery industries (Jalo et al., 2022; Saghafian et al., 2021; Ventura et al., 2020). VR adds value through an increased ability for decision-making (Berg & Vance, 2017; Sekaran et al., 2021), improves workflow efficiency thereby accelerating design processes (Wolfartsberger, 2019), and increases product quality through increased fault detection in early design stages of the product (Wolfartsberger, 2019).

To achieve these benefits, VR, like any technology, must be adopted into the organization in a way that enables performance increases (Kim & Chung, 2017). Among other adoption variables, the process through which technology is adopted is vital for achieving the desired outcome of the task. The adoption process is a sequence of phases that a potential adopter of a technology passes through before the acceptance of the technology (Rogers, 2003). This process of adopting technology, including VR, into a manufacturing company takes time, requiring that the technology work technically as well as provide benefits to the company (Le et al., 2023; Voss, 1992). Arguably, technology adoption is simply the continued usage of technology due to the added benefits, performance, and impact it creates.

Technology adoption is based on the performance increase and the added value it brings (Kim & Chung, 2017). Three dimensions: people, process, and technology, are described as important dimensions to consider during technology adoption. The people dimension incorporates the human aspect, which is a key element that manufacturing companies should manage to successfully transition toward using a new technology (Kaasinen et al., 2020). The process dimension relates to the NPD process, including underlying sub-processes and work procedures as well as the changes to be made. The technology dimension refers to the tools and technologies already in use at the organization as well as new incoming technology.

Manufacturing companies are becoming increasingly aware of the potential that VR has to offer. In one study, approximately 60% of manufacturers surveyed reported being well aware of VR's potential, yet nearly 60% had also reported never using the technology (Jalo et al., 2022). Although the previously mentioned capabilities exist and are known, a process on the adoption of VR technology is lacking, including organizational know-how (Saghafian et al., 2021), process changes (Delgado et al., 2020), and technology integration into existing systems (Sekaran et al., 2021).

1.2 Problem Formulation

The adoption of VR technology consists of a myriad of intertwined factors, such as the technology and its integration into existing infrastructure, different stakeholders using the technology, and work procedures, further adding to the complexity. The adoption of VR technology into the NPD process causes incompatibilities in systems that affect people's workflow between them (Jalo et al., 2022). Workflow and data management challenges remain a large challenge (Berg & Vance, 2017; Delgado et al., 2020), thereby leading to lower perceived performance and value of capabilities that VR technology provides. Continued uncertainty in capabilities and value (Jalo et al., 2022; Delgado et al., 2020) leaves a gap in what manufacturers should be aiming for in order to utilize VR technology efficiently.

A holistic view of the VR adoption process is lacking (Saghafian et al., 2021). Adoption factors such as technology, stakeholders, work processes, and value are often investigated separately in the literature. For instance, work conducted from a process view focuses on value and work procedures. Choi et al. (2015) categorized and correlated VR usages along the NPD process, suggested which usages give the most value. Some literature has focused on step-by-step procedures to carry out VR for design validation purposes (Berg & Vance, 2017; Ventura et al., 2020). Berg and Vance (2017) covered procedures from fully mature VR teams whereas Ventura et al. (2020) suggested procedures for preliminary adoption attempts, although they did not follow up on or validate these procedures. The problem lies in the gap between the two sides of adoption maturity examples. For example, Berg and Vance (2017) generalized the workforce roles involved in the VR usage; however, they did not include the strategic level or how adoption was achieved.

Regarding the people dimension, the literature focuses on challenges facing management related to technology maturity, communication, and support for coordination (Saghafian et al., 2021) or enablers related to top management knowledge and first-hand experience with VR, availability of resources and personnel for VR, and facilitation of the initial adoption (Jalo et al., 2022). Yet from an adoption process view, both fall short in describing how to achieve VR usage within the NPD process in the first place. Regarding the technology dimension, Sekaran et al. (2021) focused on technology by discussing challenges involving the lack of interoperability, poor data management, and the low degree of immersion achieved, but did not explore non-technology solutions such as upskilling champions (main new technology users) or forming organizational teams to combat these issues. As can be ascertained, no work encapsulates a holistic view toward describing VR adoption through all three dimensions (i.e., people, process, and technology). Thus, further exploration is needed to fully knit these dimensions together.

1.3 Purpose and Research Questions

The purpose of this thesis is to facilitate the adoption of VR technology into the NPD process by holistically considering the dimensions of people, process, and technology.

RQ1: What are the challenges when adopting VR in the NPD process?

RQ2: How can the challenges when adopting VR in the NPD process be mitigated?

1.4 Scope of the Licentiate Thesis

This thesis explores the adoption of VR in the NPD process, with a focus on the manufacturing industry. In earlier studies, the subject focused on extended reality (XR) integration. The subject of XR was eventually deemed to be too broad of scope and not mature enough for adoption, mainly regarding the augmented reality portion. Thus, studies were narrowed to VR specifically. Integration was eventually deemed too narrow and was expanded to implementation and even further to adoption. The scope and lens of adoption (Rogers, 2003) were taken into account not only for technology integration and implementation, but also for initiating decisions and confirmations at the beginning and end of each adoption stage as well. This approach allows for a wider scope of literature to be considered, which in turn matched the themes being uncovered. The even wider scope of the diffusion of innovation (DOI) (Rogers, 2003) includes additional phases such as knowledge and persuasion. Although these phases are relevant to the work, a detailed exploration and discussion lie beyond the scope of this study and can be a matter for future research. Regarding the NPD process, the focus in this study has been the intertwined product development and production development processes. Thus, market research and aftermarket portions have been excluded.

This thesis focuses on the adoption of VR in the NPD process, including the people from different organizational levels involved in the change. The flow of data before and after VR usage is also included; as such, this work does not limit itself to the usage of VR technology, but extends to other departments in the organization. Finally, the VR hardware and software are included in the work, primarily in terms of how they affect the usage of VR technology. The development of hardware and software is excluded and is treated as a static, unchanging technology when considering its adoption.

1.5 Outline of the Thesis

The remainder of this thesis is organized as follows. Chapter 2: Theoretical Framework describes the current research on the subject. Chapter 3: Research Methodology presents the methods that this research followed and how the research was conducted. Chapter 4: Summary of Appended Papers presents a summary of papers included in this thesis, and Chapter 5: Adopting VR in the NPD Process offers an analysis and summary of the results. Finally, Chapter 6: Discussion and Conclusion summarizes concluding remarks, contributions to theory and practice, and limitations and avenues for future research.

2 Theoretical Framework

This chapter presents the theoretical framework for this research. The theoretical framework is divided into three parts central to this research: the NPD process, adoption of technology into the NPD process, and the effective application of VR into the NPD process.

2.1 New Product Development Process

The NPD process is defined as the sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product (Ulrich & Eppinger, 2016). The NPD process is a critical component for manufacturing organizations and has become a strategic entity to improve as it is directly related to the overall organizational performance and, thus, success of a new project. Methods to enhance the performance of the NPD process include studies to quicken the process (Müller-Stewens & Möller, 2017) or to bring a new product to scaled production, increase product quality while decreasing overall cost (Yang, 2019), and enhance environmental and sustainability factors (Buchert et al., 2017; Delaney et al., 2022).

Figure 1 presents Ulrich and Eppinger's (2016) NPD process. It consists of several phases: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up.

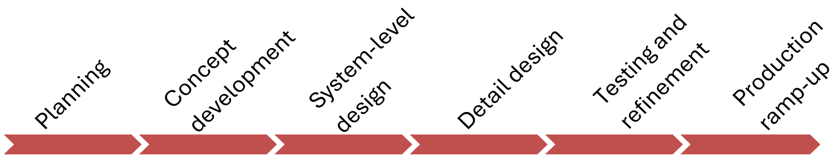


Figure 1: NPD process and accompanying phases based on Ulrich & Eppinger (2016)

Throughout the NPD process, the production development process is performed in tandem. The NPD process and production development process are integrated processes significantly dependent on each other and work toward bringing a product to realization (Bellgran & Säfsten, 2010). Such cross-functional integration is vital as it has the potential to lead to many operational performance benefits, such as cost, conformance, quality, design flexibility, volume flexibility, development lead time, and product innovativeness (Turkulainen & Ketokivi, 2011).

Production development refers to development and the operation of production systems, whether new or existing ones. Production refers to the process of producing products and services with support from different production factors, such as labor, machinery, and raw materials (Bellgran & Säfsten, 2010). Thus, production is the process of producing the designed products at scale. Among these two processes, several functions support the ongoing work, including production engineering, quality, engineering material, process development, and IT support (Gabrielsson, 2002). Product development and production development have evolved to work simultaneously, where activities are carried out in parallel (Ulrich & Eppinger, 2016). Thus, the phases from the NPD process can also be used to describe the activities carried out by production development stakeholders (Ulrich & Eppinger, 2016). Selected NPD process phases are described further in Table 1 in terms of both product development and production development activities.

Table 1: Description of product development and production development activities based on Ulrich & Eppinger (2016).

NPD Process Phase	Product development activities	Production development activities
Concept development	Virtual product concepts are generated and assessed. A final product concept is selected.	Initial production cost is estimated based on virtual product concepts.
System-level design	Selected product concept is further developed from a sub-system view. A parts list of the product is created.	Production and assembly processes are elaborated (e.g., final assembly scheme). Suppliers for key components are investigated, and investment cost is updated.
Detail design	All parts of the product are specified, and finalized drawings with technical specifications are made.	Production process is defined and necessary fixtures are designed. The quality assurance process is defined, and the investment of equipment and tools with a long lead time is initiated.
Testing and refinement	Engineering prototypes are used to evaluate product functionality and customer requirements.	Factory prototypes are used to verify and refine production processes. Workforce is trained, and quality assurance process is tested.

2.1.1 Strategies to enhance NPD process competitiveness

Several approaches exist to restructure and enhance the NPD process, including stage–gate process, front-loading (Thomke & Fujimoto, 2000), concurrent engineering (Koufteros et al., 2001), lean product development (Salgado & Dekkers, 2017), product platforms (Shamsuzzoha & Kekal, 2010), and additional hybrid approaches (Gomes, 2021), to name a few. These approaches share similar purposes, including carrying out phases and activities in parallel, creating interdisciplinary teams, integrating departments such as product development and production to reduce NPD process lead time, and efficiently utilizing resources. Ultimately, the approaches are found to be designed toward specific parameters, including adaptability, flexibility, velocity, and integration (Gomes, 2021).

Perceived uncertainty on the market considerably influences an organization's structure and processes toward such integrated approaches (Sutcliffe & Zaheer, 1998). Integrated product development is an approach to the NPD process that integrates functions across the product lifecycle, such as product development and production development. Integrated product development's approach steers different functions toward working more concurrently, such as by involving production early in the NPD process. Early involvement gives downstream participants input before decisions are finalized, enabling the concurrent planning of product, process, and production, thereby addressing manufacturability issues in the final design. This approach can significantly speed up the production process development, whereas slow development can negatively affect both the speed and quality of prototype development and testing, which can lead to delays or repetitions of tests (Calantone, et al., 2002).

To be successful, the approach requires integration, referring to an efficient transfer of information across functions and the ability of the organization to exploit such information (Galbraith, 1977). Such information channels must be both established and deployed in an appropriate manner for such transfer to occur (Daft & Macintosh, 1981). In relative terms, the timely and effective transfer of product information (CAD data for example) from the NPD process to the production development process is vital.

2.1.2 Complexities and mitigations of integrated product development

The integrated product development approach creates new complexities in the NPD process, especially in the management and coordination of the multitude of stakeholders and the exchange of information. As previously mentioned, the NPD process is no longer a single process, but a spliced process in which functions across the product lifecycle work simultaneously. They are working toward not only product development, but also production, quality, material handling, process development, and IT support (Gabrielsson, 2002), leading to a multitude of stakeholders and information to be considered. This context leads to complexities, particularly in capturing and disseminating critical information to all necessary stakeholders (Idrees et al., 2023).

Integration by incorporating essential departments and stakeholders into the early design phases greatly helps anticipate production concerns, enabling the NPD projects to reach production, and thereby the market, faster (Kharub et al., 2022). Boundary-spanning activities (interacting with stakeholders and parties external to the team [Marrone, 2010, p. 914]) assist NPD process teams in acquiring the needed resources, support, and guidance from external parties (Carbonell, 2023). A key actor in boundary spanning is typically the project manager, who receives and distributes information among intra-organizational actors (Jepsen, 2013). The project manager must guarantee that the information transferred is accurate and distributed to the right people. However, intra-organizational actors increase during later NPD process phases, potentially overloading the project manager with information. Additional challenges arise from spanning boundaries to other stakeholders, such as from one NPD process team to other stakeholders in production, quality, service, etc., thereby creating further challenges, including identifying the specific stakeholders, coordinating with them, identifying how they can help, and carrying out the action (Edmondson & Nembhard, 2009). Once all stakeholders have been identified and included, project managers then face challenges on how to effectively respond to and resolve conflicting issues posed by all those included (Barrane, et al., 2021), particularly as their issues may be in conflict and, ultimately, need to be prioritized (Driessen & Hillebrand, 2012). Nevertheless, the adoption of integrated product development leads to competitive advantages (Morash, et al., 1997). Some mitigations to these challenges include the acknowledgment of stakeholder issues, coordination mechanisms such as written instructions or checklists, the use of multiple prioritization principles, and the engagement of NPD process checkpoints (Driessen & Hillebrand, 2013).

Traditional approaches to mitigating problems arising from boundary spanning, particularly between product development and production, include the use of design for x (DFx) tools. DFx tools act as a set of guidelines and aid in integrating requirements from other departments (e.g., production development) into early design phases. DFx tools cover a vast range of usages, such as design-for-assembly (DFA), -manufacturing (DFM), -maintainability, -serviceability, and -quality, to name a few (Benabdellah, et al., 2019). More recent design tools have emerged to incorporate the environment as well, such as design-for-environment, -sustainability, and -remanufacture (Benabdellah, et al., 2019). Overall, DFx tools enable more predictable products to better meet customer needs, ensure a quicker and smoother transition to manufacturing, and produce a lower total life-cycle cost (Kuo, et al., 2001).

DFA and DFM (more commonly known as DFMA) involve designing products with ease of assembly and manufacturing in mind. This practice focuses on reducing the number of parts, simplifying assembly processes, and minimizing the need for specialized tools or equipment. By prioritizing DFMA, companies can lower production costs (Benabdellah, et al., 2019) as the tool leads to fewer production delays, reduced waste, and higher overall product quality. These tools are used between concept development and the later detail design phase, although most studies on the subject have been conducted on simple products (Formentini, et al., 2022) due to the noted challenge of utilizing DFMA on large complex assemblies, which require much more data for such analysis. Thus, these tools are typically applied to product sub-systems (sub-assemblies). The typical uses of DFMA during concept development include identifying installation and assembly issues among the sub-assemblies, such as the interfaces among sub-assemblies and attachment points, as well as the accompanying ergonomics analysis to carry out the assembly (Formentini, et al., 2022). Yet DFx tools, including DFMA, are hardly used as they are too complex or too time consuming (Benabdellah, et al., 2019). Additional challenges to their adoption include organizational barriers and simple resistance to change (Kuo, et al., 2001).

