THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Balancing Value Trade-Offs in Automotive Platform Evolution

A Proactive Flexibility Modelling Approach for Efficient Technology Introduction

IÑIGO ALONSO FERNÁNDEZ

Department of Industrial and Materials Science

CHALMERS UNIVERSITY OF TECHNOLOGY

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ABSTRACT

In a rapidly evolving automotive landscape, with quick technological advancements and shifting customer demands, the ability to design flexible product platforms has become a critical competitive advantage. This thesis aims to develop design supports for the iterative design and analysis of the incorporation of new technology into automotive product platforms, by investigating how these platforms can adapt to rapid technological changes and diverse customer demands, i.e., expand their *external variety*. The intense competitive landscape and minimal profit margins in the automotive industry have necessitated its platform development to focus on cost efficiency and standardization, i.e., limiting the *internal variety*. However, with the increasing pressures of sustainability and the need for quicker market responses, traditional approaches have shown that the rigidity of the constraints they impose limits their ability to adapt swiftly.

This thesis proposes a model-based framework that emphasizes the early integration of flexibility, value-based decision-making, resilient design strategies, and proactive risk management to address these challenges. A new method using the concept of *platform margins* was introduced to assess platform flexibility over time. Further, the concept of *resilient objects* was developed, which are platform components that can easily adapt to or absorb changes. The research also addressed *change propagation*, especially considering *Field Effects* (FE). These methods were validated through real-world tests involving experienced practitioners from Swedish automotive OEMs.

This thesis highlights the importance of prioritizing flexibility from the initial stages of platform design when the impact of architectural decisions is greater. By employing value-based decision-making techniques, the framework balances short-term and long-term goals, aligning the control of current costs with the necessary buffers to address future needs. Proactive risk management techniques are employed to predict and mitigate potential risks from the higher-order effects of technology changes. This framework, with its focus on platform design margins, provides a strategic approach to optimizing the trade-off between both *internal* and *external variety*, ensuring platforms are not only efficient today but also ready for the innovations of tomorrow.

Keywords: Flexibility, Model-Based Design, Product Development, Product Platforms, Technology Integration, Systems Engineering, Platform Margins, Resilient Objects

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Lastly, I owe my profound gratitude to my family. Your unending patience, love, and belief in my abilities gave me the strength and determination to persevere through the challenges of this academic endeavour. Thank you, your support made all the difference.

Sincerely,

Iñigo Alonso Fernández

Gothenburg, Sweden, June 2024

List of Appended Papers

The following research papers form the foundation of this thesis. The work for each paper was distributed among the authors as described below.

Paper A ***Identification of Technology Integration Challenges at Two Global Automotive OEMs***

Iñigo Alonso Fernández, Massimo Panarotto, and Ola Isaksson.

Presented at the DESIGN Conference 2020, (Cavtat, Croatia, hosted online). Published in the Proceedings of the Design Society: DESIGN Conference, pp. 2245–2254.

Iñigo Alonso Fernández conceptualized the paper, performed the literature studies, performed the data collection and analysis, and coordinated the contributions of the other authors. Massimo Panarotto and Ola Isaksson also contributed to the empirical data collection and contributed knowledge and critique of the paper's concept, content, and form.

Paper B ***Reconciling Platform vs. Product Optimisation by Value-Based Margins on Solutions and Parameters***

Iñigo Alonso Fernández, Massimo Panarotto, Ola Isaksson, Thomas Krusell, and Timo Kero

Published in the *Journal of Engineering Design. https://doi.org/10.1080/09544828.2024.2396200*

Iñigo Alonso Fernández conceptualized the paper, developed the theoretical prescriptive contributions, performed the case study, coordinated the contributions of the other authors, and wrote the main body of the paper. Massimo Panarotto wrote the methodology step related to the value and market models and led some of the rewrite efforts after revision requests were received from the journal reviewers. Ola Isaksson contributed knowledge and critique to the paper's concept, content, and form. Thomas Krusell and Timo Kero contributed to the case studies and the theory development, as well as the industrial perspective to the paper's concept and content.

Paper C ***Designing Multi-Technological Resilient Objects in Product Platforms***

Iñigo Alonso Fernández, Massimo Panarotto, and Ola Isaksson.

Presented at the NordDesign 2022 conference, hosted in Copenhagen (Denmark). Published in DS 118: Proceedings of NordDesign 2022, Copenhagen, Denmark, 16th - 18th August 2022, pp. 1–12.

Iñigo Alonso Fernández and Massimo Panarotto co-wrote the main body of the paper with a review and additional comments by Ola Isaksson. Massimo Panarotto initiated the idea of the paper and Iñigo Alonso Fernández developed and tested the method and worked through the associated examples. Iñigo Alonso Fernández led the writing process with section contributions by Massimo Panarotto and constructive critique also by Ola Isaksson through the writing process.

Paper D ***Incorporating Field Effects into the Design of Modular Product Families***

Jan Küchenhof, Markus C. Berschik, Julia Beibl, **Iñigo Alonso Fernández**, Kevin Otto, Dieter Krause, and Ola Isaksson.

Presented at the ICED 2023, hosted at Bordeaux, France. Published in the Proceedings of the Design Society, 3, pp. 2275–2284.

All authors coordinated the conceptualization and development of the paper during the 5th International Summer School "Product Architecture Design - PAD2022". Jan Küchenhof led the writing of the paper. Julia Beibl worked on the application of the guidelines. Markus C. Berschik developed the MIGs based on the discussions among all authors. Iñigo Alonso Fernández contributed to the sections on function modelling and the discussion and conclusion, as well as with overall editing. Kevin Otto, Dieter Krause, and Ola Isaksson reviewed and provided additional feedback.

Paper E ***Modeling Technical Risk Propagation Using Field-Effects in Automotive Technology Infusion Design Studies***

Iñigo Alonso Fernández, Massimo Panarotto, and Ola Isaksson.

Published in the ASME *Journal of Mechanical Design*. December 2024; 146(12): 121702. https://doi.org/10.1115/1.4065611

Iñigo Alonso Fernández conceptualized the paper, developed the theoretical prescriptive contributions, performed the case study, wrote the main body of the paper and coordinated the contributions of the other authors. Massimo Panarotto contributed to the background section, as well as to the iterative development of the proposed approach. Ola Isaksson contributed knowledge and critique to the paper's concept, content, and form.

Paper F ***Design Support Efficacy in Risk Perception and Mitigation: Quantitative Evaluation of Design Interactions***

Iñigo Alonso Fernández, Massimo Panarotto, and Ola Isaksson.

Submitted for Journal publication

Iñigo Alonso Fernández and Massimo Panarotto conceptualized the paper and the experimental setup. Iñigo Alonso Fernández developed the software tools and led the data-gathering and data-analysis activities, as well as the writing of the main body of the paper. Massimo Panarotto introduced the topic and background of the paper. Ola Isaksson contributed knowledge and critique to the paper's concept, content, and form.

LIST OF ADDITIONAL PAPERS

The additional papers listed encompass related studies that hold significance for the content of this thesis.

Paper 1 **Alonso Fernandez, I.**, Panarotto, M., and Isaksson, O., 2020, "Interactive Model-Based Decision-Making Tools in Early Product Platform Design," *Proceedings of NordDesign 2020*, The Design Society, Lyngby, Denmark, p. 1— – 12.

Paper 2 Panarotto, M., Giordano, V., Chiarello, F., Brahma, A., **Alonso Fernández, I.**, and Fantoni, G., 2023, "Text Mining of Resilient Objects Absorbing Change and Uncertainty," *Proc. Des. Soc.*, 3, pp. 3325–3334.

Paper 3 Panarotto, M. and **Alonso Fernández, I.**, 2024, "Local Absorption of Uncertainty in Complex Systems using Resilient Objects," *Journal of Engineering Design*, pp. 1-19. doi:10.1080/09544828.2024.2327913.

Paper 4 Küchenhof J., Berschik M. C., Beibl, J., **Alonso Fernández, I.**, Panarotto M., Isaksson O., Otto K., Krause D. "Incorporation of Field Effects in the Design of Modular Product Architectures with Application to Electric Vehicles", Submitted for Journal publication.

Paper 5 Martinsson Bonde, J., **Alonso Fernández I.**, Kokkolaras M., Malmqvist J., Panarotto M., Isaksson O. "Managing Combinatorial Design Challenges Using Flexibility and Pathfinding Algorithms", Under review for Journal publication.

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LIST OF ACRONYMS

ADAS	Advanced Driver Assistance Systems
AR	Augmented Reality
BMS	Battery Management System
C	Constraint
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CCB	Cross Car Beam
CI	Coupling Index
CM	Configuration Management
CMA	Common Modular Architecture (Volvo Cars)
CPA	Change Propagation Analysis
CPM	Change Propagation Method
CSP	Concentrating Solar Power
DA	Decision Analysis
DFMEA	Design Failure Mode and Effects Analysis

DOE	Design of Experiments
DP	Design Parameter
DRM	Design Research Methodology
DS	Design Solution
DSIP	Digital Sustainability Implementation Package
DSM	Design Structure Matrix
DSS	Decision Support System
ECU	Electronic Control Unit
EF-M	Enhanced Function-Means
EOP	End of Production
EV	Electric Vehicle
FE	Field Effects
FR	Functional Requirement
FMEA	Failure Modes and Effects Analysis
FoV	Field of View
FPDP	Flexible Platform Design Process
FUP	Front Underrun Protection
GM	General Motors
GVI	Generation Variety Index
HO	Higher-Order
HUD	Head-Up Display
ICE	Internal Combustion Engine
IDEF0	Icam DEfinition for Function modeling, where **ICAM** is an acronym for "Integrated Computer Aided Manufacturing"

IPDE	Industrial/Product Design Engineer
JIT	Just-In-Time
KBE	Knowledge-Based Engineering
LF	Lower Front
LPD	Lean Product Development
MATChEM	Mechanical, Acoustic, Thermal, Chemical, Electrical, and Magnetic
MATE	Multi-Attribute Tradespace Exploration
MCS	Monte Carlo Simulation
MDO	Multidisciplinary Design Optimization
MBSE	Model-Based Systems Engineering
MFD	Modular Function Deployment
MIG	Module Interface Graph
MRL	Manufacturing Readiness Levels
NPD	New Product Development
NPV	Net Present Value
OEM	Original Equipment Manufacturer
OOP	Object-Oriented Programming
PD	Product Development
PDP	Product Development Process
PFMEA	Process Failure Mode and Effects Analysis
PLE	Product Line Engineering
PLM	Product Lifecycle Management
RQ	Research Question

SBCE	Set-based Concurrent Engineering
SbW	Steer-by-Wire
SE	Systems Engineering
SOP	Start of Production
SPA	Single Page Application (web development)
SPA	Scalable Platform Architecture (Volvo Cars)
SUV	Sport Utility Vehicle
SV	Surplus Value
TD	Technology Development
TDN	Time-expanded Decision Network
TOGAF	The Open Group Architecture Framework
TRIZ	Theory of Inventive Problem Solving
TRL	Technology Readiness Level
TRM	Technology Roadmapping
UAV	Unmanned Aerial Vehicle
UOPP	Uncertainty-Oriented Product Platforms
VCS	Value Creation Strategy
VDD	Value-Driven Design
VISP	Value and flexibility Impact analysis for Sustainable Production
V&V	Verification & Validation

1 INTRODUCTION

This chapter introduces the research area of product platforms for product development. It focuses on arguing for the importance of designing flexible product and production platforms to better introduce new technologies. The industrial and academic problems are clarified, and their relevance is assessed, leading to the purpose and research questions explored in this thesis as well as the limits of its scope.

At the dawn of the 20th century, the world was in the midst of a technological revolution, with the advent of automobiles playing a key role. In 1909, Ford released the Model T, a vehicle that would become iconic not only for its engineering but also for its production philosophy. Henry Ford famously declared, "*Any customer can have a car painted any color that he wants so long as it is black*" (Crowther and Ford, 1922). This statement underscored Ford's vision: the Model T would be the quintessential car for everyone—adequately sized, sufficiently powerful, comfortable, and, most importantly, affordable.

Ford's approach capitalized on the innovations of the Second Industrial Revolution: mass production, interchangeable parts, and the assembly line. These advancements enabled the production of affordable vehicles by standardizing processes and minimizing variation. Initially, the Model T was available in various colours, including red, grey, and green. However, only by 1914, the "*any color so long as it is black*" mantra was fully realized, primarily because black paint dried the fastest, streamlining production even further.

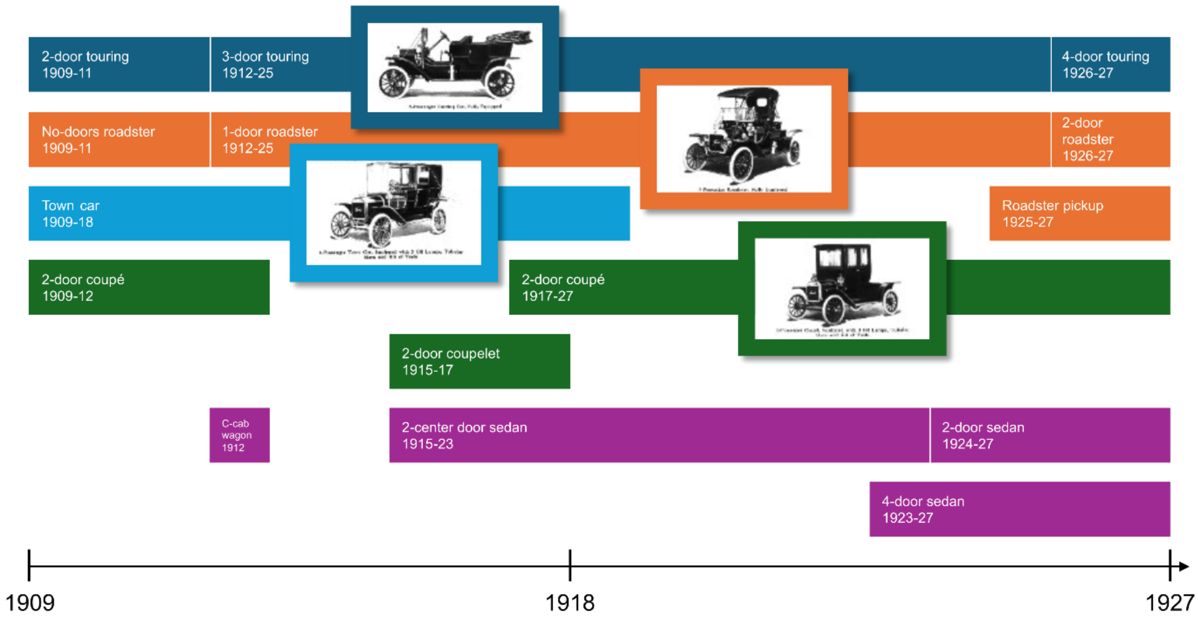

FIGURE 1 TIMELINE OF THE INTRODUCTION OF NEW PRODUCT VARIANTS BASED ON THE MODEL T PLATFORM.

Despite this rigid standardization, the Model T was inherently a product platform. Different body styles could be affixed to a common chassis, allowing for some degree of customization to meet diverse consumer needs (Figure 1). However, as competitors like General Motors (GM) introduced more variants and integrated newer technologies, the Model T's market share dwindled (see Figure 2, with data from the Federal Trade Commission's Report on the Motor Vehicle Industry, 1939). Initially, up until the early 1920s, the Ford Model T gained significant market share due to its cost advantages, which allowed Ford to offer the Model T at a low price, making it widely accessible and popular. However, as the market evolved, Ford's lack of competitiveness became apparent, and sales stagnated and started declining by the middle of the decade. Under Alfred P. Sloan's leadership, GM introduced the concept of "*a car for every purse and purpose,*" allowing customers to start with basic models like Chevrolet and progressively upgrade to more luxurious brands such as Oldsmobile, Buick, or Cadillac. This strategy provided greater variety in terms of models, features, and colours, making GM vehicles more attractive to consumers seeking personalization and the latest technologies.

By 1927, Ford's factories were shut down, officially the reason being the need to retrofit the factories for the release of a new model. In reality, the Ford team had to scramble to use that time to design a new platform from scratch (Sorensen, 1956), highlighting a critical limitation: the lack of flexibility in the Model T platform to adapt to rapid technological changes.

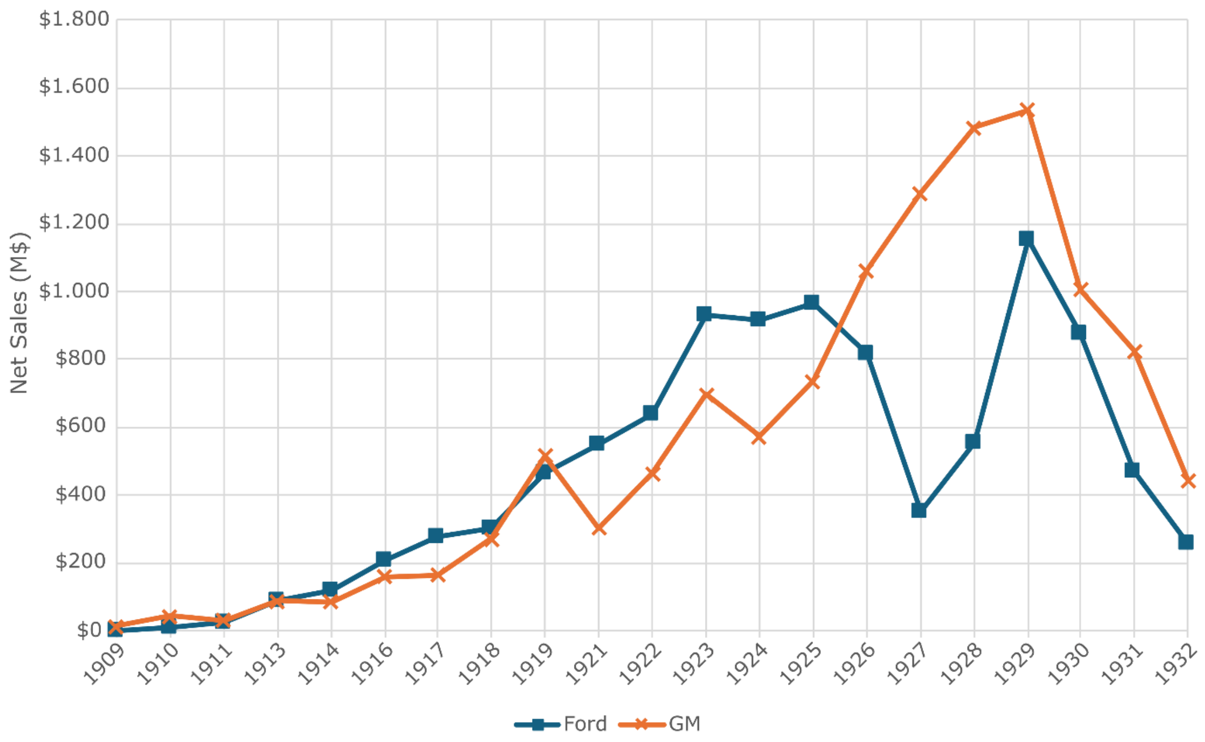

FIGURE 2 REVENUE EVOLUTION OF THE FORD COMPANY AND GENERAL MOTORS FROM 1909 TO 1932.

This historical case underscores the tension between the value of platform reuse and the need for flexibility in technology integration. Excessive standardisation can constrain innovation, while excessive variety can drive up costs. This thesis aims to explore and develop methodologies for designing flexible product platforms that can adapt to technological advancements while maintaining cost efficiencies through controlled internal variety and sufficient external variety.

In today's fast-paced market, the ability of the product development teams to easily change the characteristics of a product to deal with new circumstances is still crucial. A product platform is a set of shared components, processes, technologies, and interfaces that serve as a foundation for a series of related products. Flexibility in this context refers to the capacity of the platform to adapt to new technologies, market demands, or regulations with minimal redesign and cost. Product platform flexibility is thus needed to offer an answer to rapid technological change and the diverse demands of customers. This thesis addresses the critical issue of how product platforms can be designed with the necessary flexibility to keep up with these changes.

1.1 BACKGROUND

The automotive industry is characterized by rapid technological advancements, evolving customer preferences, and stringent regulatory requirements. In this context, the ability to integrate new technologies swiftly and efficiently into product platforms is paramount. Traditional product development approaches, which often focus on optimizing individual products, are increasingly insufficient. Instead, a shift towards flexible product platforms that can accommodate various technologies and customer needs is necessary (Suh, de Weck and Chang, 2007).