2.2 Adoption of Technology into the NPD Process

2.2.1 The process of adopting technology

Adoption involves a series of decisions and actions over time, during which an entity evaluates a new idea (innovation) and determines whether to integrate it into ongoing practices. Technology adoption has been studied with the help of different theories, like the diffusion of innovation (Rogers, 2003), the technology acceptance model (TAM), and the technology–organization–environment (TOE) model. The diffusion of innovation process is of particular interest as it highlights how different attributes affect the decision-making process of going forward with a specific technology and follows the approaches to carry out that decision, thereby giving insights into the success or failure of such a technology adoption event.

According to Rogers (2003), adoption is a component of a larger five-stage innovation-decision process. The adoption process is divided into three stages:

(1) decision, (2) implementation, and (3) confirmation, representing the beginning, middle, and end of adoption. Roger (2003) defined the three phases as follows:

- Decision: This phase occurs when an individual undertakes activities that lead to a choice to fully adopt a new technology or reject it.

- Implementation: This phase occurs when a decision-making unit puts the technology into use through various actions. Implementation concludes when the technology becomes a regular part of the entity's operations and loses its novelty.

- Confirmation: This phase occurs when the decision-making entity chooses to continue or discontinue the use of the technology. A decision to continue results in ongoing implementation, continuing the cycle.

From the DOI theory, some attributes associated with a successful, and thus continued, technology adoption are as follows: (1) the new technology needs positive and valuable characteristics, (2) the new technology must have a relative advantage and lower complexity compared to technological alternatives, (3) the adoption decision is made if the attributes mentioned promote change in the preference of the manager responsible for making the adoption decision, and (4) an adequate amount of organizational resources related to the innovation adoption process is developed (Vagnani, 2019). Further adoption dimensions include the adoption process itself (Langley, 1994) and the people who carry out the process (Borkovich, et al., 2015; Pozzi, et al., 2023).

2.2.2 Technology adoption dimensions

Manufacturing companies and their products' performance are considerably affected when introducing and using new technology (Becker et al., 2005; Durmuşoğlu & Barczak, 2011). Technology adoption is based on the performance increase and the added value it brings to the NPD process itself. The three dimensions of people, process, and technology are described as underlying elements to consider for forming an efficient process such as the NPD (Liker & Morgan, 2006) and, as such, would be affected during a new technology adoption. Thus, it is the people, process, and technology dimensions that are investigated to explore how to facilitate technology adoption in the NPD process.

The people dimension refers to the workforce surrounding the NPD process, from top managers to operational employees. General aims among people factors to aid in an efficient NPD process encompass the training and professional development of employees, leadership, organization, learning, and culture (Liker & Morgan, 2006). Thus, when adopting a new technology, it is necessary to consider the same factors. Becker et al. (2005) argued that the resulting impact of new technology adoption is highly dependent on organizational and management structures and is not a technical issue in itself. In addition, staffing of the adoption team is important, and the need to integrate different bodies of knowledge pushes the adoption of not only multiple functional areas, but also people with different experiential backgrounds (Becker et al., 2005).

The process dimension refers to workflow procedures and information management processes that serve as the foundations for knowledge transfer among stakeholders. The adoption of new technology has a significantly positive effect on new product performance when used in the NPD process, as it can enhance workflows and information management among different stakeholders (Durmuşoğlu & Barczak, 2011). However, whenever a new technology is adopted, new procedures will most likely also be required (Becker et al., 2005). Becker et al. (2005) exemplified this by describing how the adoption of testing through virtual predictions also necessitated the results to be compared against physical test results to confirm reliability of the new virtual tool. Information management processes include the storing and transfer of data. Data transfer is needed when sending data between stakeholders or transferring data from one software to another. Related technology includes file transfer protocols (networks for transferring computer files between a client and a server), which enables the efficient sharing of engineering data (product designs and other technical information) among storage servers and stakeholders (Durmuşoğlu & Barczak, 2011). Durmuşoğlu and Barczak (2011) demonstrated that file sharing technology is vital to product performance overall as it affects all phases of a product's development and the sharing of data among all stakeholders.

The technology dimension refers to the tools and technologies used to develop and build the product within the NPD process and beyond. From the information technology and NPD process perspective, digital technology can be further categorized as (1) communication and IT tools (email, group-ware, video conferencing platforms for team interaction), (2) product design IT tools (CAD, simulation modeling and analysis), (3) project management IT tools (project management software), and (4) product data and knowledge management IT (shared parts databases) (Marion & Fixson, 2021). Regarding product design tools, virtual tools lead to substantial organizational changes (Becker et al., 2005). However, the adoption of digital tools can lead to a lasting impact on the NPD process in that they can integrate a broader group of stakeholders into a process, help achieve higher performance such as knowledge generation and design speed, allow a lower barrier to entry regarding the use of the tools, and allow new ways of collaborating and doing work (Marion & Fixson, 2021). In contrast, adding technology to a fundamentally flawed NPD process will do little to help performance, and it is more important to ensure that the technology fits and enhances an already optimized process along with highly skilled people (Liker & Morgan, 2006).

Although performance increases are expected with any thought-out technology adoption, certain challenges arise, especially with drawn-out adoption processes. Sometimes new technologies are pushed through adoption merely for the sake of supporting, instead of also simultaneously removing, technology interfaces, thereby creating more overall work and waste (Thomke, 2006). These added technologies may also require extended time to learn to use them effectively, thereby delaying the adoption process (Thomke, 2006). Thus, utilizing VR for integrated product development purposes should be carried out in a thoughtful manner.

2.2.3 Adoption roadmap

It is imperative that the organization have a clear business value connected to the to-be-adopted technology, which will outlast the additional work and expense brought about by the adoption (Ghobakhloo, 2020). To this end, a roadmap can act as a blueprint of actions to ensure that the adoption delivers its expected advantages (Ghobakhloo, 2020). A roadmap can be described as a structured, visual, chronological plan with a strategic intent (Kerr & Phaal, 2022), connecting the short-term and long-term and aligning multiple perspectives (Siebelink et al., 2021). In addition, the roadmap can take on various scopes, such as from an organization-wide strategic perspective or from a more specific, targeted perspective (Freitas et al., 2022). A roadmap can help circumvent critical strategic challenges, such as keeping a joint short-term and long-term perspective, aligning activities of various functional disciplines, and communicating visions that are often too vague and abstract, making them difficult for employees to understand in order to transform into action (Siebelink et al., 2021).

Within the strategic roadmap, phases may include (1) define, (2) measure, (3) evaluate, (4) optimize, (5) develop, (6) validate, and (7) implement (Butt, 2020). Although perceived benefits of the technology are a key determinant of initial adoption (Ghobakhloo, 2020), continuous improvements enable further adoption (Pozzi, et al., 2021) or continued usage.

2.2.4 Adoption teams

A multitude of people in the organization become involved when adopting new technology, and several different classifications exist to describe the different organizational levels involved. Frambach and Schilewaert (2002) found that technology adoption takes place at two levels: the organizational adoption level and the individual adoption level. At the organizational level, adoption involves the entire entity, such as the company choosing to implement new strategies or technologies, whereas individual adoption refers to a single person deciding to make a change in behavior. Other literature expands the levels, describing that adoption must be a coordinated and aligned effort between several levels of workforce roles, ranging from upper management down to the general user of the technology itself (Nayernia, et al., 2021; Szász, et al., 2020). A third classification is to state specific adoption roles that are taken on during technology adoption. Some of these roles include the driver, the facilitator, and the champion (Johnsson, 2018).

A fourth view is to view an organization from strategic, tactical, and operational levels (Schmidt & Wilhelm, 2000), where decisions would take place regarding technology adoption. Personnel at the strategic level design the environment in which tactical and operational levels must perform and may deal with a relatively long planning horizon of 5 years. For instance, the strategic level may choose and acquire software, integrate software to streamline workflows, ramp up and provide support through training courses, and establish user networks for collaboration and knowledge sharing. Personnel at the tactical level prescribe management policies, distribute work, and may deal with mid-range horizons of 6–24 months. For instance, the tactical level may involve managing specific NPD processes among specific sites and acquiring resources such as software or hardware for a specific site. The operational level schedules operations to ensure the delivery of final products to customers and, thus, adheres to a daily schedule relative to current projects in process. For instance, the operational level may carry out work within the NPD process and utilize the available resources (e.g., software).

The latter three classifications are of interest here as they describe roles for individuals and capture the multitude of existing levels within an organization that individuals may be part of.

Different roles have key differing responsibilities as well. From an organizational level, management should drive adoption through not only support, but also commitment to the technology's adoption as well as setting the strategy, providing training and educational programs, and empowering employees to use the technology (Virmani & Salve, 2023). Employees should have spaces and support for knowledge sharing and adaptive learning that allow for their development during work on their specific task (Kaasinen et al., 2020). From specific adoption roles, the driver must have a holistic overview of the company's situation and be familiar with innovation strategies, product portfolios, and changing management. The facilitator educates, advocates, and advises. The driver and facilitator raise organizational awareness about adoption, standardize and communicate related vocabulary, provide tools, and develop training activities (Andrew & Sirkin, 2008). They also guide the complex adoption process involving many individuals, teams, divisions, and departments (Hunter & Cushenbery, 2011). The champion actively promotes technology adoption during an organization's existence (Howell & Boies, 2004). The individuals not only have specific roles during adoption, but also form an adoption team, which is key for aligning the technology adoption among the different organizational levels (Butt, 2020).

During adoption, the strategic vision from the driver must be translated throughout the organization, which is also referred to as alignment. Alignment includes understanding the strategic importance of the technology's benefits (Virmani & Salve, 2023). Overall, implementing parallel changes should be coordinated so as to not increase the workload for those affected (Saghafian et al., 2021).

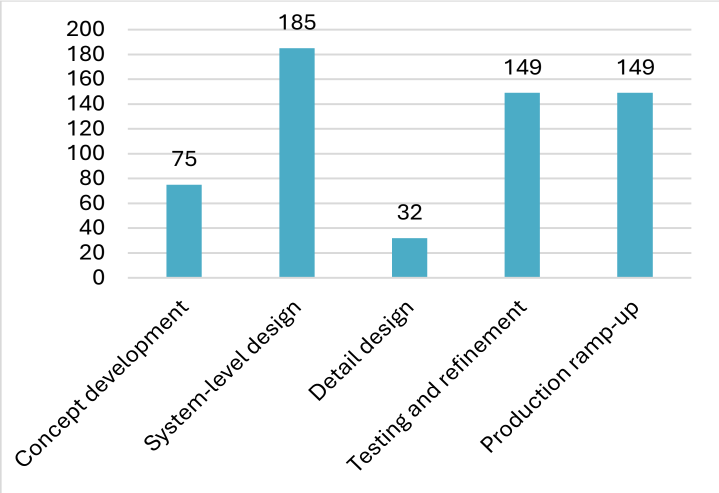
2.3 Effectively Applying Virtual Reality into the NPD Process

2.3.1 Value and usage of VR in the NPD process

Integrated product development practices such as concurrent engineering can be supported by leveraging advanced technologies to enhance the rate at which development issues are detected and resolved through three key concepts: simultaneous work on various NPD process phases, integrated teams, and early stakeholder involvement (Koufteros et al., 2001). In terms of integrated teams and early stakeholder involvement, VR allows stakeholders or an NPD process project team to visualize, interact with, and analyze machine concepts together, long before any physical prototypes need to be made. Engineers from both product development and production development can be involved. In this case, the technology may then enhance the team's decision-making at earlier stages in the NPD process (Berg & Vance, 2017; Sekaran, et al., 2021). Overall, the adopted VR technology has the potential to accelerate the design review process by improving workflow efficiency through enhanced common understanding (Wolfartsberger, 2019). Continuous improvement by increasing VR user capabilities allows for the added performance attribute to compound (Jalo, et al., 2022).

VR applications range across the spectrum of the NPD process as well as the simultaneous production development process. Some applications have been tied directly to the different phases of the NPD process (Choi et al., 2015; Choi et al., 2010). In addition, the review by Choi et al. (2015) included quantifiable evidence as to which NPD process phases experienced the most and least usage of VR (Table 2).

Table 2: Implemented usages of VR across NPD process phases. Adapted from Choi et al. (2015)



According to Berg and Vance (2017), VR is used in the concept development phase in efforts such as testing driver visibility, testing ergonomics and reachability, and evaluating aesthetic qualities such as lighting. Berg and Vance (2017) further touched upon VR in production development, where VR is used as part of the planning for the organization of large spaces, such as production layouts. Ventura et al. (2020) also described how VR is used within production development to analyze the usability of sections in a factory, including assembly, ergonomics, layouts and maintenance, as well as training. Among these usages, several capabilities can be derived as the underlying functions that provide value to the user, no matter what phase or side they are on.

VR capabilities cover a range of categories. Choi et al. (2015) categorized VR capabilities as expression, interaction, authoring, and collaboration. Expression is defined as usages that stimulate humans' senses (i.e., sight, hearing, touch, smell, and taste) while interaction refers to usages that interface with humans through motions, symbols, and biosignal means. Authoring refers to technology to generate VR content and a supporting database, and collaboration refers to networking in a VR environment with multiple participants. The same study (Choi et al., 2015) found expression to be the most used type, followed by authoring, interaction, and, lastly, collaboration. Berg and Vance (2017) categorized capabilities as visibility/viewability, ergonomics/reachability, abstract data visualization, and communication. The authors identified visibility as the most common type; it includes evaluating human visibility, such as with vehicle drivers, and for production ergonomics purposes, like understanding operator perspectives during tasks such as transmission docking. Ergonomics/reachability usage involves testing different persons' heights to assess the safety of assembly tasks. Other VR applications include communication across disciplines, departments, and hierarchies. Finally, Horvat et al. (2022) identified eight categories of VR software capabilities specifically for design reviews: input, representation, navigation, manipulation, collaboration, editing, creation, and output. The authors further highlighted the importance of capabilities being related to design flows. A capabilities framework adapted from Choi et al. (2015) and Berg and Vance (2017) is displayed in Table 3.

Table 3: VR technology capability classification, adapted from Berg and Vance (2017) and Choi et al. (2015).

VR Capability	Description
Visibility	Technology related to human sensory systems. Includes evaluating the visibility of a human and understanding others' perspectives. Examples include driver visibility and understanding operator perspectives.
Ergonomics/ reachability	Technology used to interface humans and computers through motion, symbols, and biosignal means. Examples include human posture, reachability, and access/removal of parts.
Authoring	Technology that generates VR content and a supporting database. Examples include designing hoses and cables within the VR space.
Communica-tion	Refers to using the technology for communicating across disciplines, departments, and managers. Also includes the collaboration of multiple participants, in the form of avatars, in the same VR environment.
Abstract data visualization	Refers to visualizing data that does not have a real-life representation. Includes visualizing various forms of simulation data, such as for wind and fluid dynamics and lidar scans of geospatial information.