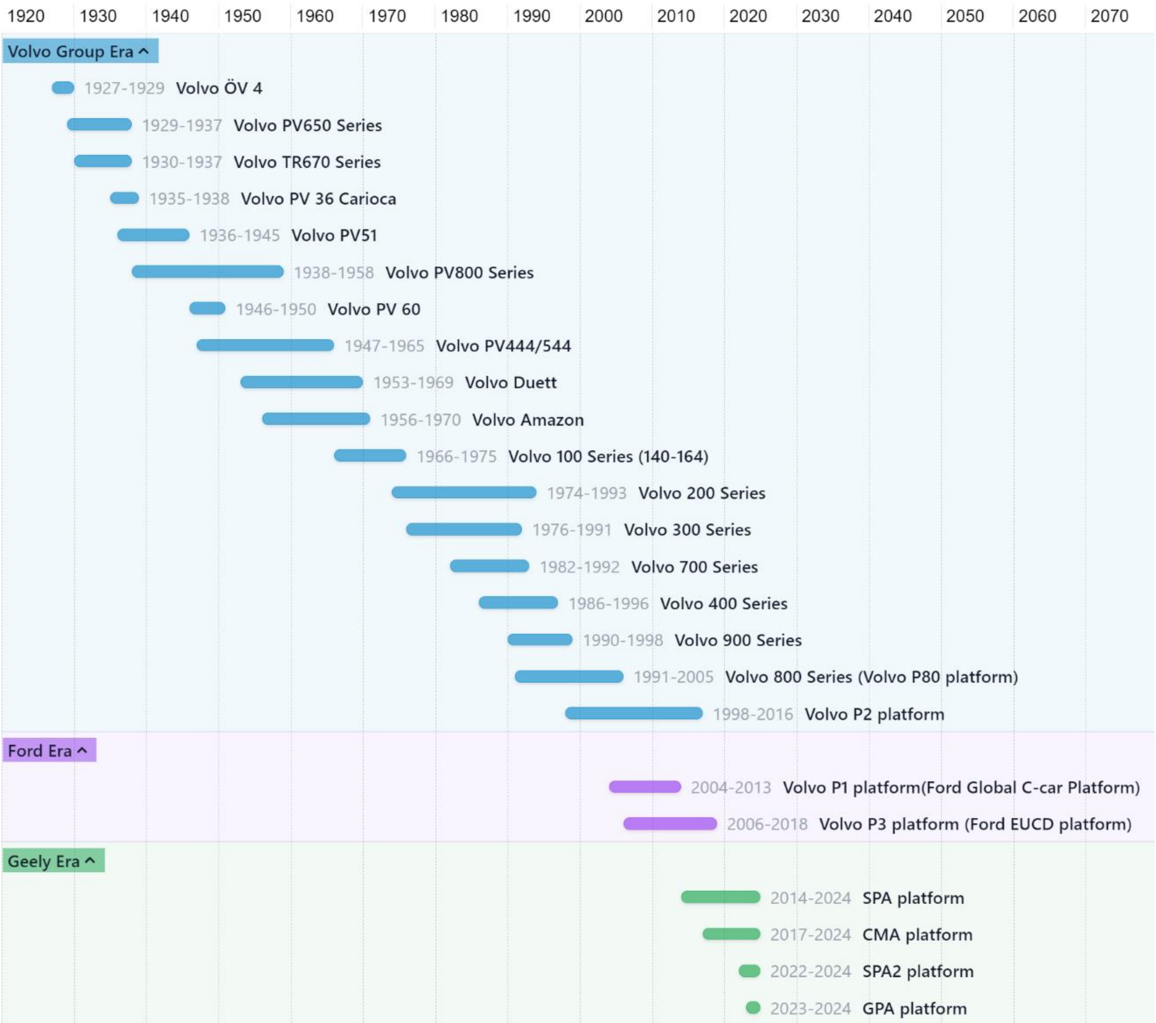

FIGURE 3 VOLVO HISTORICAL CAR PLATFORMS

From an industrial perspective, Original Equipment Manufacturers (OEMs) face numerous challenges in technology integration. These include managing the complexity of new technologies, ensuring compatibility with existing systems, and maintaining cost efficiency. For instance, the integration of electric vehicle (EV) technologies into traditional automotive platforms requires significant modifications in powertrain architecture, battery management systems, and overall vehicle design (Patel *et al.*, 2021).

The Figure 3 illustrates Volvo's long-standing tradition of developing cars using platform-based strategies. Notably, it highlights how the rate of technological and design changes has accelerated in recent years. This acceleration underscores the necessity for even more flexible and adaptive product platforms to keep pace with rapid advancements and evolving market demands.

For example, modifying the powertrain architecture to enhance platform flexibility involves incorporating design margins and addressing potential risks. According to Eckert *et al.* 2019), a design margin is defined as "*the difference between a design parameter's minimum required value to ensure functionality, and its actual capability*."

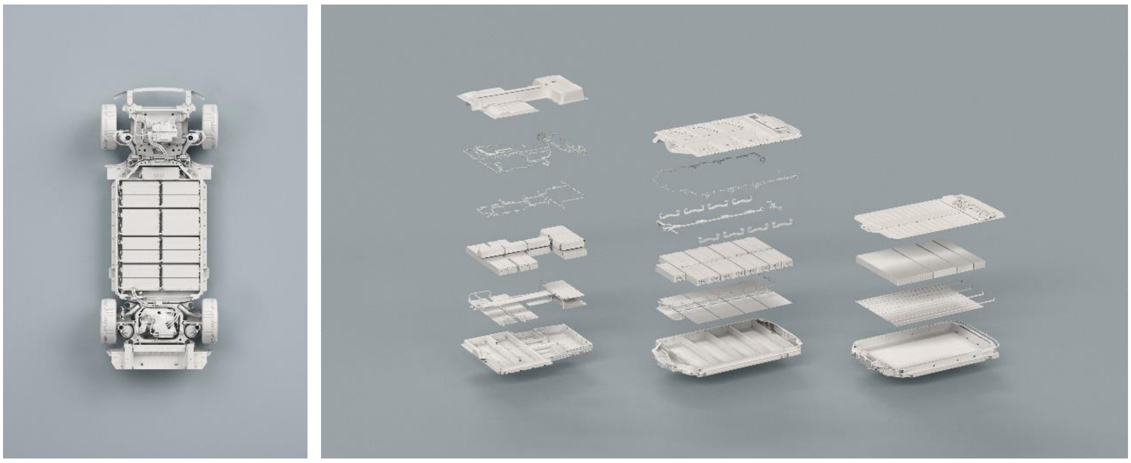

FIGURE 4 INTEGRATION OF DIFFERENT BATTERY PACKS INTO THE FLOOR OF THE CAR. COPYRIGHT 2021 VOLVO CAR GROUP, CORPORATE COMMUNICATIONS, SE-405 31 GOTHENBURG.

For instance, consider an OEM developing a flexible platform to support both ICE and EV variants. The mounting system might be designed with extra space and additional attachment points to accommodate different sizes and shapes of motors and batteries (Figure 4). Similarly, the battery compartment could be designed with modular sections, allowing for different battery capacities without significant redesign. These design margins ensure adaptability but increase the initial design complexity and cost. Risks associated with this approach include over-engineering, such as designing the cooling system to handle both ICE and EV requirements, which might lead to unnecessary bulk and inefficiency. Additionally, maintaining compatibility across different technological iterations, such as new battery technologies or motor designs, can be challenging.

Balancing these factors requires careful planning and innovative engineering solutions, such as using standardized interfaces and modular components, to achieve a truly flexible and future-proof product platform. Moreover, the need for shorter development cycles and faster time-to-market compels OEMs to adopt more agile and adaptable development processes (Palsodkar *et al.*, 2022).

On the scientific front, research on product platforms emphasizes the importance of modularity, scalability, and robustness. Modularity allows for the easy replacement or upgrading of components without redesigning the entire system (Schwede *et al.*, 2022) ; however, the upfront cost can be substantial, as well as the cost of replacing or upgrading components can be significant due to the constraints on future modules. Scalability ensures that platforms can be expanded to incorporate new functionalities (Ross *et al.*, 2008). Robustness, on the other hand, pertains to the platform's ability to perform reliably under diverse conditions and over time (Sullivan *et al.*, 2023) ; however, the problem with robustness is that it considers a "fixed" variation in performance and conditions, failing to account for the tails of the distribution, which can have severe impacts. These attributes are critical for developing product platforms that can adapt to technological changes and meet varying customer requirements. Therefore, introducing the concept of resilience, which goes beyond robustness by considering the tails of distributions, becomes essential. Resilience concerns the capabilities a system needs to respond to inevitable surprises (Woods, 2018).

For example, the integration of emerging technologies such as autonomous driving, advanced driver-assistance systems (ADAS), and connectivity solutions further underscores the need for flexible product platforms. These technologies require not only new hardware and software but also novel design paradigms that can seamlessly incorporate them into existing platforms (Venter and Grobbelaar, 2023). A concrete example is the design of the battery management system (BMS) in electric vehicles (EVs). A flexible BMS can be designed today to accommodate different battery chemistries and capacities, which allows the same EV platform to support various battery technologies as they evolve. This flexibility can enable quick adaptation to improvements in battery technology without requiring a complete redesign of the EV's electrical architecture. However, this approach can lead to over-design, where the system is more complex and costly than necessary for current battery technologies, or under-design, where the system may not fully support future advancements, highlighting the challenge of balancing present and future needs in the design process.

Research in this area focuses on developing methodologies and tools that support the design and evaluation of flexible platforms, ensuring they can accommodate future technological advancements with minimal disruptions (Moon and Suh, 2023).

The industrial and scientific landscapes underscore the critical need for flexibility in product platforms. This flexibility is essential to manage the complexities of technology integration, meet dynamic market demands, and ensure sustainable production practices. The subsequent sections of this thesis will address these aspects, providing a comprehensive analysis of the challenges and proposing model-based methods to address them.

1.2 Problem Statement

In the automotive industry, the problem at present is that companies relying on platforms to develop new products cannot design product platforms that are sufficiently flexible to efficiently integrate new technologies, meet evolving customer demands, and comply with regulatory requirements. For instance, many automakers are transitioning from traditional internal combustion engine platforms to modular EV platforms. In performing this transition, the development of the new platforms must account for the uncertainty regarding the availability of new technologies when defining the architecture and thus the platform margins of the new platforms. For example, how much space needs to be reserved for the battery pack? Assuming that there is no revolution in the chemistry of batteries, there might be a need to accommodate different sizes of packs with the same energy density. But if the technology changes, the volume needed for enabling the same effective ranges will change. These compound uncertainties regarding the market demand for certain performance levels, and the readiness of technologies, make the task of sizing the space reservation for the batteries complex. The current state of knowledge is limited in ways of balancing the lifecycle cost and value involved with incorporating means to enable flexibility at the platform level. This limitation results in increased costs, longer development cycles, and difficulties in maintaining competitiveness in a rapidly changing market.

The core research problem is that given the current state of knowledge, platform development practices do not adequately enable platform designers to comprehensively model and evaluate the flexibility of product platforms from early development stages. This deficiency leads to either under-designing or over-designing the platforms, resulting in inefficiencies and missed opportunities for embedding optimal flexibility.

The reasons for the designs to either fall short or exceed the margins needed for an optimal lifetime value delivery might relate to the designer's perception of the uncertainties involved and the organization's willingness to take risks. It is worth exploring how that perception might affect the performance of design teams in managing risks when using the design support developed in this thesis.

In theory, flexibility involves designing systems with initially low capacity that can expand as needed (if needed). For instance, de Weck *et al.* (2003) illustrate that launching a constellation of small, lightweight, affordable satellites and adding more as needed is preferable to deploying a few high-powered, heavy satellites. This approach minimizes initial capital expenditure and allows for incremental growth as demand or technology evolves. Similarly, De Neufville and Scholtes (2011) emphasize that flexibility is a powerful means to enhance system performance in uncertain environments. They note that "*Flexibility is an effective way to improve the expected performance of systems in uncertain environments. The gains to be made can be impressive. This is especially so when the flexible design also reduces the initial capital expenditure required for the project*." However, in practice, the product platform strategy often conflicts with this principle. Platforms are typically designed to serve a broad range of products, leading to compromises that undermine the system's ability to adapt efficiently. This is because the need to accommodate a variety of future products can result in over-designed platforms with excessive initial capabilities, or under-designed platforms that lack sufficient flexibility to adapt to new requirements.

Existing research lacks robust methodologies and tools for predicting the impact and managing the integration of new technologies into these platforms so that platform designers can "right-size" their constraints and initial capital allocations, concerning the impact of the existing uncertainty, i.e., the risk involved. This lack of design support leads to under- or over-designed platforms, that either are not flexible enough or are wasting resources, hindering the development of adaptable and sustainable design strategies.

Rephrasing the core problem in terms of the TRIZ *if-then-but rule* for finding the contradiction of a problem (Kamarudin *et al.*, 2016):

- **IF** the platform increases its flexibility to efficiently integrate new technologies and meet evolving customer demands,
- **THEN** it can maintain competitiveness in a rapidly changing market,
- **BUT** this often results in either over-designed platforms with excessive initial capabilities, wasting resources, or under-designed platforms that cannot adapt to

unforeseen requirements, thereby increasing costs and extending development cycles.

Understanding and addressing this problem is essential for advancing both industrial practices and academic knowledge in product platform design. Consequently, this study not only seeks to bridge the current gaps in knowledge but also aims to foster a new paradigm in the design and development of flexible product platforms.

1.3 Aim

This thesis aims to develop design support, i.e. knowledge, guidelines, checklists, methods, tools, etc. (Blessing and Chakrabarti, 2009), for the iterative design and analysis of new technology integration in automotive product platforms over time. By focusing on design support, it seeks to offer practical solutions and decision-making tools that can help manufacturers navigate these changes successfully, ensuring both competitiveness and efficiency in production.

To realize the aim, the research will focus on the following refined objectives:

- **Explore decision-making processes** in the integration of new technologies within automotive platforms, identifying key barriers and enablers through comprehensive case studies and a review of the literature. This objective seeks to uncover the dynamics and challenges encountered in the decision-making process, offering a foundation for developing effective platform strategies and tools to navigate these complexities.

- **Propose and refine design supports** that enhance the flexibility of automotive product platforms when integrating new technologies. This involves the creation of tools and methods that can predict the implications of technology integration on platform flexibility, thereby guiding the design process towards product platforms that are easier to adapt to changes in their environment.

- **Design and validate a model-based framework** that assesses and compares the flexibility of automotive product platforms. This framework will enable the anticipation of future market needs and technological trends, ensuring that product platforms remain competitive and relevant.

By addressing these objectives, this research aims to fill the current gaps in the capability to assess and manage the flexibility of product platforms, providing manufacturers with the tools needed to make informed, efficient, and strategic decisions in the face of ongoing changes. The following section lists the specific research questions that will guide this investigation, ensuring a structured and focused approach to achieving these objectives.

1.4 Research Questions

Based on the context, aim, and objectives detailed above, the following research questions (RQs) are proposed to address the research problem:

RQ1 *What are the barriers and enablers in deciding to introduce **new technology** into **product platforms**?*

RQ2 *How can a flexible product platform be modelled from an early stage of development, so its **flexibility** may be traded against stakeholder needs?*

RQ3 *How can the **impact** of introducing or replacing technologies on the flexibility, risk management, and value optimization of product platforms be effectively **assessed**?*

These research questions are intended to provide a coherent and systematic framework for exploring the integration of new technologies into automotive product platforms, emphasizing the development of practical, forward-looking design supports that cater to the evolving needs of the industry.

1.5 Research Scope and Delimitations

The scope of this research is focused on developing design support mechanisms for the integration of new technologies into automotive product platforms. This includes the creation and refinement of methods, tools, and guidelines to enhance platform flexibility, enabling manufacturers to adapt to technological advancements and evolving market demands efficiently. The research is primarily situated within the context of the automotive industry, leveraging case studies and empirical data from two major automotive original equipment manufacturers (OEMs). The selection of the automotive sector is motivated by its complex product platforms and the rapid pace of technological innovation inherent in this industry.

To ensure the research remains focused and manageable, several delimitations have been established. Firstly, the study is confined to the design and development phases of product platforms, excluding the later stages of production and lifecycle management, despite life-cycle flexibility being essential to measure and improve the innovative capability of products in turbulent environments (Buganza and Verganti, 2006). This focus is intended to provide deep insights into the early decision-making processes that influence the most platform flexibility and technological integration. Secondly, while the principles and methodologies developed may have broader applicability, the empirical data collection and case studies are restricted to the automotive sector, specifically within the geographical context of Sweden. This limitation acknowledges the contextual nuances and potential biases introduced by focusing on a specific industry and region, despite the global reach of the companies involved.

Furthermore, the research does not extend the financial aspects of platform development, such as cost-benefit analysis or advanced return on investment calculations. Instead, it concentrates on the technical and strategic dimensions of integrating new technologies into product platforms, using basic financial models from the established literature. This decision ensures a more concentrated exploration of the design principles and methodologies required to achieve platform flexibility.

The scope and delimitations of this research are carefully defined to ensure a focused and practical investigation into the research problem. The findings and design support developed are intended to provide valuable contributions to both the academic field of product development and the practical needs of the automotive industry while acknowledging the contextual limitations inherent in the study's design.

1.6 Outline of the Thesis

Amidst constant market shifts and the push towards more sustainable production, this research aims to shed light on the ways product platforms can be engineered to be flexible and responsive to new technological advancements. It explores both the industrial and academic perspectives to understand the role of flexibility in product platforms, setting the stage for a discussion that could influence the direction of automotive product platform development.

Building on the initial focus on flexibility, this research explores the main aspects of product platform development: how they keep up with new technologies, meet customer needs, and fit into efficient production processes. These areas are crucial for understanding how product platforms can stay useful and competitive as everything around them changes. The reason for this study lies in the challenge of staying ahead in the market while also making sure our ways of making things are sustainable and can adapt over time. This thesis will look closely at real-world examples and create new design support means for evaluation, aiming to give practical advice and methods for designing product platforms. The goal is to ensure that product platforms can satisfy today's market and be ready to evolve for tomorrow's needs.

The intersection of engineering innovation and market dynamics provides a rich backdrop for this study, highlighting the critical role that flexible product platforms play in contemporary product development. This backdrop sets the context for a deeper exploration of how industry and academia currently approach platform design and where they may be headed in the face of new technological challenges and opportunities.

The chapters of this thesis are structured as follows:

Chapter 1 introduces the topic and its context, delimits the problem, and outlines the research questions.

Chapter 2 gives the research a reference framework and presents the state-of-the-art as extracted from the literature.

Chapter 3 describes the research approach followed in the research.

Chapter 4 compiles the summaries of the appended papers.

Chapter 5 synthesises the findings of the appended papers, logically linking them together.

Chapter 6 discusses the results from Chapter 5 as they relate to the objectives and research questions stated in Chapter 1, and the existing literature.

Lastly, **Chapter 7** summarizes the contributions and claims of the thesis and concludes this thesis with an outlook on the future.

Appendices collate the full-text versions of six papers published during the research:

Paper A Identification of Technology Integration Challenges at Two Global Automotive OEMs

Paper B Reconciling Platform vs. Product Optimisation by Value-Based Margins on Solutions and Parameters

Paper C Designing Multi-Technological Resilient Objects in Product Platforms

Paper D Incorporating Field Effects into the Design of Modular Product Families

Paper E Modeling Technical Risk Propagation Using Field-Effects in Automotive Technology Infusion Design Studies

Paper F Design Support Efficacy in Risk Perception and Mitigation: Quantitative Evaluation of Design Interactions

2 Frame of Reference

The development of a new product platform is a costly and lengthy endeavour. Despite the benefits it can deliver in terms of cost reduction and increased external variety, changes in the preferences of the market and the development of new technologies both pressure companies into extracting as much value out of their platforms as possible before they become obsolete. For product platforms to remain relevant for their expected lifetime of around a decade in the automotive sector, they must be designed with such pressures in mind. This chapter begins by describing the field of Product Development, followed by an introduction to Technology Integration. Then the concepts of risk, flexibility, and value assessment are presented. The chapter also highlights the identified gaps in the current state-of-the-art.

2.1 Product Development

2.1.1 Product Development Process

Ulrich *et al.* (2020) define the Product Development Process (PDP) as the sequence of steps or activities that a company utilizes to conceive, design, and commercialize a product. The generic product development process they present consists of six phases as illustrated in Figure 5:

1. **Planning:** This initial phase links advanced research and technology development activities. The output of the planning phase is the project's mission statement, which guides the development team and provides the necessary input for the next phase.
2. **Concept Development:** In this phase, ideas generated during planning are transformed into concepts. Various concepts are evaluated, and the most

promising ones are selected for further development. This phase includes feasibility studies and initial design sketches.

3. **System-Level Design:** Here, the chosen concept is broken down into subsystems and major components. Detailed specifications for each subsystem are created, and the overall system architecture is established.
4. **Detail Design:** This phase involves creating detailed plans, drawings, and specifications for each component. Prototypes may be developed, and iterative testing and refinement occur to ensure all components work together as intended.
5. **Testing and Refinement:** During this phase, prototypes are tested to identify any issues. Feedback from testing is used to refine and improve the design. This may involve multiple iterations of testing and redesign to achieve the desired performance and reliability.
6. **Production Ramp-Up:** The final phase involves scaling up production to prepare for market launch. Any last-minute issues are resolved, and full-scale manufacturing begins. The product becomes available for purchase in the marketplace at the conclusion of this phase.

Each phase builds upon the previous one, ensuring a structured approach to product development that minimizes risks and maximizes the chances of successful market entry.

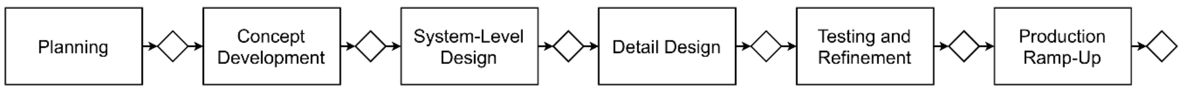

FIGURE 5 GENERIC PRODUCT DEVELOPMENT PROCESS

Based on this generic process, many firms have traditionally followed some variation of the Stage-Gate design process (Cooper, 1990, 2014, p. 201), while others followed a more informal ad-hoc method, and a minority opted for other functional or sequential methods or using no method at all. However, agile methods are becoming more widespread (Palsodkar *et al.*, 2022). Agility signifies an organization's capacity for rapid response to change. Agile methodologies introduce a shift from traditional command-and-control management to practices emphasizing values, principles, and benefits. In new product development, agility manifests through swift adaptation to evolving or new customer demands, dynamic project portfolio reprioritization, and the ability to pivot from original plans based on changing circumstances, underscoring the importance of flexibility in contemporary organizational strategy (Bstieler and Noble, 2023).

Finally, it is common for product development processes to be iterative, with feedback loops between the different stages. This iterative approach allows for continuous refinement and optimization of designs. It enables designers to evaluate and adjust multiple alternatives based on feedback, improving key criteria such as weight, cost, and lead time. It enhances product quality, increases efficiency, and reduces time-to-market by identifying and addressing issues early in the development process (Sunnersjö *et al.*, 2006).