2.3.2 VR adoption in the NPD process

The procedural approach to VR adoption has been studied in a range of ways, from the wide scope of technology digitalization, including all "new" technologies, to singular technology adoption such as VR.

According to Frank et al. (2019), technologies can be categorized among smart manufacturing, smart products, smart supply chain, and smart working; the sub-technologies are then ordered in terms of adoption sequence. VR falls under the smart working technologies umbrella, referring to the new ways workers perform their activities with the support of emerging technologies. VR is recorded as being used either for workers' training or for visualizing for NPD process purposes. According to Frank et al., among all the technologies, VR usage for smart working is typically adopted by companies last, if at all.

From the singular technology standpoint, VR adoption has been examined from a procedural standpoint, detailing the step-by-step process to execute a VR session. Ventura et al. (2020) elaborated on the procedures, phases, and activities required for conducting a design review of architectural projects. The outlined process comprises seven stages: (1) preliminary (planning) activities, (2) objectives of the session, (3) introduction to the project, (4) introduction to the technology, (5) alignment of perspectives, (6) design review session, and (7) collection of feedback. Berg and Vance (2017) similarly described the general VR usage process employed by various manufacturing organizations through seven stages: (1) VR request, (2) model acquisition, (3) model preparation, (4) virtual environment build, (5) proof-of-concept demo, (6) VR session, and (7) outcome summary. Both Ventura, et al. (2020) and Berg and Vance (2017) addressed scenarios in which the individuals experiencing or using the VR (i.e., users) are distinct from those responsible for preparing and maintaining the VR technology.

2.3.3 Challenges of VR adoption in the NPD process

Adopting VR for purposes such as increasing integrated product development comes with many challenges, including those related to the organization, changes to people's work procedures to affect the flow of information, and integrating the VR technology itself.

Regarding the people dimension, challenges relate to top management's lack of knowledge and awareness regarding the details for such a VR roadmap (Jalo et al., 2022) as well as communicating and supporting the coordination of workload from a multi-stakeholder perspective that is needed for VR (Saghafian et al., 2021). General people-related challenges during adoption include lacking a clear project vision to which to align and facing set-up preparation difficulties among management as well as skill development issues and individual resistance among employees (Stornelli et al., 2021).

In terms of the process dimension, adapting an NPD's process to adopt VR has continued to prove challenging, especially as simply demonstrating added value to others can be challenging due to difficulties in measuring return on investment (Berg & Vance, 2017). Changing the NPD process to support the use of VR has also proven challenging, as the way forward to changing workflows and data management processes remains unclear (Delgado et al., 2020). Difficulties also arise surrounding the VR facilities themselves, as simply starting a VR facility from the ground up is difficult, as are operating and maintaining it (Berg & Vance, 2017). These factors have contributed to the overall challenge of facilitating the initial adoption of VR overall (Jalo, et al., 2022).

Regarding the technology dimension, challenges relating to compatibility (e.g., standardization in data formats and protocols) are still common. Additional challenges stem from the fact that the sense of immersion and interaction is not enough to mimic real life scenarios, and the interfaces toward the VR software are unintuitive (Sekaran et al., 2021). Overall, some experts argued that the VR is simply not technologically mature enough to handle the workload (Saghafian, et al., 2021).

2.3.4 Summary

The presented theoretical framework culminates in the adoption of VR in the NPD process, particularly from the DOI perspective. VR technology is distinguished as a tool that supports integrated product development, particularly by integrating stakeholders into the NPD process and production development process through the unique capabilities that VR offers. Challenges related to the adoption of VR are noted, especially among the people, process, and technology dimensions. The discussion has highlighted the importance of adoption teams among different organizational levels and a clear roadmap to process changes in order to secure the continued adoption of the technology, despite adoption challenges.

3 Research Methodology

This section presents the research method and design, a description of the two case studies, and a description of the joint analysis carried out on these case studies. Finally, this section presents factors related to the quality of case study research.

3.1 Research Method and Design

The research presented in this thesis, covering VR adoption in the NPD processes, has taken an explorative approach, particularly when studying RQ1. Adopting the explorative approach aims to develop propositions for further inquiry in order to define the necessary questions for developing consecutive studies (Yin, 2014), such as for explaining links between concepts. This approach has been chosen because available knowledge on the topic of this thesis has been limited and concepts such as VR adoption challenges and mitigations have not been well defined regarding the purpose of this thesis. In RQ2, the links between challenges are inferred in order to propose mitigations. The purpose is to describe how or why some conditions came to be, such as a why a sequence of events did or did not occur (Yin, 2014).

The research method and design have been formulated based upon the RQs, which were defined and iterated upon after reviewing the relevant literature. A multiple case study method was chosen for this research pertaining to VR adoption in the NPD process within two manufacturing companies. An initial context-seeking case study was also utilized to gain a preliminary understanding of and determine the context of the same phenomenon. The case study method is defined as an empirical inquiry that (1) investigates a contemporary phenomenon in depth and within its real-world context, especially when (2) the boundaries between the phenomenon and context may not be clearly evident (Yin, 2014). This method was selected as it helps understand decisions, their implementation, and the results obtained (Schramm, 1971) during real-world phenomena such as the focus of this thesis. Furthermore, the case method suits studies that are early, exploratory investigations in which the variables are still unknown and the phenomenon is not at all understood (Meredith, 1998). Other focuses of the study may include individuals, organizations, and processes. As the focus of this research is VR adoption in NPD processes (including decisions and their implementation) by individuals within an organization, the method is appropriate.

This research utilizes a retrospective multiple case study design. The multiple case study design increases the generalizability of the cases, compared to a single case study, however it also requires more resources, and less depth is garnered per case (Voss, et al., 2016). Retrospective cases allow for the collection of data on historical events and give the possibility of identifying cases that reflect either success or failure in retrospect; however, it may be difficult to determine cause and effect, and participants may not recall important events (Voss, et al., 2016). This thesis's empirical findings are based on survey data, semi-structured interviews, internal documents, observations, and informal discussions. Table 4 presents an overview of the research design, including the studies, resulting papers, and relation to the RQs.

Table 4: Overview of research design, including studies, resulting papers, and relation to the RQs. '**RQ**' denotes a strong correlation while 'RQ' denotes a lesser correlation.

<table>
<tr><th colspan="4">Overview of research design</th></tr>
<tr><td>Study</td><td colspan="2">Case study 1</td><td>Case study 2</td></tr>
<tr><td>Purpose</td><td colspan="2">Gain initial context from broad scale of VR adopters</td><td>Deeply explore VR adoption to understand the process</td></tr>
<tr><td>Research Method</td><td colspan="2">Retrospective multiple case study</td><td>Retrospective multiple case study</td></tr>
<tr><td>Data Collection</td><td colspan="2">Survey, internal documents, observations</td><td>Semi-structured interviews, internal documents, observations</td></tr>
<tr><td>Resulting Papers</td><td colspan="3"></td></tr>
<tr><td>Paper</td><td>Paper I</td><td>Paper II</td><td>Paper III</td></tr>
<tr><td>Purpose</td><td>Explore the current approaches to integrating XR technologies into the product realization process as well as the accompanying challenges</td><td>Explore teams implementing VR within the NPD process and identify the barriers influencing them</td><td>Identify key decisions and implementation activities that impact VR adoption in the NPD process</td></tr>
<tr><td>Relation to RQ</td><td>RQ1, RQ2</td><td>RQ1, RQ2</td><td>RQ1, RQ2</td></tr>
</table>

3.1.1 Research timeline

Figure 2 presents a timeline of the studies conducted toward this licentiate thesis, including the multiple case studies (Case study 1 and Case study 2), the dates the resulting papers were submitted, and the licentiate thesis defense.

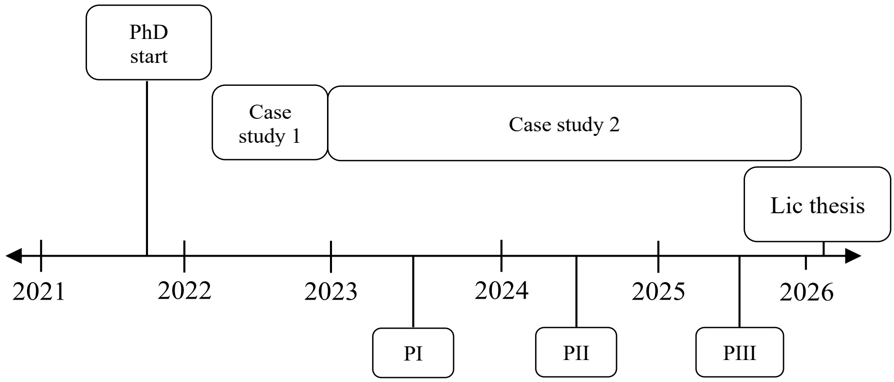


Figure 2: Timeline of the research covered in this thesis.

3.1.2 Role of the researcher

Throughout the case studies, the author was granted access to the companies, typically onsite. The author engaged in ongoing, weekly dialogues with personnel connected to the VR adoption within the company, such as the production preparations director and VR champions among multiple sites. Additional dialogues were held with IT personnel connected to VR adoption within the companies, the VR software supplier, and directors of VR adoption among two other regions.

As a precursor to the case studies, an ongoing dialogue was maintained between the author and personnel at Company 2. Discussions surrounded the current state of VR adoption and usage at the site as well as questions regarding what information was missing. During these preliminary discussions, conducting a global company-wide survey to gain a contextual understanding of the state of VR adoption and to deepen the knowledge about where to go next became a topic of interest. The survey was then created jointly with personnel.

In August 2024, the author became employed by Company 2, where Cases A and B occurred (Case study 2). This greatly increased the casual dialogues held between the author and VR users at the site (2–3 times/week), leading to the author’s deeper understanding.

3.2 Case Study 1: Contextual Study

The purpose of Case study 1 was to gain contextual understanding from a broad scale of VR adopters regarding their approach to driving the adoption, the usage of VR technology, and the challenges and enablers impacting the adoption.

3.2.1 Case selection

Based on the purpose of the case study, two manufacturing companies were selected: Company 1 and Company 2. The companies were selected based on the following criteria: (1) undergoing integration of XR technologies; (2) belonging to the manufacturing industry and, thus, following a product realization process; and (3) being similar in company size, thereby necessitating similar organizational levels and technology visions for the future.

Both case companies belong to the same group, strive to adopt VR within their NPD processes, and have defined visions and roadmaps for technology adoption. VR adoption was first initiated within both companies in 2019 using company-wide standardized VR software; its usage continues today. The participants in the studies were positioned at either the global or local levels. Both companies have developed a vision for the future factory and specified advanced digital technologies to be implemented. To actualize this vision, dedicated teams were established to oversee digital transformation across all production sites. These teams are frequently tasked with conducting pilot projects that develop and evaluate new technologies. The two companies were deemed suitable for the study as well as for comparison due to these multiple similarities. Table 5 presents an overview of the companies.

Table 5: Overview of companies included in the studies (Data from 2024)

	Company 1	**Company 2**
Employees	11500	15000
Turnover (MSEK)	360,610	88,305
Industry	Automotive	Heavy vehicle
No. of sites	12	15
Type	OEM	OEM
NPD process management model	Stage-gate	Stage-gate

3.2.2 Data collection

The purpose of the data collection was to gain an initial understanding of the overall context and current state on how the adoption of VR was progressing across Companies 1 and 2. Data was collected from a range of data sources, including a survey, internal documents, informal discussions, and observations. Table 6 summarizes all collected data within Case study 1.

Survey

The survey was distributed digitally to 58 potential respondents in 2022. Twenty-two respondents answered, resulting in a 38% response rate. The survey was divided into two parts; the first section focused on open-ended questions, and the second part focused on rated questions. The survey covered topics such as adoption approach, adoption maturity, and resulting challenges. The survey results provided an initial understanding of the phenomenon being studied, which was subsequently explored further through the case study. The survey questions can be found in Appendix A: Survey Questions.

The survey respondents were employees from Companies 1 and 2 who had worked with VR technology or had participated in its adoption. Participants' roles included heads of product and production preparation processes, project managers (from both product development and production development), product development engineers, production development engineers, service engineers, and IT personnel responsible for the integration of VR software into existing software infrastructure as well as the development of the VR software. Participants also came from a range of levels in the organizations. Some participants held a strategic level view, in which they develop and execute long-term plans for the organization, including sites globally. Other participants held a local view level, meaning they carry out their roles and responsibilities at a single site. The participants also held roles across a range of managerial and operational levels.

Unpublished data from the survey has been added and is presented in 4.4 Supplementary Data and Analysis. The data is mostly nominal in character and is represented in bar charts and pie charts.

Internal documents

Internal documents covered both case companies and included their strategic technology roadmaps (which included VR), numerical data pertaining to usage of VR per site, and development models for VR software integration into existing software architectures.

Informal discussion and observations
Informal discussions were held weekly with those working with the VR technology at Company 2. Discussions explored general challenges to VR work, experiences when conducting use cases in design reviews, and visions for future VR usage. During this time, observations were conducted since video footage of design reviews were shown. Many VR environments were also shown, giving insights into the complexity of the data included and the handling of the VR software.

Table 6: Summary of data collected within Case study 1

Company	1	2
Survey responses and respondents	10 responses	9 responses
	Heads of product and production preparation processes Project managers (from both product development and production development) Product development engineers Production development engineers Service engineers IT personnel responsible for VR software integration	
Internal documents	Technology roadmaps Usage of VR per site VR software integration models	
Informal discussions	VR ways of working General experience from conducting VR use cases Visions for future VR usage	
Observations	Video footage of ways of working VR environments, showing data complexity Handling of VR software	

3.2.3 Data analysis

In Case study 1 (Paper 1), a thematic analysis was used to analyze the data (Braun, 2006). The analysis began with a within-case analysis of each case; the results were then compared to find integration approaches, integration maturity levels across sites, and reoccurring challenges. Internal documents and informal discussions were used to find integration approaches and integration maturity levels. Integration maturity levels were then grouped by number of hours of software used per site and, consequently, level of technology maturity. The survey and observations were used to find reoccurring challenges. The initial codes for the thematic analysis were data driven, which led to the selection of the themes. Drawing inspiration from other integration studies, themes were then assigned to people, process, and technology dimensions (Liker & Morgan, 2006). A cross-case analysis (Eisenhardt, 1989) was conducted to compare cases in terms of similarities and differences in the identified themes. The analysis of the empirical data was supported using NVivo to structure and code the data throughout the analysis.

A portion of the supplementary data provided (as seen in 4.4 Supplementary Data and Analysis) originated from the survey. Table 11 data was analyzed according to an adapted VR capability classification, as seen in Table 4 (Berg & Vance, 2017; Choi et al. 2015).

3.3 Case Study 2: Retrospective Multiple Case Study

The purpose of Case study 2 was to explore the VR adoption phenomena in more depth, which allowed for both a deeper understanding and inferences to be made.