2.1.2 PRODUCT PLATFORMS

McGrath (1995) defined a product platform as a collection of common elements, particularly the underlying core technology, that is implemented across a range of products. An alternative narrower definition characterizes product platforms as a set of subsystems and interfaces that form a common structure that enables the efficient development and production of a variety of products (Meyer and Lehnerd, 1997). Robertson and Ulrich (1998) proposed a broader definition: they describe product platforms as a collection of assets (e.g., components, processes, knowledge, people, and relationships) that are shared by a set of products. Other authors have provided variations on these: e.g., "*a common base from which a number of predefined models can be built*" (Ericsson and Erixon, 1999), "*the set of elements and interfaces that are common to a family of products*" (Gonzalez-Zugasti *et al.*, 2001), or "*a collection of modules or parts that are common to a number of products, and this commonality is developed intentionally to attain certain effects*" (Harland and Uddin, 2014). In this thesis, the following definition is adopted:

A product platform is a set of assets (including components, processes, knowledge, and relationships), strategically designed to efficiently create and evolve a diverse range of products that meet user needs within economic and technological constraints.

This range of products might form a product family, which consists of related products manufactured by the same company under a unified brand. The key to a successful product family is the product platform from which it is derived (Simpson, 2004), as product platform-based product families are efficient means to reduce lead time (Muffatto, 1999) and increase product quality simultaneously (Landahl *et al.*, 2016). This strategy enables a company to capitalize on the brand loyalty of its existing customer base. By offering a variety of similar yet distinct products, a product family caters to diverse needs and preferences, thereby broadening the company's customer appeal.

The efficient platform-driven development of product families requires linking theory with practice, where companies base their platforms on product architecture and apply divergent platform concepts regarding product families and market applications (Halman et al., 2003). Implementing platform strategies can help reduce manufacturing costs and development times, benefiting various industries seeking optimisation (Weck et al., 2003). A critical component of these cost reductions is the achievement of economies of scale, where the cost per unit of production decreases as the scale of production increases. Economies of scale are primarily realized through the efficient use of resources, bulk purchasing of materials, and the spreading of fixed costs over a larger number of units. In the context of product platforms, this means that common components and subsystems used across multiple products allow manufacturers to order larger quantities of materials and components, negotiate better prices with suppliers, and optimize manufacturing processes, all of which contribute to lower per-unit costs.

Economies of scale are often modelled using learning curves, also known as experience curves. The learning curve effect suggests that with every doubling of cumulative production, the cost per unit decreases by a constant percentage due to increased efficiency, worker proficiency, and process improvements. This concept is particularly relevant in industries like automotive manufacturing, where production volumes are high and continuous improvement is a strategic focus. For example, as an automotive company produces more vehicles on a shared platform, it gains insights into optimizing assembly line processes, reducing waste, and enhancing quality control, leading to progressively lower costs per vehicle (Argote and Epple, 1990).

In addition to learning curves, the use of digital tools and advanced analytics further enhances the realization of economies of scale. By employing computer-aided design (CAD) and manufacturing (CAM) systems, manufacturers can simulate production processes, identify bottlenecks, and streamline operations before actual production begins. This pre-emptive optimization reduces trial-and-error during production runs and accelerates the learning process. Additionally, data analytics can provide insights into production performance, allowing for continuous monitoring and adjustment of manufacturing practices to sustain cost reductions over time (Williamsson, 2021).

While the advantages of product platforms are significant, adapting platforms to individual product requirements may incur additional costs (Boute et al., 2018). For example, the combination of different parts is not always optimally designed to work together creating a modularity penalty, as parts are overdesigned and include additional interfaces, resulting in additional material use (Kamrad, Schmidt, and Ülkü 2017).

Product platforms are accompanied by several other additional challenges that must be addressed to fully realize their potential. One notable concern is the risk of architectural inertia. Companies that heavily invest in optimizing current platform architectures might become resistant to adopting new, innovative designs, potentially stifling long-term technological advancement and adaptation to shifting market demands (Ramdas, 2003).

Moreover, implementing a modular approach can lead to complexity in product development and management. Schwede *et al.* (2022) highlight that the process of modularization requires careful consideration and extensive planning to ensure proper integration of modules, which can lead to complexity and inefficiency if not managed correctly. The integration of business strategies with technical modularization is essential but often difficult to achieve, making the overall process more cumbersome and prone to errors.

The economic impacts of modularization can also be inconsistent. While modular systems aim to reduce costs through economies of scale, the initial setup and ongoing maintenance of these systems can be expensive. Schwede *et al.* (2022) also discuss the difficulty in effectively linking modularization methods to clear economic benefits, which can make it challenging for companies to justify the upfront investment. Additionally, the introduction of modular systems often requires significant changes in organizational structure and processes, further adding to the complexity and cost (Fixson, 2007).

Furthermore, the flexibility offered by modular platforms can sometimes come at the expense of performance. Common components designed to fit a wide range of products may not be optimal for specific applications, leading to performance trade-offs (Fixson, 2007).

Another significant risk associated with modular platforms is the potential for competitive disadvantages. Piran *et al.* (2016) argue that while modularity can facilitate innovation within a company, it also makes products more susceptible to imitation by competitors. The standardized nature of modules means that once a competitor understands the module design, they can more easily replicate or improve upon it, thereby eroding the original company's market position.

Despite these challenges, the strategic use of product platforms remains a powerful tool in the automotive industry. For instance, companies like Scania have successfully utilized modular product architectures to maintain a high degree of customization while controlling production costs and ensuring high quality (Williamsson, 2021). Scania’s modular approach is claimed to allow for the efficient production of diverse truck models that meet various customer needs without sacrificing performance or reliability.

Vehicles such as cars and trucks are complex systems containing numerous interacting subsystems and components, necessitating modifications to the generic product development process to address system-level concerns (Ulrich *et al.*, 2020). During the concept development phase, the architecture of the entire system is considered, often with multiple architectures competing as overall system concepts. The product architecture process aims to identify and abstract all component variants, by associating all functional requirements to design solutions on one hand and identifying and describing the generic components and their variants on the other (Kreimeyer, 2016).

The adoption of modular platforms in the automotive industry revolutionized product architecture and production processes (Lampón *et al.*, 2019). Modular platforms offer significant flexibility by allowing variations in structural dimensions, enabling manufacturers to produce different models across various segments on a single platform (Schuh *et al.*, 2014). This approach combines the benefits of traditional platform strategies, such as economies of scale and standardized production processes, with the advantages of modularity, which includes greater design and manufacturing flexibility. By integrating modular platforms, automotive manufacturers can streamline design processes, reduce costs, and quickly adapt to changing market demands without substantial retooling or overinvestment (Lampón *et al.*, 2017).

Following the modular platforms, the adoption of scalable platforms offers additional benefits in the automotive industry by enabling the design of product families that can easily adapt to different sizes and specifications. Scalable platforms focus on a core structure that can be parametrically adjusted to produce a wide variety of models, ranging from compact cars to large SUVs, all based on the same foundational architecture. This approach leverages parametric design principles, where key dimensions and features can be scaled up or down to meet different market needs without the need for entirely new designs (Pirmoradi *et al.*, 2015). By implementing scalable platforms, automotive manufacturers can achieve significant cost savings through economies of scale while maintaining the flexibility to quickly adapt to changing market demands, enhancing their ability to innovate and compete in a dynamic industry (Al Handawi *et al.*, 2020).

The system-level design phase is critical, involving the decomposition of the system into subsystems and components, with teams assigned to develop each component and additional teams focused on integrating these components into subsystems and the overall system. The detail design of components is highly parallel, with many development teams working simultaneously, typically independently and often by external suppliers.

In the automotive sector, where performance and reliability are paramount, trade-offs between those characteristics and the flexibility of the platform can impact customer satisfaction and brand reputation. Additionally, the rigidity that platforms can impose on the development of new models can be particularly problematic in the automotive industry, where continuous innovation is critical to staying competitive.

Finally, systems engineering specialists manage the network of interactions across components and subsystems. The testing and refinement phase includes extensive testing and validation at all levels, encompassing both component and system integration.

2.1.3 Means of Achieving Flexible Product Platforms

Achieving flexibility in product platforms involves several key strategies, including the use of modules, parameterization, and other innovative approaches. However, these strategies also come with inherent challenges.

A module is an independent building block of a larger system with a specific function and well-defined interfaces (Hölttä-Otto, 2005). Modules can be independently designed, developed, and integrated into various products. This modular design approach allows for easy replacement, upgrade, and customization of components, facilitating the rapid incorporation of new technologies without necessitating a complete redesign of the platform.

An example of modular design is the integration of modular battery packs in electric vehicles (EVs). This approach allows manufacturers to adjust battery capacity and performance based on customer needs and technological advancements. However, designing such modules requires careful consideration of interfaces and compatibility standards to ensure seamless integration across different vehicle models. Despite the benefits, the complexity of ensuring compatibility and standardization across modules can be significant, requiring extensive coordination and rigorous testing. Additionally, there is a risk of over-designing a modular architecture (Krishnan and Gupta, 2001), making affordances for potential modules that cater to all potential use cases, leading to increased weight, cost, and inefficiency. Managing a diverse range of modules and ensuring their availability and quality across global supply chains also presents substantial challenges, necessitating robust supply chain management practices.

Parameters refer to the specific attributes or characteristics of components that can be adjusted to achieve different performance levels or functionalities. Suh (1998) defines design parameters (DPs) as *"the key physical (or other equivalent terms in the case of software design, etc.) variables in the physical domain that characterize the design satisfying the specified functional requirements (FR)."* This parameterization allows for scalable and adaptable designs tailored to varying requirements without significant changes to the core platform, enhancing the platform's overall versatility (Ma *et al.*, 2011). The integration of design alternatives throughout the platform development phases relies on configuring sets of design parameters concurrently (Johannesson *et al.*, 2017).

In the realm of system lifecycle value and changeability, factors such as scalability, modifiability, and robustness are quantified to understand the effects of changes on system performance (Ross *et al.*, 2008). Additionally, in managing configurable modular systems, parameters are varied to observe their impact on metrics like weight, manufacturing costs, and time (Borgue, Stavridis, *et al.*, 2021). Parameters are also defined to manage the future diversity of product designs by setting degrees of freedom in design parameters (Küchenhof *et al.*, 2022).

For example, in truck cooling systems, parameters such as airflow and pressure are adjusted based on different engine configurations. A company might have chosen to use two sizes of cooling fans, based on worst-case scenarios to ensure reliability (Eckert *et al.*, 2020). For instance, a truck designed for temperate climates might also be sold in Africa, operating under heavy loads in extreme heat. Designers might choose a larger fan (68 cm instead of 63 cm) to handle these conditions. However, this leads to over-design for temperate climates. The larger fan increases efficiency in the hot, but it is heavier and bulkier, and adding more fan sizes is not viable due to long lead times and redesign costs.

While parameterization offers flexibility, it has limitations. Optimizing for a wide range of scenarios can result in conservative designs that are inefficient for typical use cases. Predicting future technological needs and market demands to set appropriate parameter ranges is challenging. Additionally, discrete steps in design solutions, such as limited fan sizes, constrain the ability to fine-tune performance, leading to compromises in efficiency and adaptability.

Another significant means of enabling flexibility in product platforms is through strategic geometrical location and spatial planning. As discussed by Isaksson *et al.* (2014), the intentional design of geometrical locations to create spaces can serve as a vital buffer for future modifications and integrations. For instance, by disallowing the placement of fuel tanks between the frame rails in trucks, manufacturers can create margins for other critical components, such as various routing and cross-member solutions. This spatial flexibility ensures that there is reserved space within the vehicle architecture that can be utilized for different purposes as technology evolves. This approach not only allows for the integration of new components without significant redesign but also provides a practical solution for managing the physical constraints of the platform.

Configuration Management (CM) and Product Line Engineering (PLE) are key enablers of flexible product platforms. CM is a discipline focused on systematically controlling and documenting changes in a product's configuration throughout its lifecycle, ensuring consistency, integrity, and performance. PLE, on the other hand, is an approach that creates a portfolio of similar products from shared core assets, streamlining development and maximizing reuse to reduce time, cost, and complexity. By integrating CM principles into PLE through versioned feature models, as suggested by Lameh *et al.* (2023), manufacturers can systematically manage product variability and temporal evolution. This integration allows for consistent documentation and control of different feature versions over time. Developing Uncertainty-Oriented Product Platforms (UOPP) can also enhance enterprise adaptability to uncertain market conditions, customer requirements, and technologies, emphasizing flexible, adaptable, market-driven, and sustainable product platforms (Han *et al.*, 2020).

Achieving flexibility in product platforms can also be enhanced through other means, beyond architectural approaches, such as strategic financial planning and agile supply chain management. Financial flexibility involves maintaining cash reserves, securing lines of credit, and flexible budgeting to quickly invest in emerging technologies or opportunities (Opler *et al.*, 1999). Agile supply chain management, including diversifying suppliers, strategic inventory management, and using advanced logistics solutions, allows for quick responses to demand changes and supply disruptions. Just-in-time (JIT) inventory systems and strong supplier relationships further enhance responsiveness and reduce risks (Golhar and Stamm, 1991). Utilizing digital tools for real-time data analytics ensures coordinated and efficient supply chain operations, supporting flexible production schedules. These strategies collectively enhance the resilience and adaptability of product platforms in a dynamic market environment.

To support flexibility, these strategies inherently create design margins—buffers or excess capacities that allow for future adjustments and changes without extensive redesigns (Brahma *et al.*, 2023). Modules and parameters play a crucial role in enabling these margins. A modular approach allows for easy upgrades and replacements, ensuring the platform can adapt to future technological improvements without significant redesign. Parameters, such as adjustable airflow in cooling systems, provide similar benefits by allowing fine-tuning to meet specific performance requirements, creating a buffer against varying operational conditions.

However, these approaches can lead to over-design if not carefully managed. For instance, over-designing a cooling fan for extreme scenarios, as seen in trucks sold in both temperate and hot climates, can result in unnecessary weight and inefficiency for most use cases. Conversely, under-design can occur if margins are too narrow, limiting the ability to adapt to new technologies or market demands. An example of under-design might be a platform that lacks the space to accommodate larger future battery modules, thus restricting the potential for performance upgrades. The key is to balance these margins to provide adequate flexibility without incurring unnecessary costs or inefficiencies.

Problems with achieving flexible product platforms often stem from the challenge of balancing present needs with future uncertainties. Over-design increases cost and complexity, while under-design risks obsolescence and reduced competitiveness. Effective management of design margins requires a nuanced understanding of market trends, technological advancements, and precise forecasting.

2.1.4 Architecture Modelling

Early system architecture decisions are critical in determining a product's lifecycle costs, performance, and adaptability (Eckert and Jankovic, 2016). These initial decisions involve navigating trade-offs between conflicting constraints and require a comprehensive understanding of the product's entire lifecycle and usage context. One of these decisions automotive manufacturers need to make to achieve a truly flexible platform is adopting both modular and scalable (parametric) platform strategies. A modular platform involves designing the vehicle architecture around interchangeable modules, each serving specific functions, such as the engine, chassis, or infotainment system. This approach allows manufacturers to mix and match modules to create a variety of vehicle models from a common base, enhancing customization and simplifying the introduction of new technologies. In contrast, a scalable or parametric platform focuses on a core structure that can be easily adjusted in size and configuration to accommodate different vehicle types and segments. This adaptability enables the production of a wide range of models—from compact cars to SUVs—on the same platform, optimizing resource utilization and reducing development costs. Both strategies require robust architecture modelling, ensuring that all system elements are effectively integrated, aligned with strategic goals, and capable of evolving with changing market demands and technological advancements.

From a manufacturing network perspective, modular platforms facilitate greater operational flexibility and resource sharing among production plants (Simpson, 2006). This is achieved through the compatibility of structural modules that can be assembled in different configurations (Hölttä and Otto, 2005), allowing the production of various models within the same plant. As a result, manufacturers can optimize their global production networks by shifting production between plants to balance capacity and meet regional demand fluctuations. This flexibility enhances the efficiency of the manufacturing network, enabling better coordination and knowledge transfer among plants, which is critical for maintaining competitiveness in the automotive industry (Lampón *et al.*, 2019).

The implementation of modular platforms also necessitates significant changes in production systems, particularly in body-in-white shops and final assembly lines (Untiedt, 2008). These changes include the adoption of scalable production lines that can handle multiple models and segments, improving production versatility and efficiency. The increased modularity and integration capabilities lead to better economies of scope and scale, allowing manufacturers to produce a higher volume of units across different models while maintaining lower costs (MacDuffie, 2013). This approach not only enhances production efficiency but also aligns with the strategic goals of automotive manufacturers to innovate and remain agile in a highly competitive market.

A parametric platform leverages detailed component placement strategies to ensure scalability and adaptability. As illustrated in Figure 6 (reproduced with permission from Papageorgiou *et al.*, 2020), the constituent system level analysis focuses on the precise geometrical placement and integration of components within the vehicle architecture. This includes defining the locations of major elements such as the propulsion units and electrical systems, taking into account factors like weight distribution, aerodynamics, and clearance margins. By employing parametric models, manufacturers can adjust these placements dynamically to accommodate different vehicle and component designs without significant re-engineering efforts.

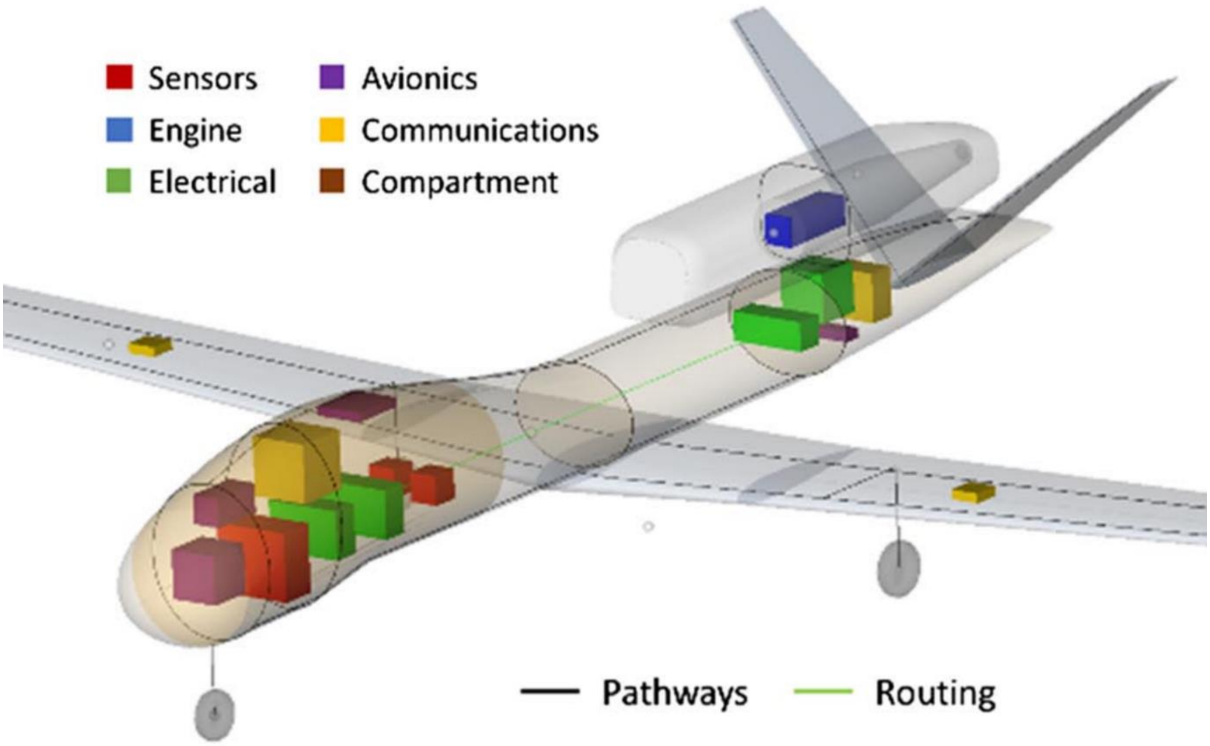

FIGURE 6 ELECTRICAL ARCHITECTURE WITH PLACEMENT OF COMPONENTS AND CABLES FOR AN UNMANNED AERIAL VEHICLE (UAV).

In the context of systems, the ISO/IEC/IEEE 42010 standard defines architecture as the "*fundamental concepts or properties of an entity in its environment and governing principles for the realization and evolution of this entity and its related life cycle processes*." Similarly, The Open Group Architecture Framework (TOGAF) describes architecture as "*a formal description of a system, or a detailed plan of the system at component level to guide its implementation*." These definitions underscore the importance of a well-defined architecture in ensuring that all system elements fit and work together harmoniously through its life cycle.

The concept of product architecture is somewhat more specific, and multifaceted, encompassing various perspectives that collectively define its essence and functionality. Ulrich, Eppinger, and Yang (2020) describe product architecture as "*the arrangement of functional elements into physical blocks*", emphasizing the organization of these elements to form a coherent system. Ulrich (1995) further refines this by identifying three key aspects: *"(1) the arrangement of functional elements, (2) the mapping from functional elements to physical components, and (3) the specification of the interfaces among interacting physical components*". Sillitto (2014) elaborates on system architecture, stressing the importance of setting out the parts of the system, their functions, and how they fit and work together within their operating environment to achieve the intended purpose without unintended consequences. These definitions collectively highlight the critical role of organization, mapping, interfacing, and integration in ensuring that a product's architecture effectively meets its intended goals and functions.

Product platform design involves multiple stakeholders, both within and outside a company, making it a complex and collaborative process (Choi, 2020). In the automotive industry, the platform definitions, interfaces, and constraints serve as critical means for effective communication and collaboration with suppliers. These elements help delineate the boundaries, goals, and functions of the system, reducing ambiguity and ensuring all stakeholders, including tiered suppliers, have a clear understanding of the project requirements. However, the complexity of the multi-tiered automotive supply chain can "stiffen" the architecture through design iterations, as novel technologies at the lower tier levels need to be aggregated through several layers. If these technologies do not fit seamlessly, it can lead to significant integration challenges and delays.