3.3.1 Case selection

Case selection for the multiple case study was carried out by choosing three cases overall: two of similar character (where the technology adoption was largely discontinued) and a third with an opposing outcome (where the technology adoption continued), as proposed by (Eisenhardt, 1989). The outcomes of all cases were known as they were studied retrospectively, allowing for the selection of both replications as well as opposing cases. The case selection was based on the following: (1) The NPD project incorporated VR technology; (2) VR usage was initiated from the same top-down strategic decision; and (3) the cases represented different stages of the NPD process to ensure variety. Consideration (2) enabled a known shared vision and purpose for the VR technology usage among the cases. Furthermore, each case represented the VR adoption process carried out among the subsequent adoption teams within the NPD process.

The three cases were selected from Company 2, as described in Section 3.2.2. The cases are all located in Sweden, where Case A took place at Production site 1 and Cases B and C took place at Production site 2. These production sites were chosen as they both carried out both product development and production development. The VR technology was used in early concept development phases among all cases, ranging from concept development to system-level design and finally detail design. A further description of the three instances of VR adoption follows, referred to as Cases A–C.

Case A followed a VR adoption process initiated at the VR technology's first introduction in 2019 until early 2021. The technology was used primarily for ergonomics testing with a sub-assembly of a larger product.

Case B followed a VR adoption process initiated in 2022 that continues today (studied retrospectively). The technology has been used primarily toward design for assembly, manufacturing, and service within the full product.

Case C followed a VR adoption process initiated in 2019 that continues today (studied retrospectively) The technology has been used within production development, primarily for validating ease of assembly, manufacturability, and production floor layout. Case C followed the technology adoption through three consecutive NPD projects. An overview of all adoption cases is presented in Table 7.

Table 7: Overview of cases in Case study 2

Case	A	B	C
Years	2019–2021	2022–2025	2019–2025
NPD Phase Scope	Concept development	System-level design	Concept development, system-level design, detail design
VR Usage	Driver ergonomics	Design for assembly, manufacturability, and service (Product development view)	Design for assembly, manufacturability, and production floor layout (Production development view)

3.3.2 Data collection

Data was collected to gain a deeper understanding of the adoption of VR among the three cases. Therefore, the data was collected from a range of data sources, including semi-structured interviews, internal documents, observations, and informal discussions. Table 8 provides a summary of all collected data within Case study 2.

Interviews

The purpose of the semi-structured interviews was to form a deeper understanding of the results of the survey, such as key challenges found, and to understand the VR adoption process taken. Data was collected in 2023–2024. Semi-structured interviews were conducted with all of those who had taken part in VR usage during the VR adoption attempts among the selected cases (See Appendix B for Interview Questions). The interviews followed an interview protocol, using a combination of closed- and open-ended questions, followed up by "why" or "how" questions. Questions pertained to the interviewees' initial role before adoption and their additional role during the team's VR transition. Questions also covered the context in which the technology was applied (e.g., NPD process phase) and procedural events of the technology adoption within the case (e.g., decision to start or continue with the technology, all implementation activities carried out, and reasons for continuing or stopping the usage), as well as possible mitigations. Finally, questions covered the relationship between the individual and their VR adoption teammates. Participants' roles included two site managers positioned at the tactical level and three project managers and three engineers positioned at the operational level. Conducting interviews at the tactical and operational levels was pertinent to understanding how VR adoption was driven at the sites from a tactical view and then how it was accepted and used by the operational level. Table 8 summarizes the interviews.

Internal documents

Internal documents included VR kickoff presentations from all cases that focused on the desired impact and vision of the VR usage, in terms of both cost savings and advantages of usage. Internal documents also included VR validation process presentations and data regarding number and type of product faults found from Case C. These included stakeholders involved, step-by-step work processes, and recorded impact of VR usage from the number of product faults found.

Observations and informal discussion

Throughout the multiple case study, several VR environments were observed from all cases used during the VR adoption process (approximately 5 total), giving insights into the use cases and types of VR capabilities the teams were trying to achieve and how. Informal discussions occurred with those working with VR technology, project managers, and the head strategic driver of VR at varying intervals, starting when interviews were ongoing and continuing until the submission of this thesis. Informal discussions were held alongside interviews with Case A. During Cases B and C, discussions were held two to three times a week. Discussions included experiences when conducting ongoing use cases, challenges surrounding VR usage, organizational challenges, and possible mitigations.

Table 8: Summary of collected data within Case study 2

<table>
<tr><th></th><th>Case A</th><th>Case B</th><th>Case C</th></tr>
<tr><td>Production site</td><td>1</td><td colspan="2">2</td></tr>
<tr><td rowspan="2">Interviewees</td><td rowspan="2">Site manager (2h)
Project manager (2h)
Engineer (1h)</td><td colspan="2">Site manager (2h)</td></tr>
<tr><td>Project manager (2h)
Engineer (1h)</td><td>Project manager (2h)
Engineer (1h)</td></tr>
<tr><td>Internal documents</td><td>PowerPoint presentation: step-by-step VR validation process
Review of all design faults found</td><td>PowerPoint for VR kickoff including impact and vision</td><td>PowerPoint for VR kickoff including impact and vision</td></tr>
<tr><td>Observations</td><td>Experienced VR environment with full assembly
VR studio visit</td><td>Recorded video: VR session conducting validation of full sub-assembly with more than 20 stakeholders
VR studio visit</td><td>Experienced different iterations of assembly (approximately 5) in VR to understand VR usages
VR studio visit</td></tr>
<tr><td>Informal conversations</td><td>Every 2 weeks alongside interviews</td><td colspan="2">Discussions held with VR personnel 2–3/week</td></tr>
</table>

3.3.3 Data analysis

In Case study 2 (Paper II and Paper III), the data analysis was based on interviews, internal documents, observations, and informal conversations. The interviews were first transcribed and read systematically. In both Paper 2 and Paper 3, the analysis began with a within-case analysis; these analyses were then compared.

In Paper II, a theory driven analysis was first carried out to identify roles within the VR adoption team. Interviews and internal documents were then used to determine the roles of the VR adoption team members. First, roles within the VR adoption team were identified and grouped into managers and users and further refined into four specific roles. Then, a data-driven analysis was carried out to find reoccurring barriers affecting team members. Reoccurring barriers were mapped to people, process, and technology dimensions (Liker & Morgan, 2006). Finally, the relationship between roles and barriers was inferred (based on the data) to understand how barriers propagate through the adoption structure. All data types were used toward this endeavor.

In Paper III, the analysis followed Rogers's (2003) DOI process, structuring the empirical material into decisions, implementation activities, and confirmation steps for each case. Once the material was structured among the three steps, the material was further coded and set into data-driven themes (Braun, 2006). In one case (Case C), this process was carried out for three consecutive DOI processes. All data types were utilized throughout this process. A cross-case analysis (Eisenhardt, 1989) was conducted to compare cases in terms of similarities and differences in the identified themes. Findings from the case studies were also compared to existing theories (Maxwell, 2013).

3.4 Joint Analysis

In this thesis, the data analysis was based on the three appended papers and the supplementary data to determine challenges and mitigations.

For RQ1, the empirical material underlying each paper—namely, challenges (from data collection methods ranging across a survey, semi-structured interviews, internal documents, observations, and informal discussions)—were extracted across all three studies. These empirical excerpts were then recoded to themes and mapped across the three dimensions (i.e., people, process, and technology) as well as the organizational levels (i.e., strategic, tactical, operational [Schmidt & Wilhelm, 2000]) where the challenges were experienced.

For RQ2, the same empirical material underlying the papers was used as the base, which follows an approach that allows for links to be formed between concepts. Thus, the links between concepts, such as mitigations of challenges, were inferred with the support of multiple data sources and supporting theory. Results from Paper III, particularly the adoption process, were utilized for a cross-case synthesis to further validate the proposed mitigations. These multiple viewpoints strengthened the picture of the phenomenon (in this thesis, the VR adoption process), thereby allowing for the information to converge and reach a higher clarification (Voss, et al., 2016). Explanation building and cross-case synthesis methods were utilized to avoid incorrect inferences. The cross-case synthesis was carried out by comparing two similar cases (Paper II) while also contrasting these to a third case in Case study 2 (Paper III).

3.5 Quality of Case Study Research

The quality of case study research can be assessed using the variables of construct validity, internal validity, external validity, and reliability (Yin, 2014).

3.5.1 Construct validity

Construct validity is the extent to which correct operational measures for concepts are being studied. Construct validity is supported by using multiple sources of evidence, establishing a chain of evidence, and having key informants review draft cases and study reports (Yin, 2014). All three of the aforementioned methods were utilized in this thesis. In terms of the multiple sources of evidence, the range extended among utilizing internal documents, interviews, observations, and informal discussions. A chain of evidence was also established, from data collection to conclusions, to keep the process transparent. Finally, study reports were presented to key informants in group meetings, and full papers were reviewed with the purpose of validating that the findings and impressions were congruent with the views of the research participants, further strengthening construct validity (Bryman, 2016).

3.5.2 Internal validity

Internal validity is relevant to research specifically when seeking to establish causal relationships (Yin, 2014), as in when explaining how and why event *x* led to event *y*. The case study method provides a good understanding of the "why," enabling the establishment of theoretical relationships (Karlsson, 2016). This is enabled by the strength of qualitative research, which allows for the prolonged participation in the studied group over a long period of time, further enabling the research to develop congruence between concepts and observations (Bryman, 2016). Throughout this research, the researcher was involved in the studied group by being on site one to three times per week for several years, deepening the understanding and allowing for congruences to be made. In terms of establishing internal validity, challenges relate to incorrect inferences being made when an event is not directly observed (Yin, 2014). Methods to mitigate this include pattern matching, explanation building, addressing rival explanations, using logic models, and conducting a cross-case synthesis. In this thesis, explanation building and cross-case synthesis methods were utilized to establish internal validity and attempt to avoid incorrect inferences. Cross-case synthesis was carried out by comparing two similar cases while also contrasting these to a third case in Case study 2.

3.5.3 External validity

External validity deals with the notion of the generalizability of a study's findings, determining the extent to which the findings can be analytically generalized to other situations. Achieving external validity represents a noted challenge for qualitative research as the tendency is to employ case studies on small samples (Bryman, 2016). Utilizing replication logic is a method to ensure external validity within multiple case studies specifically (Yin, 2014). This approach was incorporated into this research as a multiple case study method was used throughout this thesis, leading to increased generalization. Furthermore, the initial case study (Case study 1) integrated cases from two separate manufacturing companies, thereby allowing for increased variance among the cases and leading to increased generalizability.

3.5.4 Reliability

Reliability is the consistency and repeatability of the research procedures used in a case study, with the goal of minimizing errors and biases (Yin, 2014). Reliability can be increased by keeping a case study database, maintaining a chain of evidence (Yin, 2014), and using multiple sources of data on the same phenomenon (Karlsson, 2016) to mitigate biases. All three methods were used in this thesis to ensure the reliability of the results. Multiple data sources on the same phenomenon were used to increase the contextual understanding of the cases. Data that led to understanding ways of working was first gathered from respondents' descriptions during interviews. However, the weaknesses of interviews include the possibility of bias due to poorly articulated questions and response bias. To expand upon the picture of ways of working, observations in the form of video recordings and documentation from those same described meetings were reviewed. As the meeting was recorded, the data collection method weakness of reflexivity was mitigated. The resulting contextual understanding was strengthened as the use of multiple data sources helped mitigate bias.

4 Summary of Appended Papers

This chapter presents an overview of the findings within the appended papers and describes how they contributed to the thesis. It also presents supplemental unpublished survey data.

4.1 Paper I

Title: "Integrating XR Technologies in the Product Realization Process: Current Approaches and Challenges"

Research gap: Descriptions of overall approaches to XR integration from an organizational perspective are lacking.

Purpose: To explore the current approaches to integrating XR technologies into the product realization process as well as the accompanying challenges

Research method: A retrospective, multiple case study was conducted, coupled with a survey. Data were collected between 2022 and 2023. The timespan of the studied cases occurred between 2019 and 2022.

Findings: The study of current approaches to XR integration revealed key components of an approach and the resulting impact of said approach on the outcome of the integration. Key components included the ownership of the VR work within the manufacturing company, such as toward product development departments or production development departments. Another key component included how to structure the technology competence within the organization, such as either creating a large team of VR experts at one site and additional VR experts at remaining sites or training all employees within the organization at the same base level of VR competence. The outcome of these approaches led to a noticeable difference in the level of integration between the two manufacturing companies. The approach giving ownership of the VR work to product development and focusing on creating expert competence with a select few resulted in a higher level of VR integration overall when compared to the other approach. Furthermore, the ownership type had a direct impact on types of technology usages carried out: Product development ownership led to VR usages mainly within product development and vice versa.

The paper then explored overall challenges that arise during XR integration and further differentiated the challenges according to the different approaches. Overall, 10 challenges were found, which were categorized among people, technology, and process dimensions. The approach taken seemed to mainly influence the people dimension of challenges and, to a lesser extent, the technology and process dimensions. Among the people dimension, the challenges included difficulty matching VR education to needs (including workflows and software), a lack of adequate VR software skills, and a lack of collaboration among other stakeholders. Technology challenges included inadequate software/hardware stability and cumbersome workflow between CAD systems and VR. Process challenges included difficulty changing ways of working, imbalanced CAD maturity and quality compared to VR needs, a lack of time to prepare VR, a lack of purpose, and a lack of dedicated roles and support.

4.2 Paper II

Title: "What Not to Do: VR Implementation Teams and the Barriers that Inhibit them"

Research gap: General studies to understand workforce roles at different organizational levels toward the implementation of VR in the NPD process are lacking.

Purpose: To explore teams implementing VR within the NPD process and identify the barriers influencing such efforts

Research method: A retrospective, multiple case study was conducted. Data were collected in 2023. The timespan of the studied cases occurred between 2019 and 2023.

Findings: The study of VR implementation teams revealed that specific roles emerge within the team, including two main categories and four sub-categories. The roles included the main roles of manager (top driver and gatekeeper sub-roles) and users (key user and general user sub-roles). Overall responsibilities included carrying out and sustaining implementation (top driver), planning and carrying out VR activities within NPD processes (gatekeeper), being responsible for the VR lab and keeping software updated (key user), and generally using VR in their work (general user).

The study further revealed eight barriers that the team faced, which were further categorized among people, technology, and process dimensions; most barriers fell within the people dimension. Barriers were also correlated to the role they influenced the most. This analysis revealed that technology barriers affected only the general users, process barriers affected all other role types, and people barriers affected a mix of all role types. The study suggested that key users are a vulnerable link within the team, as the rest of the team depends on them. Thus, sites should focus more on expert competence among key users and less on training new general users.

4.3 Paper III

Title: "Adoption of VR in the New Product Development Process: Key Decisions and Implementation Activities"

Research gap: Information regarding how to adopt VR in NPD processes (e.g., decisions and implementation activities to carry out those decisions) is lacking.

Purpose: To identify key decisions and implementation activities that impact VR adoption in the NPD process

Research method: A retrospective, multiple case study was conducted. Data was collected between 2023 and 2026. The timespan of the studied cases occurred between 2019 and 2026.