There are two main different approaches to architecture design, focusing on either functional decomposition or addressing quality attributes of the system. The function modelling approach, in general, tries to capture the functions, or "*the intended behavior of the product*" (Gero, 1990), without the need to clarify its geometry. For instance, the Enhanced Function-Means (EF-M) method provides a structured way to map functions to forms and is capable of representing the design space and supporting the integration of novel solutions into existing product structures while enabling the exploration of alternative design variants (Müller *et al.*, 2019). It integrates Functional Requirements (FRs), Design Solutions (DSs), and Constraints (Cs) to comprehensively represent product architectures. FRs define the necessary functions the product must perform, describing desired behaviours or outcomes. DSs are how these FRs are fulfilled, outlining technical principles or designs that accomplish the FRs. Unlike in axiomatic design (Suh, 1998), where DSs are physical solutions, in EF-M, DSs can remain in the functional domain, representing means rather than physical forms. Constraints limit the design space by defining requirements that DSs must adhere to or avoid, ensuring solutions meet specific conditions or limitations. The EF-M model employs a hierarchical tree structure where top-level FRs are broken down into sub-FRs, each with associated DSs and constraints, enabling a systematic exploration of the design space by iterating between functional requirements and potential solutions while respecting the defined constraints.

Managing the design of the architecture by looking at its quality attributes requires being able to measure the architecture by different metrics (Jankovic, 2017) depending on the intended emergent qualities that are required from it. Parametric modelling allows for the creation of highly adaptable and dynamic models where geometry and associated properties, including 'ilities' of the overall system, can be controlled through parameters. This is particularly beneficial for optimizing design configurations and managing dependencies across different components. The parametric associative models, as demonstrated in aircraft pre-design processes, enable efficient updates and modifications, ensuring that all related components adapt automatically to changes in key parameters (Ledermann *et al.*, 2005).

For either approach, generic architecture structures, such as tree-structured hierarchies, layered hierarchies, and networks, each offer varying degrees of flexibility and complexity (Moses, 2010). Tree structures, while straightforward, are relatively inflexible. Layered hierarchies provide more flexibility but are not always feasible. Network structures, although highly flexible, can be challenging to control.

A widely used approach for modelling the architecture of products and other complex systems is the Design Structure Matrix (DSM). A DSM is a compact, matrix-based tool used to capture and analyse the dependencies between components, tasks, or teams (Browning, 2016). DSM helps visualize and manage the interactions and relationships within a system. The main benefit of the DSM in engineering design automation is its ability to organize and manage complex knowledge and dependencies within design systems (Johansson and Elgh, 2013). DSM thus enhances the maintainability and efficiency of these systems by providing a clear visualization of relationships between knowledge objects and parameters, enabling dynamic and flexible execution sequences, and supporting the identification and resolution of circular references.

As an Industrial/Product Design Engineer (IPDE), who designs both functional and formal aspects of a product system for industrial production (Chakrabarti, 2023), the role of a product architect is multifaceted. They reduce ambiguity, employ creativity to develop concepts, and manage complexity by decomposing the system into manageable parts. Effective architecture modelling in automotive product platforms requires balancing flexibility and control, clear communication across the supply chain, and robust methods for integrating new technologies. By adhering to these principles, automotive manufacturers can design platforms that are not only efficient and adaptable but also capable of evolving to meet future technological and market demands.

2.2 Incorporating New Technology

"Technology integration" refers to the seamless incorporation of new technologies into existing products or platforms to enhance functionality or performance. This process involves embedding technology in such a way that it becomes an integral part of the product, improving its overall effectiveness without altering its core design significantly. For instance, adding advanced navigation systems to a car model would be an example of technology integration. On the other hand, “technology infusion” is a comprehensive and strategic approach where technology adoption is a fundamental aspect of the entire product development lifecycle, influencing every stage from initial concept to final production. This approach ensures that new technologies are not merely added but are deeply embedded within the design and manufacturing processes, facilitating the creation of flexible product platforms capable of evolving with technological advancements. An example of technology infusion would be developing a car platform with a modular electric drivetrain system, allowing for easy upgrades and customization as technology advances. The primary difference lies in the scope and depth: integration focuses on enhancing specific aspects of a product, while infusion involves a holistic transformation, embedding technology deeply within the development process to enable continuous innovation and adaptability.

It is critical to recognize the differences between Technology Development (TD) and Product Development (PD) as a means to manage risks effectively when incorporating new technologies (Stolt *et al.*, 2015). Separating TD from PD allows companies to validate new technologies thoroughly before integrating them into product development, thereby minimizing risks associated with unproven technologies. By developing robust product and technology platforms companies can handle fluctuating requirements more efficiently and streamline the creation of customized product variants. This approach ensures that the transition from TD to PD is well-structured, with clear deliverables and validated technologies, thereby enhancing overall development efficiency and risk management. Integrating Lean Product Development (LPD) principles further enhances this approach by emphasizing value creation and waste elimination throughout the development process. LPD encourages front-loading projects, which involves making critical decisions, such as what technology to use, early and exploring multiple solutions concurrently to keep the design space as broad as possible (Andrè *et al.*, 2014).

So, there is a significant difference when we are engineering a new variant based on an existing platform and considering new technology for specific functionalities, compared to when we are assessing technologies to form the foundation of the platform design itself. When creating a variant, the focus is on technology integration, where the new technology is evaluated for its ability to enhance or add specific functionalities to the existing platform. For example, in the automotive industry, this might involve integrating advanced driver assistance systems (ADAS) into a current vehicle model to improve safety features without altering the core vehicle architecture.

In contrast, when designing the platform itself, the approach shifts to technology infusion. This involves a thorough assessment of emerging technologies to determine how they can fundamentally shape and define the platform's architecture. The goal here is to create a flexible and future-proof foundation that can accommodate a range of variants and adapt to technological advancements over time. For instance, in developing a new electric vehicle platform, considerations would include the integration of state-of-the-art battery technology, drive systems, and software architecture from the outset. This ensures that the platform is not only optimized for current technologies but also capable of integrating future innovations seamlessly. Therefore, the distinction lies in the scope and strategic depth of technology consideration: integration for enhancing specific features in variants, and infusion for embedding technology as a core aspect of platform design, enabling ongoing adaptability and innovation.

In this context, understanding the difference between technology integration and infusion is crucial for driving innovation effectively. When we distinguish between integrating new technologies into existing product variants and infusing them into the very foundation of platform design, we lay the groundwork for strategic innovation. Innovation encompasses three critical dimensions (Joubert and Belle, 2022). Firstly, unlike inventions, innovations necessitate successful market adoption (Garcia and Calantone, 2002). Secondly, innovation is iterative, with continuous introductions of enhanced versions. Lastly, there can be different types of innovation within an organization, including product, service, process, and technological innovations.

A useful way to characterize technological changes into four innovation categories (incremental, modular, architectural, and radical) is summarized in Table 1 (Henderson and Clark, 1990). Radical innovation introduces new dominant designs and core concepts in a product's architecture, fundamentally altering the component arrangement. Incremental innovation, on the other hand, focuses on refining and extending existing designs, and improving individual components while maintaining the original core concepts and their interconnections. Modular innovation involves changing core design concepts within a technology, such as transitioning from mechanical to Steer-by-Wire steering, without altering the overall product architecture. Architectural innovation reconfigures existing systems, creating new linkages between existing components, and triggering changes in component interactions. This innovation type preserves the core design concept and underlying scientific and engineering knowledge, emphasizing reconfiguration over component alteration.

TABLE 1 THE FRAMEWORK FOR DEFINING INNOVATION (HENDERSON AND CLARK, 1990)

		Core Concepts	
		Reinforced	Overturned
Linkages between Core Concepts and Components	Unchanged	Incremental Innovation	Modular Innovation
	Changed	Architectural Innovation	Radical Innovation

However, for a technology to even be considered, it needs to have reached a certain level of maturity, or Technology Readiness Level (TRL). Then the relationship between technology maturity and its performance is complex and multifaceted. Redo-Sanchez et al. (2013) highlight the impact of TRL on the practical application of Terahertz technology, with higher TRLs correlating with better performance. However, Tomaschek et al. (2016) emphasize the need to extend the TRL method from a component-readiness context to a system-readiness context, suggesting that the relationship between TRL and performance may be influenced by broader system factors. Nambiar and Poess (2011) further complicate the picture by discussing the limitations of Moore's Law in predicting performance improvements, indicating that other factors may also play a role. Expectedly, the more mature a technology is, the cheaper it tends to be to use in products (Yang *et al.*, 2011). Nevertheless, Servert et al. (2018) highlighted the slower cost reduction experienced by certain technologies, such as Concentrating Solar Power (CSP), due to factors like construction time and plant size. Moreover, Eden and Ronen (1987) introduced the concept of the declining-price paradox, which suggests that the more a technology's price is expected to decrease, the more urgent it is to invest in it. Yet, this paradox may not apply universally. Finally, Labro (2004) emphasized the need for further research on the cost effects of component commonality, indicating that the relationship between cost and TRL is not straightforward. Further insights into the management of these issues can be gleaned from the literature reviewing Technology Roadmapping advances (de Alcantara and Martens, 2019; Carvalho *et al.*, 2013). Technology Roadmapping (TRM) is a widely used strategic management tool known for its visual simplicity and comprehensibility. TRM facilitates the aggregation of big data and provides a comprehensive overview of various company activities.

Another maturity measurement system, the Manufacturing Readiness Levels (MRL) assesses the production readiness of systems and components during product development (Areth Koroth *et al.*, 2024). MRL helps align design and production phases by evaluating the maturity of manufacturing capabilities. This ensures that production requirements are prioritized effectively based on their readiness, thereby improving the efficiency and success of the development process.

The literature on the insertion of a new technology demonstrates that it tends to increase the structural complexity of a product. The method for the quantification of this increase by Sinha and de Weck (2013) can be used with both a binary DSM of interfaces and also with a numerical DSM with the number of relationships included as weights. The traditional binary DSM was favoured in the use cases Sinha explored (Sinha, 2014), while the numerical DSM appeared to better indicate the increased complexity in a use case involving satellite constellations (Moreno and Fortin, 2020). Increased complexity might inhibit the flexibility of product platforms.

Other studies, such as the work by Ravn *et al.* (2016), addresses the integration of new technologies into product platforms. Their multi-layered approach facilitates the evaluation and testing of novel technologies within existing product architectures, providing a structured framework that enhances team collaboration and supports efficient adaptation in manufacturing and supply chains. However, while their research offers valuable insights, it does not fully address the specific challenges of integrating emerging technologies into flexible automotive product platforms that must dynamically respond to rapid technological advancements and evolving customer needs. Specifically, their approach lacks a focus on the long-term scalability and modularity required to accommodate continuous updates and new technology integrations.