Findings: The study of VR adoption, particularly decisions and implementation activities performed, revealed distinct choices made that led to the continuation or discontinuation of the technology within a given team. Key choices included whether to allow for structured or ad-hoc exploration of the technology within the NPD process and what level of VR complexity to attempt first. The study showcased that the key choices to carry out structured exploration at low VR complexity levels led to the continued adoption of one case. On the other hand, an ad-hoc exploration at medium VR complexity levels led to a discontinued adoption in two cases.

The study further revealed which variables were pertinent to the continued adoption within one case to mature over time and the degree of value added to the NPD process as a result. These variables included adding additional resources (e.g., personnel) to work with the technology, increasing VR usage difficulty and data complexity, and continuing to develop and adapt ways of working. The study suggested that teams should first start at low complexity levels of VR usage to gain a foundational understanding of the technology, even if they generate a lower resulting value for the NPD process. Over time, if adoption continues, the VR usage can mature, resulting in more value being experienced from the NPD process in terms of both shortened time spans and increased quality.

4.4 Supplementary Data and Analysis

The following supplemental, unpublished data was retrieved from Case study 1, which was a contextual study. A portion of the data was further categorized or analyzed (Tables 10 and 11). All survey questions can be found in Appendix A: Survey Questions.

Table 9 is based on the response from survey questions 7 and 8. The results show that VR adoption in the NPD process affects roles differently among organizational levels (operational, tactical, strategical) while also causing challenges in the people, process, and technology dimensions. The operational level personnel were most affected by the challenges, followed by the strategic level, whereas the tactical level did not experience any of these challenges. This result suggests that there is a lack of coordination among the three organizational levels (Nayernia, et al., 2021).

Table 9: Adoption challenges and influenced organizational level roles.

		Influenced organizational role		
Dimensions	**Challenges**	**Strategic**	**Tactical**	**Operational**
People	Difficulty matching VR education to needs, including workflows and software	x		
	Lack of dedicated VR role and support			x
Process	Difficulty changing way of working			x
	Imbalanced CAD maturity and quality to VR needs			x
	Lack of time to prepare VR			x
	Lack of purpose			x
Technology	Inadequate software/hardware stability	x		
	Cumbersome workflow between CAD systems and VR			x
	Difficulty readying software/ hardware infrastructure	x		
	Difficulty integrating due to security policies	x		

Table 10 is based on the responses from survey question 17. The results highlight in which NPD process phases VR was used by different organizational functions. The results show that VR was mainly used in the concept design and system-level design phases, followed by the detail design and testing and refinement phases. Interestingly, mostly product development engineers (i.e., NPD process engineers) utilized VR predominantly in early NPD process phases (concept design and system-level design), but then usage tapered off. This result may be due to the fact that the engineers shifted to relying on the physical prototype for later phases. Comparatively, production development engineers utilized VR relatively equally among all phases. This result may be due to the fact that the VR has capabilities suited for work to be carried out in these later phases, such as tool design, quality assurance, and assembly process refinement (see Table 1 [Ulrich & Eppinger, 2016]). Interestingly, these results differ from the extent of VR usage in NPD process phases that Choi et al. (2015) found.

Table 10: Phases of NPD process in which VR was used.

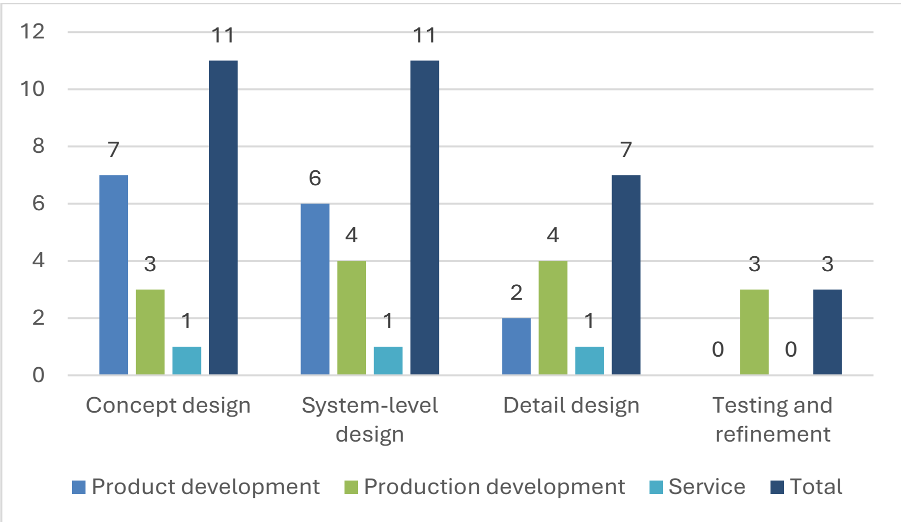


Table 11 is based on responses from survey questions 19–20. The responses were further analyzed and categorized among the adapted VR capability classification found in Table 3 (i.e., expression, interaction, authoring, and collaboration). The results show which VR capabilities were used most and least often, as well as the amount of usage among different organizational functions. The capabilities of expression and interaction were mostly used within the VR, whereas authoring and collaboration capabilities were used sparingly. This result may suggest that certain capabilities are easier to carry out and, thus, are used more often. This result may also indicate a gap in software functionality when it pertains to capabilities for certain organizational functions and the work they are carrying out.

Table 11: VR capabilities used by different organizational functions.

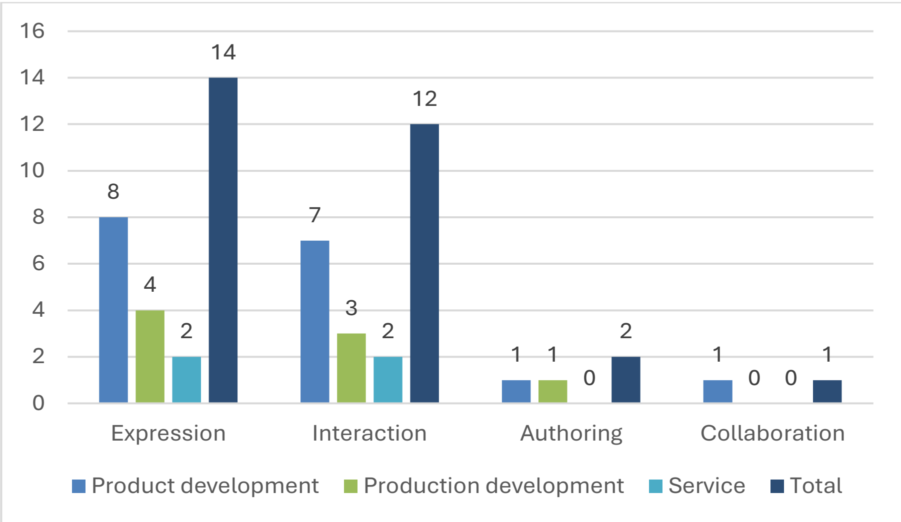


Table 12 is based on responses from survey question 21. The results show the extent to which different organizational functions were aware of their department's VR roadmap. Assuming that "No" and "Don't know" responses both translated to not having knowledge of a roadmap, most stakeholders were not aware of a VR roadmap for their department. This situation would be disadvantageous for the department as a roadmap could help guide stakeholders in the form of definitive actions to ensure that the adoption of VR would deliver its expected advantages (Ghobakhloo, 2020).

Table 12: Awareness of a VR roadmap among organizational functions.

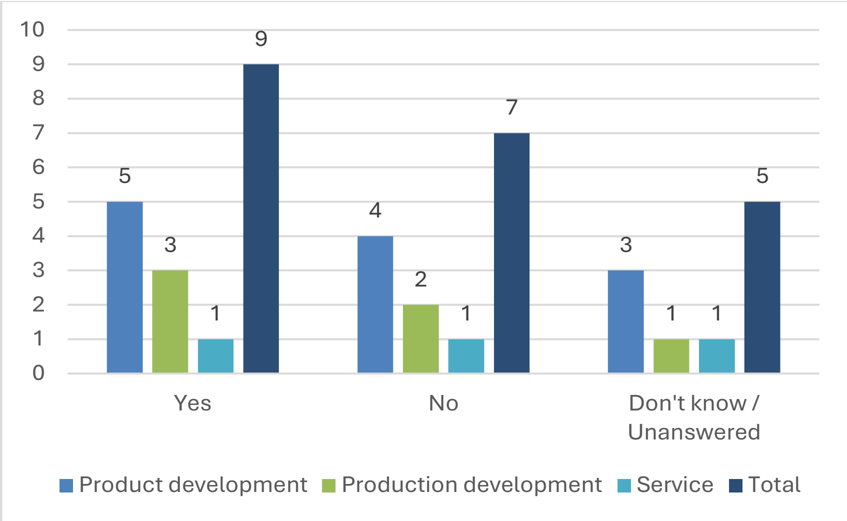
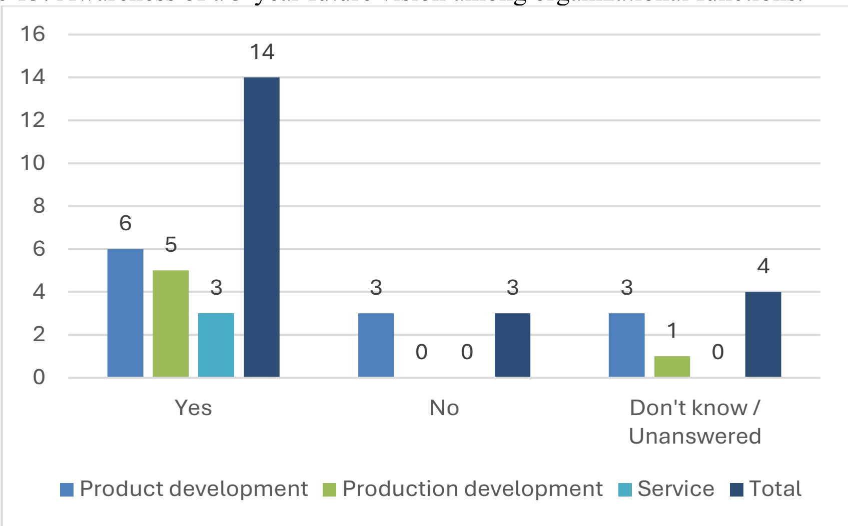


Table 13 is based on responses from survey question 22. The results show the extent to which different organizational functions were aware of their department's 3-year future vision of VR. Most stakeholders responded that they were aware of the 3-year future vision for their department, suggesting that the vision had indeed been pushed successfully through the organization and the organization was aligned on the strategic importance of the VR technology's benefits (Virmani & Salve, 2023).

Table 13: Awareness of a 3-year future vision among organizational functions.



5 Adopting VR in the NPD Process

This section analyzes and discusses the findings in order to answer the research questions.

The purpose of this thesis is to facilitate the adoption of VR technology in the NPD process. This licentiate thesis identifies VR adoption challenges and mitigations to those challenges, as presented in 5.1 and 5.2, respectively.

5.1 Challenges When Adopting VR in NPD Process

RQ1 asks: What are the challenges when adopting VR in the NPD process? This section presents a summary of the challenges related to VR adoption within NPD processes, organized among people, process, and technology dimensions. The challenge is correlated to the organizational level role of the respondent who experienced the challenge, not where it originated. A summary of the 19 challenges is presented in Table 14.

The challenges were further categorized into seven themes. Challenges were divided equally among the people and process dimensions, closely followed by technology. The operational level roles experienced by far the most challenges, followed by the strategic level role and, lastly, the tactical level role. After accounting for the three dimensions, the strategic level was mostly affected by technology challenges whereas the tactical level was affected by people and process challenges. The tactical level was not affected by technology at all. However, the experienced challenges did not uncover the source of the problem. No evidence indicated that work was taken away in lieu of the new technology, which in turn just created more overall work for operational level stakeholders, as corroborated by Thomke (2006). The added technology also required an extended time to learn to use effectively, which would also extend the duration of increased levels of work (Thomke, 2006).

Table 14: List of challenges found among the people, process, and technology dimensions

Dimensions	Themes	Challenges	Strategic	Tactical	Operational
People	Upskilling Challenges	Difficulty matching VR education to needs, including workflows and software	x		
		Lack of adequate VR software skills among users			x
		Skill development issues related to VR software usage			x
		Distrust of technology			x
	Lack of role/s on user level	Lack of dedicated role and support			x
		Loss of VR key user		x	x
		Lack of critical mass using VR		x	x
Process	Challenges structuring VR work	Lack of time to prepare VR			x
		Lack of standardized way of working when using VR in NPD process		x	x
		Difficulty changing way of working in NPD process			x
	External NPD process phase commitment	Imbalanced CAD maturity and quality to VR needs			x
		Lack of other stakeholders' collaboration			x
	Vision/value misalignment	Lack of purpose for using VR			x
		Lack of perceived value of using VR			x
Technology	Difficult VR usage due to technology immaturity	Inadequate software/hardware stability	x		x
		Cumbersome workflow between CAD systems and VR			x
		VR set-up preparation difficulties			x
	Challenges integrating software	Difficulty readying software/ hardware infrastructure	x		
		Difficulty integrating software due to security policies	x		

5.1.1 Challenges related to the people dimension

Among the people dimension, two overarching themes were identified: upskilling challenges and lack of role/s on user level.

In the upskilling challenges, four sub-challenges emerged: difficulties matching VR education to needs, including workflows and software as experienced by strategic level roles; a lack of adequate VR software skills among users; skill development issues related to VR software usage; and distrust of the VR technology, as experienced from the operational level roles. Developing VR skills among the operational user group, including employee resistance, is a known challenge (Stornelli et al., 2021). However, what is not apparent is the equally difficult task from top management's side to provide appropriate technology education in both the technology itself as well as communicating new workflows to match users' needs. This challenge needs support, as inappropriately implemented technology such as VR in the form of incorrectly matched training may lead to added waste due to the overly long time required to learn and use the technology effectively (Thomke & Fujimoto, 2000), thereby leading to user development issues and resistance.

The theme lack of role/s on the user level consists of a lack of dedicated VR roles and support, the loss of VR key users, and a lack of critical mass using VR, which affect both mid-level management and project leads at the tactical level as well as the VR users at the operational level. Although seemingly obvious, the challenges relating to the lack of onboarding VR users and key users are not found in the VR literature and need further investigation. What is found, however, is that an adoption team in general should comprise of experienced personnel who should be further trained to become digital key users, or champions (Butt, 2020). Either lacking a dedicated person, or champion, for the VR technology or having one and then losing the champion leads to a stop in the usage of the technology altogether in that specific team. Indeed, the challenge is that there is a lack of VR champions altogether. Furthermore, there is a lack of general users as well, who would feed the pool of champions.

Finally, an additional incident was observed such that the people dimension generally affects the operational level roles the most, followed by the tactical management level, and, lastly, the strategic level. Ultimately, all stakeholders are challenged in various ways throughout adoption, suggesting that the coordination of such efforts across various workforce levels adds an additional layer of complexity, which is in line with the literature (Saghafian et al., 2021).

5.1.2 Challenges related to the process dimension

Among the process dimension, three main themes emerged: challenges structuring VR work, external NPD process phase commitment, and vision/value misalignment.

Among challenges structuring VR work, three underlying challenges were found: a lack of time to prepare VR, a lack of a standardized way of working when using VR in the NPD process, and difficulty changing the way of working in the NPD process. These results suggest that there is no set standard for what the new work for VR should look like, much less how to make the changes needed to get there, nor do users feel like they have the time to use the technology itself, let alone develop these work procedures. This result relates to the challenge found in the literature that changing processes to support VR is challenging as workflows and data management processes remain unclear (Delgado et al., 2020). However, the challenge related to time to prepare (VR environments) was not found. This result may suggest that it is an underlying issue causing difficulties in changing way of working in the NPD process, stemming from workload overload from the added VR technology (Saghafian et al., 2021). Additional overload without also removing work simply adds more wasted time due to preoccupation with yet another support tool, especially when neither the work itself nor people's behaviors have changed (Thomke, 2006). Thus, the challenge of time needs further exploration. All challenges affected the operational level users; however, the lack of a standardized way of working when using VR in the NPD process also affected the tactical level role. This result may be due to this stakeholder finding it difficult to manage this change over multiple different stakeholders, as VR demands. This result is in line with the literature stating that managerial challenges include challenges related to spreading the workload across stakeholders (Saghafian et al., 2021).

Among external NPD process phase commitment, two underlying challenges were identified: imbalanced CAD maturity and quality to VR needs and a lack of collaboration from other stakeholders. In this case, "other stakeholders" refers to personnel from other functions within the company; such functions are upstream or downstream from where the VR work is taking place (e.g., CAD delivery from product development over to production development, where the VR work is taking place). This theme was not found in the literature specifically, which may be due to the fact that this comes from the perspective of the operational user team using the VR. From a wider perspective, the literature does describe how the VR workflows and data management process remain unclear (Delgado et al., 2020). As the challenge comes from the operational level team, this result may shed light as to why this is so, being that the workflow mentioned covers a range of departments; there is also a lack of coordination and alignment among them. This understanding is supported by the challenges in the literature regarding difficulties managing multiple stakeholders, including through communication and coordination (Saghafian et al., 2021). However, these challenges are from a management perspective, and the listed challenges highlight how the operational level team is experiencing the issue, which has not been mentioned in the literature.

In terms of the vision/value misalignment, two underlying challenges were defined: a lack of purpose for using VR and a lack of perceived value in using VR, both of which are described from the operational level view. These newfound challenges have not been specifically listed in literature. What the literature does mention are the challenges related to proving the added value of VR to others (Berg & Vance, 2017); however, that is from the sense that a purpose is known for VR usage and then perceived value was gained from that usage. Therefore, vision/value misalignment warrants further exploration. Furthermore, from a strategic and tactical level perspective, there are extensive vision and expectations for what VR technology should achieve. However, as seen here, this information was not being translated down to the operational users. This result might give insights into the challenges related to communication and coordination (Saghafian et al., 2021) as well as an overall lack of alignment among the organizational levels (Nayernia et al., 2021; Szász et al., 2020).

5.1.3 Challenges related to the technology dimension

Among the technology dimension, one main theme was defined: difficult VR usage due to technology immaturity. This theme comprises several sub-challenges, including inadequate software/hardware stability, cumbersome workflow between CAD systems and VR, and VR set-up preparation difficulties. As Saghafian et al. (2021) pointed out, challenges in VR usage still arise from the immaturity of the VR technology itself, as the software is still unintuitive in itself, and data formats and protocols for exchanging data among different data storage centers have not been standardized, leading to low levels of interoperability (Sekaran et al., 2021). These challenges may be the culprit leading to set-up difficulties during preparation phases of adoption (Stornelli et al., 2021).

5.2 Mitigating VR Adoption Challenges

RQ2 asks: How can the challenges when adopting VR in the NPD process be mitigated?

This section summarizes the mitigations inferred as solutions to the challenges listed in Section 5.1, organized among people, process, and technology dimensions. Table 15 presents a summary of all mitigations. As others have corroborated, the number of people mitigations and type (pertaining to organizational and management structures) are important during such technology adoption (Becker, et al., 2005).

Table 15: Presents all mitigations identified, themed according to the people, process, and technology dimensions.

Dimensions	Mitigations
People	Dedicated facilitator role
	Increase number of key users of VR technology
	Management commitment to using VR in NPD process
	Establishing ownership of VR work
Process	Vertical alignment among organizational levels
	Roadmap to VR adoption
Technology	Decrease data complexity for advanced VR usage

5.2.1 Mitigations related to the people dimension

Having a dedicated facilitator role is a mitigation as it fills the need for providing additional in-depth training, specifically toward work procedures for team workshops and specific competence expertise. As described in Paper III, one priority is developing the ways of working to incorporate VR into ongoing work processes. In this case, this priority was addressed by the software supplier. However, this priority can also be achieved by the additional role of a facilitator, which could mitigate the challenge of the difficulty in matching VR education to needs, including workflows and software. It would also mitigate the lack of adequate VR software skills, as concluded in Paper III, describing that the lack in a specific role led to a lack in sufficient knowledge to manage and support not just the technical skills, but also the soft skills such as ways-of-working. Incorporating a dedicated support role or facilitator is further strengthened by the literature (Johnsson, 2018), which noted that communication and support for the coordination of workload from a multi-stakeholder perspective is needed (Saghafian et al., 2021).

Increased number of key users for VR technology (technology champions) is another mitigation as increasing the number of key users on the same team to match the increase in the work is related to higher levels of VR adoption within that team. As presented in Paper III, "the number of key users was increased after every adoption cycle to match the increase in VR work needed to be carried out." The VR team is wholly dependent on the VR key users, and an increased amount of work can overload a key user if there are not enough such users to meet the growing work demand. This was discussed in Paper II, which concluded that key users were the bottleneck of VR work. Increasing the number of key users for VR technology mitigates several challenges, including the loss of a technology champion and the lack of critical mass. In the loss of a technology champion challenge, having additional key users as a back-up would enable the VR technology to survive on that team, whereas otherwise it would easily spell the end of the usage of VR within the department, as described in Paper II.

Management commitment to using VR in the NPD process is also vital to the success of the VR adoption, and not just within the department that owns the VR team, but also within those in other, integrated departments (e.g., product development and production development). From the VR team perspective, the project manager (gatekeeper) needs to commit to using the technology by scheduling VR checks in the NPD process, as described in Paper II: Managers are needed to transform project processes to include and call for virtual prototype validations. Indeed, "if the managers do not push for this, then the virtual prototype will be deprioritized by the engineers." This conclusion is directly supported by the literature stating that management should drive adoption through not only support, but also commitment to the technology's adoption (Virmani & Salve, 2023). Management commitment to using VR in the NPD process mitigates challenges related to structuring VR work, as in the lack of a standardized way of working and difficulty in changing the way of working. Such scheduling would allow deadlines for multiple departments and stakeholders to be prepared for an analysis using the VR technology. Adding this responsibility is strengthened by the literature stating that a key actor in boundary spanning is typically project management, who receives and distributes information among intra-organizational actors (Jepsen, 2013). Yet identifying the specific stakeholders, coordinating with them, identifying how they act, and carrying out the action are challenges themselves (Edmondson & Nembhard, 2009). One way forward can be for the (project) managers of both departments to lead the efforts, as Paper III demonstrated: The continued VR team's project manager (in production development) coordinated with the project manager from product development.

Establishing ownership of the VR work, or to a specific operational level team, is vital. The research covers VR adoption from different steps throughout the NPD process and, hence, from different stakeholders. As seen from both the survey and case studies, VR use varied among the different stakeholders, including product development engineers and production development engineers. Table 9 highlights how different stakeholders utilized VR among NPD process phases at different rates. Product development engineers used VR in earlier phases whereas production development engineers used VR evenly throughout all NPD process phases. This finding suggests that the engineers use the VR for different purposes within the software. Thus, if one was to consider the users of the VR, or who "owns" the work, then more specific training could be matched to those users, which would mitigate the challenge of the difficulty matching VR education to needs, including workflows and software. The education would be tailored to a specific purpose for those users, thereby helping to mitigate the challenge of the lack of purpose among users. In addition, a tailored roadmap to VR work and, thus, towards the vision would be useful. As seen in Table 12, not all stakeholders were clear on what the vision was for using VR, and Table 11 demonstrates that not all were knowledgeable about their department's roadmap, if there was one.

Figure 3 displays the utilized roles during the investigations of VR adoption into the NPD process, identified in the results of Papers I, II, and III. These roles proved to be key in the success of continued adoption. These roles have been categorized among three organizational levels: strategic, tactical, and operational levels. The strategic level consists of the strategic driver, the tactical level consists of the tactical driver, and the operational level consists of the gatekeeper, key user, and general user.

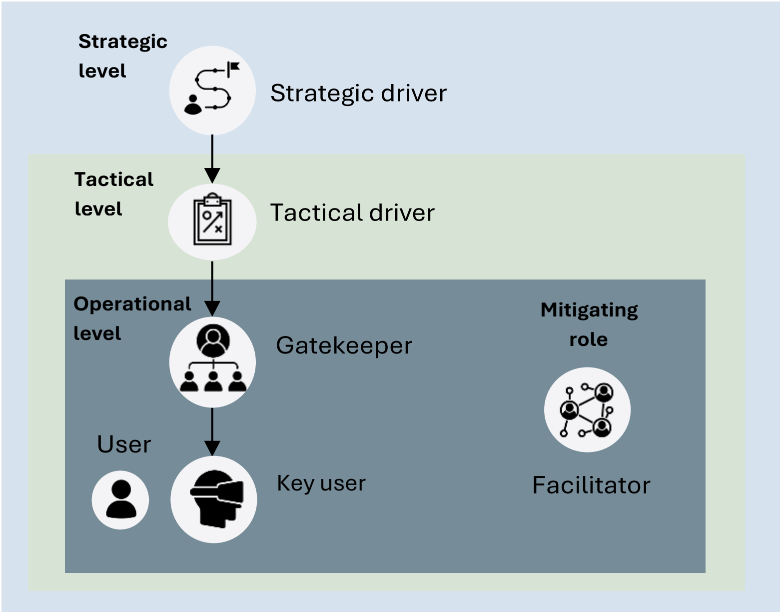


Figure 3: Identified roles during VR adoption.

Table 16 presents a detailed list of utilized roles and a description of their responsibilities, identified in the results of Papers I, II, and III. Also included is the mitigation of an additional role: the facilitator. The operational level was categorized as such as these roles have direct contact with VR usage, whether they make the VR themselves (key user), use the information gained from the VR usage within the same NPD process phase, or directly manage the project in that NPD process phase (gatekeeper). The drivers were themed as such as these roles had direct influence on the adoption of VR technology usage as their responsibilities entailed making decisions and carrying out activities directly toward this endeavor (strategic driver and tactical driver). An additional facilitator role was highlighted as a mitigation to several challenges, supported by findings in the literature (Andrew & Sirkin, 2008; Hunter & Cushenbery, 2011; Johnsson, 2018).

Table 16: VR adoption roles and their responsibilities

Role		**Responsibilities**
Strategic level	Strategic driver	• Creating VR technology roadmap and incorporating it into technology-wide strategic roadmap • Identifying potential use cases and forecasting impact on NPD process • Committing to, acquiring, and supplying standardized software to sites • Communicating strategic importance, use cases, and forecasted impact on NPD process • Creating and carrying out training material and ongoing support networks
Tactical level	Tactical driver	• Acquiring initial funding for equipment • Communicating strategic importance, use cases, and forecasted impact on NPD process • Creating and maintaining continuous improvement through local support networks • Committing resources for increased personnel • Committing to increased virtual testing events in NPD process
Operational level	Gatekeeper	• Planning and carrying out VR events within the NPD process • Communicating NPD process updates to other stakeholders

	Key user	• Keeping up VR lab and software updates
		• Facilitating VR usage to others
		• Following work procedures for creating VR environments for operational team
		  ○ Help plan events in NPD process
		  ○ Prepare and carry out VR events
		  ○ Record results from VR events
		  ○ Reflect and make improvements to ways of working
		• Committing to increasing VR skills and capabilities

	User	• Receiving and responding to results from VR events • Using VR in own work
Mitigating role	Facilitator	• Educating, advocating, and advising on VR adoption • Raising organizational awareness about adoption • Standardizing and communicating related vocabulary • Providing tools and training activities • Guiding the adoption process involving individuals, teams, divisions, and departments

5.2.2 Mitigations related to the process dimension

Strengthening the vertical alignment among organizational levels is a mitigation indicating the need for the strategic vision to be translated to the operational level. In the case of the continued VR adoption team (Paper III), the message to utilize and develop their usage toward increased DFMA purposes and the removal of early physical prototypes was clear. As described in Paper III, the top driver of the VR usage in the organization had initially decided to go forth with the VR technology as "it would theoretically align with the company's strategy toward model-based manufacturing, virtual prototyping, and increased concurrent engineering between departments" (head of production preparation processes), translated into increased DFAM and the removal of early physical prototypes. The VR team at the operational level eventually achieved both of these goals in their later NPD projects using the VR. Other teams who discontinued VR adoption described the vision as unclear when presented to them (see Paper II). Thus, aligning the vertical strategy with the operational strategy is paramount and mitigates the lack of purpose challenge. Indeed, the literature concurs, stating that alignment among all stakeholders includes understanding the strategic importance of the technology's benefits (Virmani & Salve, 2023), meaning that the benefits need to be translated directly to the operational team's needs. In addition, the alignment effort takes place among several workforce roles, ranging from upper management to the general user of the technology itself (Nayernia et al., 2021; Szász et al., 2020).

Having a roadmap to VR adoption is another mitigation, which refers to a plan describing the roles of people, responsibilities, and actions to take during each adoption phase of the new technology. None of the studied cases had such a roadmap, which may suggest why certain challenges arose, such as difficulties in changing the way of working and a lack of a standardized way of working. The roadmap would remove confusion related to what to do and help reach adoption more quickly. Figuring out the way forward with VR adoption takes considerable time. For example, in Paper I, "respondents described needing the time to develop a new work process, adjust the work descriptions accordingly, and allow space for this adjustment." In Paper III, the continued VR adoption team took approximately 5 years to reach a higher level of maturity. A noted argument in the literature is the lack of top management's awareness of the details necessary to create such a roadmap (Jalo et al., 2022). However, this challenge can be mitigated, as in Paper III, by striving for certain NPD process design parameters during various adoption phases (e.g., incorporating DFAM or boundary-spanning initiatives).

Furthermore, the roadmap should act as a blueprint of actions to ensure that the adoption delivers its expected advantages (Ghobakhloo, 2020) while helping overcome common challenges related to strategic visions often being too vague and abstract (Siebelink et al., 2021). Having distinct goals to reach within the roadmap during adoption phases can further support efforts to address the challenges of a lack of purpose and a lack of perceived value as it would include design parameters to reach. A noted argument is that measuring return on investment has proved challenging regarding VR adoption (Berg & Vance, 2017); however, it could be better measured if data is collected according to the design parameters (e.g., theoretical time saved and faults found among the additional included stakeholders). The roadmap would also act as a communication tool, enabling other stakeholders (e.g., managers) to understand the capabilities their team can achieve at a given adoption phase. The roadmap directly coincides with vertical alignment as clear purposes should be translated to the operational level.

During the investigation of VR adoption in the NPD process (Paper III), a VR adoption process was identified (Figure 4). The adoption process was mapped over the course of three consecutive NPD projects. Within each project, the roles made decisions and carried out specific activities (as described in Table 5). These decisions and activities took place in consecutive adoption processes: initial adoption and then continued adoption. As displayed, the entire adoption started with the strategic driver, followed by the tactical driver. The entire VR usage pitch was then given to the gatekeeper, the project manager of the NPD project. This person initiated the use among their team, including the key user, who carried out the VR usage procedure (plan, prepare, record, reflect). Once work procedures were finalized and the results communicated, the initial adoption process ended. Based on the results of VR usage within the NPD project, the tactical driver made the decision to continue using the VR in the next NPD project, and the adoption process continued, with additional developments. Additional developments included an increased commitment to the technology usage by the tactical level driver, increased capabilities to be carried out by the key user, and a feedback loop from the upstream/downstream stakeholders. Developments in the second adoption iteration of VR usage led to increased value back to the team because they had more resources and skills to carry out more complicated tasks. The adoption process was again confirmed to give enough value to make the decision to continue its usage and develop it further through even more increased commitment (resources and virtual testing) and increased capabilities.

The mapping presented in Figure 4 showcases how the team was steered toward integrated product development approaches, such as simultaneous work, integrated teams, and early stakeholder involvement, which is important to deliver the expected advantages (Ghobakhloo, 2020). The mapping also shows how more stakeholders from upstream and downstream NPD phases were included over time. An increase in the coordination of workflows also occurred over time, such as CAD packages being delivered to work concurrently, as seen in the later adoption phases. The occurrence of these developments tended to occur after the initial adoption phase. Although not specifically stated, this example may be a deeper descriptor of what Pozzi, et al. (2021) alluded to—namely, that continuous improvements enable further adoption.

Figure 4 displays the mapping of the roles, decisions and activities, and development through iterative adoption phases; such mapped out procedures has a likeness to how a roadmap can be formulated, thereby can serve as a de-facto roadmap. A portion of the mapping is in line with roadmap literature, specifically the work procedures carried out by the key user (i.e., plan, prepare, record, reflect), which reflect the work procedures outlined by Ventura (2020). However, the mapping displayed here highlights adoption at a larger, organization-wide scope. The mapping seemingly coincides with many of the phases mentioned in the existing literature (Butt, 2020), although not in the same order or at the same scale. According to Butt (2020), the mapping should include the phases of (1) define, (2) measure, (3) evaluate, (4) optimize, (5) develop, (6) validate, and (7) implement. In the mapping (Figure 4), phases 1–3 occur during the implementation phase itself, phase 6 occurs at the end of each adoption phase, and phases 4–5 occur among the iterative adoption processes as they continue. Furthermore, in accordance with the literature, this mapping (Figure 4) describes the characteristics of work in each adoption phase (Butt, 2020); it is structured, visual, and chronological and steers toward a strategic intent (Kerr & Phaal, 2022).

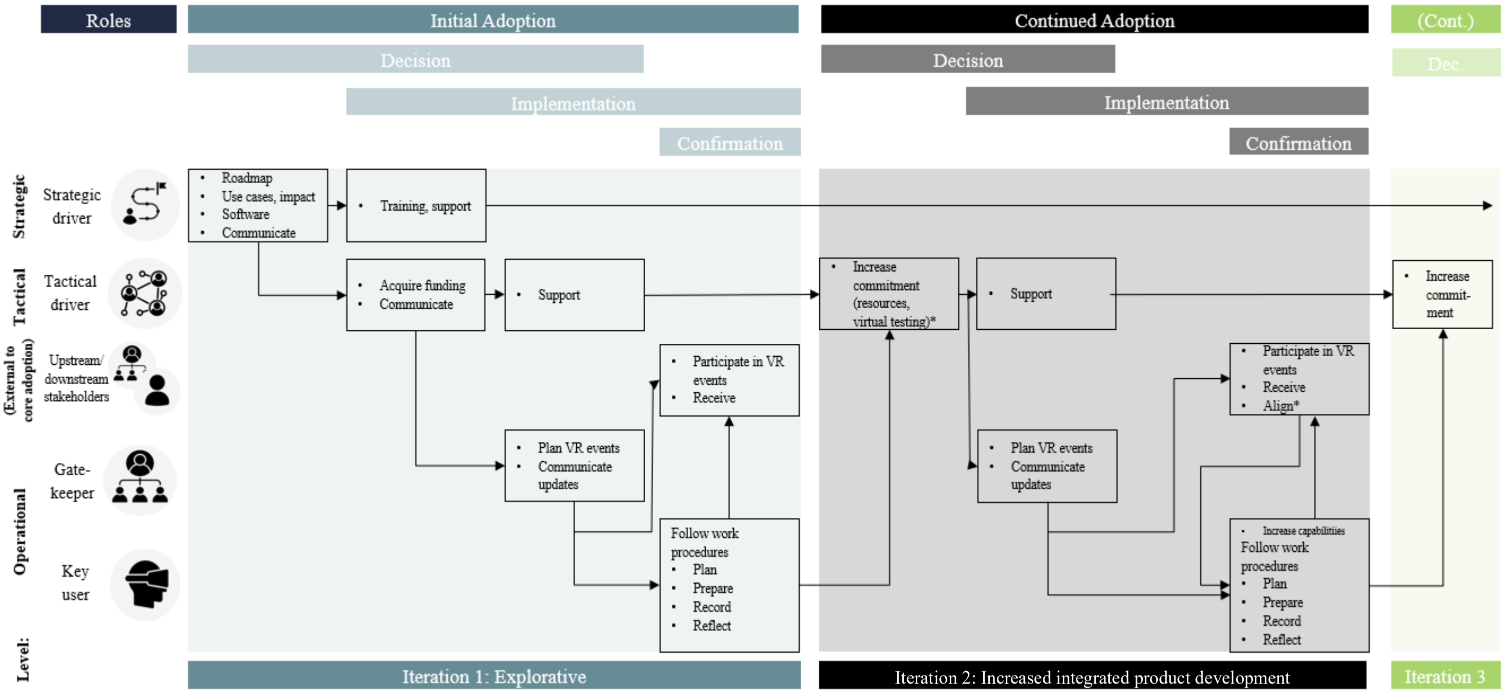


Figure 4: Mapping of adoption process, from initial to continued adoption.

5.2.3 Mitigations related to the technology dimension

The mitigation to decrease data complexity for advanced VR usage refers to decreasing the number of individual components being utilized/validated while carrying out advanced VR usages (e.g., assembly sequence validation or other simulations). More specifically, data complexity refers to the number of individual components in the machine assembly/sub-assembly that should be reduced before attempting more complex VR usages on it. This factor is highlighted in Paper III, where the continued VR adopter team eventually fine-tuned their way of working with the VR assembly capability, resulting in them carrying out analyses on only sub-assemblies. However, to achieve this, their journey with VR for assembly purposes transitioned during three consecutive NPD projects, from smaller sub-assemblies with low component counts (10–30 components, for example) to the full machine/product assembly (thousands of components) and finally full sub-assemblies (dozens to hundreds of components). This mitigation concurs with the DFMA literature, noting that the additional challenges of utilizing DFMA on larger, more complex assemblies require much more data for the analysis and, as a result, the tools are typically applied to product sub-systems (sub-assemblies) (Formentini et al., 2022). DFx tools such as DFMA are already considered to be too complex and time-consuming and, therefore, are hardly used (Benabdellah et al., 2019); thus, if the VR is to add value, it should not add to the already perceived complexity of DFMA.

This mitigation supports the challenges of a lack of perceived value, as described in Paper III from the discontinued VR adopters. The project managers in both cases described the VR tool as “too complex” and “not worth the effort” after the decision was made to discontinue its usage. Both teams had tried using advanced VR, such as interaction, on a full machine model.

This factor also helps mitigate the challenges stemming from inadequate software/hardware stability, as component count directly relates to the number of assembly actions to analyze. It decreases the amount of processing power the computer requires, thereby helping to avoid crashes and, thus, increase the stability of VR sessions. Interestingly, this approach enabled an additional change toward working in a more agile manner, thereby increasing the coordination among upstream CAD stakeholders over time. This situation was also described in Paper III: Product and production development teams had planned and increased the coordination of delivery of CAD sub-assembly models. Thus, VR test cycles were carried out more often, in shorter sprints for visualization, communication, ergonomics and interaction. Therefore, the mitigation further addresses the challenge a lack of collaboration from other stakeholders. In addition, the CAD models themselves were more mature/complete and less cumbersome to work with, partially mitigating the challenges of imbalanced CAD maturity and quality to VR needs and cumbersome workflow between CAD systems and VR (Paper I).

5.3 Roadmap to VR Adoption: Overview of Challenges, Mitigations, Roles, and Adoption Process

Table 17 presents 19 challenges and 7 mitigations related to VR adoption in the NPD process. These are later placed throughout Figure 5 according to the adoption role and adoption phase in which they take effect.

Table 17: Summary of challenges and mitigations

	Challenges
C1	Difficulty matching VR education to needs, including workflows and software
C2	Lack of adequate VR software skills among users
C3	Skill development issues related to VR software usage
C4	Distrust of VR technology
C5	Lack of dedicated VR role and support
C6	Loss of VR key user
C7	Lack of critical mass using VR
C8	Inadequate software/hardware stability
C9	Cumbersome workflow between CAD systems and VR
C10	VR set-up preparation difficulties
C11	Lack of time to prepare VR
C12	Lack of standardized way of working when using VR in NPD process
C13	Difficulty changing way of working in NPD process
C14	Imbalanced CAD maturity and quality to VR needs
C15	Lack of collaboration from other stakeholders
C16	Lack of purpose for using VR
C17	Lack of perceived value of using VR
C18	Difficulty readying software/hardware infrastructure
C19	Difficulty integrating software due to security policies
	Mitigations
M1	Dedicated facilitator role
M2	Increased number of key users for VR technology
M3	Management commitment to using VR in NPD process
M4	Establishing ownership of VR work
M5	Decrease data complexity for advanced VR usage
M6	Vertical alignment among organizational levels
M7	Roadmap to VR adoption

Figure 5 presents a roadmap for adopting a VR process in the NPD process. The framework displays how VR adoption can mature over the course of three consecutive adoption phases. The framework is a culmination of a range of interconnected variables that include the following:

- Maturity level and subsequent impact on the NPD process
- VR capabilities that can be achieved
- Roles of personnel involved in the adoption and their subsequent decisions to make and activities to carry out
- Challenges experienced by the roles along different adoption phases
- Proposed mitigations that can be applied among the roles along different adoption phases

The roadmap incorporates people, process, and technology dimensions that are essential to consider. It also describes how these dimensions are simultaneously developed over time to reach heightened adoption and, thus, increased value from the VR technology. Table 18 displays the resulting challenges and mitigations from the work, which are then included in the framework. The challenges have been assigned to the role according to who experienced the challenge during the specific adoption phase. Mitigations have been proposed under specific adoption phases and assigned to the roles that would be affected by them. The majority of challenges were experienced during the initial adoption phase; however, the challenges may continue throughout the phases if not mitigated appropriately. The overwhelming number of challenges in the first phase typically led to teams ending the adoption; as a result, ongoing challenges were difficult to trace.

By including this range of variables, future adopters can gain a deeper understanding of the intricacies at play among the different organizational level stakeholders and be better prepared to communicate the upcoming adoption journey through the artifacts presented, such as the framework, which can also work as a roadmap.

Adoption phase		Phase 1: Initial adoption	Phase 2: Continued adoption	Phase 3: Continued adoption
Maturity level / Impact on NPD process		Foundational: Exploring the use of VR usage types with low data complexity. No additional personnel needed and minimal other stakeholder involvement. NPD work procedures unchanged.	Accelerating: Committed to the use of interactive VR with increased data complexity. Additional personnel included and other stakeholders become increasingly involved. VR is officially added to ongoing work procedures.	Dynamic: Adapted use of interactive VR with heightened data complexity. Additional personnel needed and other stakeholders greatly influenced. Work procedures become greatly altered to adapt to VR.
Impact on NPD process		Minimal	Detectable	Significant
VR capabilities		Visualization, Ergonomics, Communication	Authoring	Simulation (Abstract data visualization)
Roles / Decisions / Activities	**Strategic driver**	Decisions: Determine strategic roadmap, use cases, software, communicate decisions Activities: Launch training and support Challenges/Mitigations: C1, M6	Decisions: Continue adoption Activities: Continue training and support	Decisions: Continue adoption Activities: Continue training and support
	Tactical driver	Decisions: Acquire funding, communicate decision to proceed Activities: Launch local support Challenges/Mitigations: C12, M3, M6, M7	Decisions: Increase commitment (resources, virtual testing) Activities: Continue local support Challenges/Mitigations: M2, M3, M7	Decisions: Increase commitment (resources, virtual testing) Activities: Continue local support Challenges/Mitigations: M3, M7
	Upstream personell	Activities: Participate in VR events, receive results	Decisions: Align for CAD deliverables Activities: Participate in VR events, receive results	Decisions: Increased alignment for CAD deliverables Activities: Participate in VR events, receive results
	Gate -keeper	Decisions: Plan VR events in NPD process. Communicate with team Activities: Carry out planned events Challenges/Mitigations: C6, C7, C12, C13	Decisions: Increase scope of planned events in NPD process. Communicate updates. Activities: Carry out planned events	Decisions: Increase scope and frequency of planned events. Communicate updates. Activities: Carry out planned events
	Key user	Activities: Follow work procedures: Plan, Prepare, Record, Reflect Challenges/Mitigations: C2, C5, C7, C8, C9, C11, C12, C13, C14, C15	Activities: Increase capabilities, follow work procedures: Plan, Prepare, Record, Reflect Challenges/Mitigations: M5	Activities: Increase capabilities, follow work procedures: Plan, Prepare, Record, Reflect Challenges/Mitigations: M5
	User	Challenges/Mitigations: C3, C4, C10, C16, C17, M4, M5		
	Facilitator	Challenges/Mitigations: M1		

Figure 5: A roadmap for adopting VR in the NPD process.

6. Discussion and Conclusion

This chapter discusses the insights gained from the research as well as the theoretical contributions and practical implications. The limitations and potential trajectories for future research are also presented.

6.1 Discussion

This thesis aimed to facilitate the adoption of VR technology in the NPD process. The insights from this work present several points of discussion.

The first insight questions whether VR adoption really does decrease TTM as theorized. Generally, new technology adoption has been shown to have a significant positive effect on the NPD process as it can enhance workflows and information management among different stakeholders (Durmuşoğlu & Barczak, 2011). However, according to the current research, the moment at which VR impacts the NPD process in a meaningful way, and thus TTM, occurs after several iterations of VR adoption, which takes considerable time and is a known phenomenon among new technology adoption in general (Voss, 1992). In initial adoption phases, VR usage causes more added work (especially for workflows and information management) than the NPD process impact, which is difficult to overcome for new users. One solution could be to assign dedicated personnel/teams to carry out VR work and then, through a change management perspective, communicate to different NPD process functions how the VR should be utilized. The stage in which integrated product development has been adopted would also affect VR adoption impact, which may in itself be the driving force in reduced TTM (Kang et al., 2022; Turkulainen & Ketokivi, 2011).

Second, VR usage among people engaged in engineering work is not as simple as implementing the software. More realistically, VR adoption requires adjustments to processes such as changes in the development of data management processes and the standardization of data formats to simplify the usage of complex CAD data. These known weaknesses still plague VR technology usage (Delgado et al., 2020; Sekaran et al., 2021) and, thus, VR adoption. Furthermore, VR adoption entails coordination among functions along the product life cycle, such as between new product development and the product development process to streamline deliveries of CAD data. This aspect is dependent on the maturity of integrated product development practices among the functions; as such, this needs to be addressed first or simultaneously with VR adoption. Ignoring any of these factors would likely lead to the failure of mass VR adoption within a large manufacturing organization.

The strategic vision of VR usage for a fully virtual prototype may be unrealistic. The overall vision with VR usage, along with other virtual prototyping and simulations, has been to decrease the need for physical prototypes in the hopes of saving substantial time. However, many stakeholders, including engineers, have relied upon the physical prototype to validate early concepts for many years. They can physically feel the prototype, climb into it, and see sizes and distances. The introduction of VR has resulted in some mistrust of the virtual build compared to the physical build; therefore, a quick transition or the full removal of physical prototypes could result in negative consequences. Alternatively, VR could be earmarked for products undergoing improvement as opposed to an entirely new product (Liker & Pereira, 2018), or an integrated approach could be investigated, using portions of a virtual and physical prototype in tandem (Choi & Chan, 2004; Snider et al., 2022).

Interestingly, the adoption process and iterative cycles were largely based around the NPD processes. Instead of a steady continuation of adoption overall, it was the NPD processes that marked the beginning and end of a new try and continuance of the adoption, as seen in Paper III. This may have occurred because the case team who continued with adoption was simultaneously upskilling themselves. This may be due to the case team being from production development; thus, the continuous improvement practices they carry out (e.g., planning) reflect on and carry over to lessons learned for the next project, which is a hallmark of continuous improvement (Pozzi et al., 2023). Comparatively, the other cases may not have implemented such robust continuous improvement practices (Nilsson-Witell et al., 2005).

Adoption may not need to be driven from a top-down approach, as witnessed in these cases. It could start anywhere, such as from bottom-up VR enthusiasts who are engineers within a given NPD project and from the NPD project managers themselves. However, there are still advantages to having a roadmap at the strategic level as it guides sites toward a common larger envisioned goal that they may not realize themselves. On the other hand, the individual sites may come to other larger visions more tailored to their needs. A disadvantage of driving adoption from the bottom up is that it may be more difficult to get buy-in from higher managers for resources or commitment from other departments.

Lastly, VR adoption should be considered a tool in the toolbox, where other simulation tools are also kept. Thus, VR adoption should be considered among a wider scope, especially within a virtual verification adoption, where several tools are adopted simultaneously. According to Frank, et al. (2019), VR usage is primarily used for smart working and is typically implemented last, after other technologies.

Considering the discussions thus far, this thesis concludes with theoretical contributions and practical implications, offering valuable perspectives to future VR adoption endeavors throughout the NPD process.

6.2 Theoretical Contributions

This thesis contributes to research within the field of technology adoption in the NPD process, specifically VR, by identifying challenges and mitigation from a joint people, process, and technology dimensions perspective. A list of 19 overall challenges that affect VR adoption and 7 mitigations to address said challenges have been found (see Table 14). Previous research has described a gap within organizational know-how (Saghafian et al., 2021), process changes (Delgado et al., 2020), and technology integration (Sekaran et al., 2021), albeit mostly from a narrow individual lens. By analyzing the results from RQ1 through a joint people, process, and technology dimension perspective and simultaneously looking at the organizational/process change/technology integration gaps, new results have emerged that contribute to supporting VR adoption. Notable challenges in the people dimension reveal a serious gap between the training being provided (in terms of software and workflows) and the upskilling challenges facing VR users. This gap provides insights and expands upon listed challenges, such as employees resisting VR usage (Stornelli et al., 2021). The more apparent reason is that training does not cover what is needed in terms of both software and workflow procedures. This finding overlaps another previously unlisted challenge of onboarding enough users to sustain VR usage for an NPD process. Notable challenges previously unmentioned in existing literature among the process dimension include a lack of purpose for using VR and a lack of perceived value of using VR from operational level users. These challenges represent the initial hurdle that VR adoption must overcome and can be seen as an extension to the challenges Saghafian et al. (2021) found within communication and coordination as well as those found by Berg and Vance (2017) related to challenge of proving the added value of VR to others. These findings clarify that operational teams need significantly more detailed knowledge on what to use the technology for (such as specific requirements' validations), which has been lacking during the spread of awareness. These gaps offer future opportunities for researchers to explore.

The second theoretical contribution is identifying a VR adoption process (Figure 4). Previous work on VR adoption simply listed challenges (Saghafian et al., 2021) or enablers (Jalo et al., 2022), falling short in describing how to achieve VR adoption from a process view. Other work has shown a process view, but focused only on initial implementation procedures (Ventura et al., 2020) or skipped to the VR being fully adopted (Berg & Vance, 2017). The VR adoption process found herein bridges the gap between these two extremes while simultaneously revealing that adoption increases over time. Furthermore, the process view is presented from the perspective of several organizational levels, including the strategic level, the tactical level, and the operational level. Previous research has described only the VR team roles included (Berg & Vance, 2017). By expanding the range of organizational levels and roles included, additional findings came to light, such as the interplay among the levels. This interplay and the identified challenges expand upon the previously mentioned challenge of coordinating VR adoption (Saghafian et al., 2021) as well as the notion that adoption takes place at different organizational levels (Nayernia et al., 2021). By exploring the development of the adoption process over time, a myriad of causes and effects to decisions made were found, especially changes that occurred to the operational team from each consecutive project. The development and interplay of the operational level team and the tactical level driver proved to be key during VR adoption in the NPD process, specifically how the value showcased by the operational team led to an increase in commitment from the tactical level driver, leading to more resources, more key users, and thus more value output.

The third contribution is the development of a roadmap for VR adoption within the NPD process. The roadmap describes how VR adoption can be developed over time, thereby acting as a blueprint of actions to ensure that the VR adoption delivers its expected advantages (Ghobakhloo, 2020). The roadmap presented herein contributes to the literature by unveiling a combination of vital VR variables determined to be necessary to take into consideration when adopting VR. Such variables include VR capabilities that can be realized and the development of stakeholder roles that need to take place (e.g., increased commitment by tactical level drivers through increased resources and increased upskilling of key users, which gives operational teams the ability to carry out more advanced capabilities). These variables were previously presented as standalone factors in the literature (capabilities: Choi et al. [2015]; management commitment: Jalo et al. [2022]; stakeholder involvement: Kharub et al. [2022]). The variables are further described among three maturity levels of VR adoption, which are designed to steer the usage of VR toward increased integrated product development practices. In line with Siebelink et al. (2021), the roadmap helps circumvent critical strategic challenges, such as aligning the activities of various functional disciplines and making it easier for employees to understand so they can transform their knowledge into action. Furthermore, by utilizing the adoption process for the roadmap, phases undergo iterative states of decision–implementation–confirmation, decision–implementation–confirmation, and so on, which contrasts with the existing roadmap literature (Butt, 2020); however, it automatically incorporates the paradigm for continuous improvement, which ultimately enables further adoption (Pozzi et al., 2023).

6.3 Practical Implications

The findings presented herein have practical implications. The main implication is that VR should be seen as a support tool for a direct reason for a specific team, coalescing into a larger vision. An example includes utilizing VR to support boundary spanning during integrated product development, as it can act as a coordination mechanism. As described in Paper II and Paper III, requirement validation meetings were held with a multitude of stakeholders. Everyone was able to experience the same life-sized 1:1 scale machine design and "be on the same page" in terms of information through the support of the visualization tool. Therefore, the different stakeholders would be on a more even understanding of what they are discussing and making decisions about, even if the group consists of design engineers, production engineers, managers, material procurement, and aftermarket. In Paper III, the validation meeting with many stakeholders occurred in the second iteration of adoption and was enhanced in the third iteration. Checklists should be prepared to coordinate what to validate and test in the virtual environment and then discussed among the different stakeholders.

The second implication is that commitment is needed from many levels in the organization for VR adoption to succeed. Commitment translates to allocating funds for adoption (for software, hardware, and the assignment of workers to dedicated VR roles), allotting time for VR preparation, and coordinating to improve CAD readiness. Alternatively, the software can be distributed in the hopes that engineers pick it up to use. The results from this approach can be ascertained from the challenges detailed in Paper I, including a lack of a dedicated role, a lack of time to prepare VR, imbalanced CAD maturity, and a lack of collaboration from other stakeholders.

The third implication revealed is that many aspects related to VR adoption need to be more tailored to the specific stakeholder compared to how it is implemented today. As Paper I demonstrated, VR is implemented in a blanket fashion, where the same education is given to learn the software, yet no training is provided to change one's way of working. Many experienced challenges can be tied back to this issue, such as difficulty matching VR education needs (including workflows), a lack of adequate VR software skills, and skill development issues. These challenges act as a barrier to new users, causing adoption to fail in initial tries. Alternatively, education can occur in greater depth with a smaller scope for specific users. For example, hose design can be limited to design engineers in installations whereas assembly simulations can be limited to production engineers.

Finally, a contribution of this thesis for practitioners are the description of roles and responsibilities, the mapping of work showcasing the flow of decisions and activities, and finally the roadmap summarizing a multitude of vital variables across three adoption phases.

6.4 Limitations and Future Research

Future work can be motivated by the limitations of this thesis. This work has focused on VR adoption in the NPD process in two large manufacturing companies in the automotive and heavy vehicle industries, with an emphasis on internal engineering stakeholders. The studies were qualitative and retrospective, and the identified challenges, mitigations, and adoption process were not systematically validated. These limitations point to several directions for future research.

First, there is a need to expand and test the results in other contexts. The identified challenges and mitigations could be explored in other industries (such as aerospace, process industries) or additional manufacturing organizations with different product complexities or organizational structures. Such examinations would provide insights into which challenges and mitigations are context-specific and which are more generic. Similarly, the focus has been on internal NPD process teams; thus, future work could expand to more functions to include marketing and customers to understand how these stakeholders influence VR adoption and value creation.

Second, the proposed VR adoption process and roadmap need to be empirically validated, which could be carried out through quantitative studies utilizing surveys across a larger sample of manufacturing sites or sample companies. Such work could help further test and develop the relationships among adoption stages, maturity attributes, and perceived NPD process performance effects.

Finally, future research should continue to explore the technological and data management aspects of VR usage. This thesis has highlighted data complexity, software integration, and data management as vital challenges, but technical solutions were not specified. Future research could investigate methods for simplifying data for different VR use cases and guidelines for selecting VR use cases for different NPD process activities. These solutions could be further extended to broader extended reality technologies, such as augmented reality.

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Appendix A: Survey Questions

1. What is your job title and you role?
2. What division/department do you work in? Check all that apply.
    a. Technology
    b. Operations
    c. Service
    d. IT
3. At what site are you stationed?
4. At what levels are you working?
    a. Local
    b. Global
    c. Both
5. How long have you worked at Volvo?
    a. 1-3 years
    b. 3-5 years
    c. 5-10 years
    d. 10+ years
6. How do you use VR? Check all the apply
    a. I make strategic decisions about VR
    b. I implement and support VR
    c. I create VR
    d. I use information from VR in my work
    e. I do not create or use VR in my work (go to question 9)
7. How often are you involved with VR in your work?
    a. Daily
    b. Weekly
    c. Monthly
    d. Quarterly
8. How long has VR been involved in your work?
    a. 1-3 years
    b. 3-5 years
    c. More than 5 years
9. Describe how you were first introduced to VR.
10. Describe the type of activities you have partaken in to learn more on VR.
11. Describe who drives the VR implementation in your department and how they drive it.
12. Choose a specific case where you worked with VR in the past and considered it a success. Describe the experience and why you think of it as a success.
13. Choose a specific case where you worked with VR in the past and considered it a failure. Describe the experience and why you think it was a failure.

14. What are the largest challenges for you when involving VR in your work?
15. What are the largest enablers for you when involving VR in your work?
16. Give 3-5 keywords that summarize your view of VR in your work.
17. If you currently work with VR in the Development process or Production preparation process, where do you use VR in your work: (if no, go to question 19)
    a. Technology Creation (Advanced Engineering)
    b. Feasibility Study
    c. Concept Development
    d. Solution Development
    e. Final Verification
    f. Industrialization & Commercialization
18. Please describe further the sub- process/activity which you use VR (the sub- processes would be included under the Development process, Production preparation process, etc.)
19. If you currently use VR in your daily work, please describe what you use VR for and in what type of project/tasks? (If no, go to question 20)
20. If you have worked with VR in the past, please describe what you used VR for and in what project/tasks you used it. (If no, go to question 21)
21. Does your department follow a road-map for the implementation of VR?
22. What is your vision for the use of VR within the next 3 years?
23. What is your department's vision for the use of VR over the next 3 years?
24. Please set a grade that you feel your team is at for the following dimensions (1-5):

    a. Trust
    b. Time
    c. Education
    d. Usefulness
    e. Teams
    f. Management
    g. Senses
    h. Process
    i. Roles
    j. Software
    k. Acceptance
    l. Organizational culture
    m. Support

Appendix B: Interview Questions

General

1. What is your job title and what is your role at the site?
2. Are you involved in the new product development process? Responsible for?
3. Do you use VR as a tool in the new product development process? For what and in which phases?
4. Do you make decisions on VR implementation? Describe your role in the implementation.
5. Who decided to implement VR here? Was it mandated?

Vision and Roadmap

6. Do you have a vision for what you want to achieve with VR?
7. Do you follow a road map for VR implementation?
8. Were there any factors that needed to be fixed first before VR could be implemented into the NPD process?
    a. Other I4 technologies?
    b. Global vision and roadmap?

VR into NPD process

9. How do you determine that this stage of the NPD process is suitable for implementing VR?
10. What steps do you take to integrate VR into the existing product development workflow?
11. How do you identify and prioritize the steps needed to be taken for VR implementation?
12. How does/does not VR influence and improve decision-making within this stage of the NPD?
13. What challenges or limitations did you have when implementing VR in the NPD process, and how did you address them?
14. How do you ensure that the costs associated with implementing and maintaining VR are justified by the benefits it brings to the NPD process?
15. What metrics of KPIs do/would you track to evaluate the success and impact of VR on the NPD process?

Collaboration within NPD process

16. What type of collaboration was needed from other teams in the NPD process?
17. How do you facilitate collaboration and communication among different teams, such CAD managers and engineers, when using VR in the NPD process?
18. What challenges did you have when collaborating with other teams in the NPD process?

    What were the factors for success to collaborating with other teams in the NPD process?