2.2.1 Change and Risk Propagation

In the dynamic landscape of engineering, changes are an inevitable and significant aspect of the design process, consuming substantial resources (Eckert *et al.*, 2004). These changes, often unpredictable, necessitate a comprehensive understanding of how they propagate through a system and affect its various components. The concept of 'ilities,' which includes attributes like flexibility, adaptability, and robustness, emerges from strategic thinking and decision theory (Cameron *et al.*, 2016). These 'ilities' are integral to managing change within systems, although predicting them during the early stages of product architecture development can be challenging. By embedding 'ilities' into the architecture development process, organizations can better mitigate the impacts of engineering changes. Incorporating these properties ensures that systems can effectively withstand, adapt to, and manage changes, thereby enhancing overall system stability and efficiency (Arjomandi Rad *et al.*, 2020).

A fundamental aspect of change management is understanding what constitutes a change and its broader implications. A change is any transition of a system from one state to another (Ross *et al.*, 2008). Changeability, a key system 'ility,' represents the capacity of a system to undergo structural, functional, or operational modifications through more specific ilities such as flexibility, agility, adaptability, evolvability, reconfigurability, versatility, and robustness. This overarching capability is crucial because it not only dictates what changes are possible but also delineates how these changes occur and their effects on the system over its lifecycle (Fricke and Schulz, 2005; Ross and Rhodes, 2008a; Sullivan *et al.*, 2019, 2023).

Effective decision-making in product development involves balancing multiple objectives, often requiring trade-offs and the prioritization of certain goals over others (Keeney and Raiffa, 1993). Introducing or replacing technologies within product platforms must be carefully planned to ensure compatibility and timely integration without compromising core design principles. To address risk mitigation, designers commonly employ a triad of strategies: Failure Modes and Effects Analysis (FMEA), simulation and modelling, and physical testing. Each of these methods, while prevalent, exhibits inherent limitations. FMEA often relies on speculative risk assessments due to a lack of comprehensive performance data, even at advanced stages of development. Physical testing, typically conducted on prototypes from a singular batch, fails to accurately represent the breadth of performance variations. In contrast, simulation and modelling predominantly focus on idealized geometry without considering variability, offering merely a safety margin against failure.

Integrating Design Failure Mode and Effects Analysis (DFMEA) and Process Failure Mode and Effects Analysis (PFMEA) into the product development process can significantly enhance the effectiveness of risk mitigation strategies, by facilitating better communication and collaboration between design and production teams, ensuring that risks are identified early and managed comprehensively (Fasolo and Elgh, 2022). DFMEA focuses on identifying and addressing design-related risks, while PFMEA targets failures within the manufacturing, assembly, and logistical processes.

High flexibility within a product platform enables designers to tolerate elevated levels of risk (Thomke, 1997). This flexibility acts as a buffer, allowing for a greater range of responses to unforeseen changes. From an operations research perspective, flexible platforms provide operational hedging, offering risk-averse decision-makers a strategic advantage (van den Broeke *et al.*, 2018). This adaptability is crucial in environments where change is frequent and often unpredictable, as it allows for continuous improvement and rapid response to new challenges.

Components within a system can be categorized based on their expected flexibility, which correlates with the anticipated frequency of future changes (Bauer *et al.*, 2015). This categorization aids in identifying which components are likely to require modifications and how these changes can be managed effectively. Decision Analysis (DA), a normative approach, further enhances decision quality by systematically addressing uncertainties, distinguishing them from generic risks and ambiguities, and analysing their impact on each decision alternative (Howard, 1988). This structured approach ensures that decisions are made with a comprehensive understanding of potential outcomes and their implications.

An additional perspective on change propagation is provided by the Change Propagation Method (CPM) by Clarkson *et al.* (2004), who emphasize the interconnected nature of design changes in complex systems. Their study on rotorcraft design at Westland Helicopters revealed that changes to one component often necessitate alterations to others, creating a cascade effect. By developing mathematical models to predict change propagation in terms of likelihood and impact, they demonstrated the importance of anticipating these chains of change. The use of tools like Design Structure Matrices (DSMs) and risk matrices allows engineers to visualize and manage the dependencies between subsystems, thus directing design efforts to minimize changes to critical and costly components. This proactive approach to change management not only helps in maintaining design integrity but also in optimizing resources and reducing unforeseen complications.

Recent advancements in Change Propagation Analysis (CPA) have enhanced our understanding of the impacts of design changes on complex systems. Ullah *et al.* (2017) introduced a mathematical model using a design structure matrix (DSM) to quantify propagated risks, aiding in the prediction and mitigation of engineering changes by evaluating both local and overall risks, and ensuring comprehensive impact analysis across entire product families. Brahma and Wynn (2022) emphasize the need to consider design parameters, geometry, and tasks, revealing the cascading effects of modifications. Probabilistic methods and Bayesian networks further enhance CPA by leveraging historical data and expert opinions. Brahma and Wynn's use of Monte Carlo simulation (MCS) helps trace change propagation and optimize design decisions under uncertainty. Integrating these methodologies—DSM models, probabilistic techniques, and simulations—provides a robust framework for resilient and adaptable product development. Furthermore, when long time horizons, uncertainty, and risk are involved in the decision-making process, practitioners are recommended to use probabilistic techniques (Parnell *et al.*, 2021).

The term "second-order" has varied meanings across disciplines. In mathematics, it can for example refer to second-order differential equations, where the highest derivative is the second, or in Taylor series expansions, where second-order terms matter when first-order terms are zero (Papalambros and Wilde, 2017). In science and technology, it can be used when talking about second-order cybernetics, i.e., applying cybernetics to itself, and second-order chemical reactions, where the reaction rate depends on the square of a reactant's concentration. In psychology and philosophy, it appears in second-order conditioning, i.e., learning from prior learning, and second-order desires, i.e., desires about other desires. In sustainability, "second-order effects" refer to effects beyond a technology's main objective, such as unintended environmental impacts (Piscicelli, 2023). The terms "second-order" or "higher-order" effects in the context of this study capture the concept often described through the metaphor of "ripple effects." When individuals think about the consequences of their actions, they naturally consider the immediate impact and the subsequent waves of effects that follow, much like ripples spreading across a pond after a stone is thrown. For instance, when a company adopts a new technology, such as implementing automation in their production line, they recognize that this change not only increases efficiency but also leads to further effects, such as reshaping workforce dynamics, influencing supplier relationships, and potentially sparking innovation in other areas. This intuitive grasp of "ripple effects" mirrors our use of "second-order" to mean "consequences of consequences," or "effects of effects." Other everyday layperson phrases alluding to the same concept are "knock-on effect", "domino effect" or "chain reaction". By emphasizing these cascading outcomes, we highlight how initial actions can set off a chain reaction, leading to broader and often unforeseen impacts.

2.2.2 Field Effects

In the early stages of product and system architecture design, incorporating field effects is critical for achieving functional and modular efficiency. Fields, defined as scalar or vector quantities associated with each point in space, influence the materials and physics of a system. Examples include temperature fields, pressure fields, and electromagnetic fields. The presence of such fields necessitates careful consideration during architectural trade-off decisions, as they impose constraints on where functionalities can be placed within the system architecture (Otto *et al.*, 2019).

When designing complex systems, field effects must be addressed to ensure the product's functionality and safety. For instance, in medical device design, ensuring sterility is paramount, which requires placing functionalities either inside or outside a sterile field. Similarly, in laser xerography, components must be placed around high-temperature and high-electrostatic fields to ensure proper operation. Otto *et al.* (2019) propose two primary guidelines for modularity considering field constraints: field separation and concept generation. Field separation involves creating zonal boundaries within which system modules are confined, while concept generation focuses on developing new concepts to overcome field constraints.

Field separation is crucial in systems where different zones must operate under varying field conditions, such as separating high- and low-voltage functions in an electric motor controller to ensure safety and functionality. Defining these boundaries allows designers to isolate functionalities, enhancing performance, simplifying maintenance, and reducing cross-field interference. Conversely, concept generation involves creatively violating these constraints to develop innovative solutions, like moving functionalities across boundaries or designing components that operate under multiple field conditions.

The TRIZ (Theory of Inventive Problem Solving) Su-field tool offers a complementary approach to managing field effects in design. The Su-field model, a fundamental TRIZ analytical tool, involves a triad of two substances and a field. It is particularly useful for modelling and solving problems related to interactions between different fields and substances. The Su-field analysis helps in identifying the interactions between the components and the fields affecting them, allowing designers to develop solutions that optimize these interactions (Terninko *et al.*, 1998). Field effects are analogous to the Su-field concepts in TRIZ, where the field represents the types of energy or forces acting within a system (the term MATChEM is used as a mnemonic for Mechanical, Acoustic, Thermal, Chemical, Electrical, and Magnetic). By applying Su-field analysis, designers can model the influences of fields such as electromagnetic, thermal, and mechanical forces on different system components. This approach provides a structured way to understand and manage the complex interactions within the system, leading to innovative solutions that address field-related constraints effectively (Ilevbare *et al.*, 2013).

Another promising approach leverages the inverse-square law to quantify the attenuation of field effects with distance. By considering the distances between components, the method accurately accounts for the attenuation of field effects, enhancing the precision of FE impact assessments across the system architecture. The inverse-square law states that the observed intensity of a specified physical quantity is inversely proportional to the square of the distance from the source of that physical quantity. By applying the inverse-square law in design, engineers can predict the impact of field effects more accurately and implement effective mitigation strategies, such as shielding or spatial reconfiguration of components, to reduce the influence of these fields on sensitive parts of the system.

Incorporating field effects into functional product-system architecting methods can not only address immediate design challenges but also opens avenues for innovation.

2.3 Impact Analysis

2.3.1 The Value of Flexibility

Flexibility in product platforms is the capacity to accommodate changes in design, technology, and features without requiring significant re-engineering (Saleh *et al.*, 2009). This attribute is crucial for maintaining competitiveness and responsiveness in dynamic market conditions. The assessment of flexibility can be achieved through various quantitative metrics: modularity, scalability, and adaptability. Modularity refers to the independence of components, allowing them to be developed, replaced, or modified independently. Scalability measures the ease with which a system's capacity can be increased or decreased. Adaptability evaluates how well the platform can respond to changes in its environment or requirements. Other terms have been defined in the literature to signify flexibility, such as variability, the ability to configure, customize, and exchange an artefact (any entity of a product) throughout its lifecycle (Bachmann and Clements, 2005).

Flexible designs offer significant advantages by permitting expansion when justified while avoiding unnecessary initial investments (De Neufville and Scholtes, 2011). This approach is particularly beneficial as it reduces the initial capital expenditure required for a project. Flexible designs position systems to expand as needed without committing to expansions that may not be necessary. This principle is fundamental to addressing the issues of under- and over-design. Over-design occurs when platforms are built with excessive initial capabilities to accommodate future growth, leading to resource wastage. By contrast, under-design happens when platforms lack the flexibility to adapt to new requirements, resulting in increased costs and longer development cycles. This is a crucial aspect where theory and practice often diverge, as flexible designs often cost less than inflexible ones, contrary to the intuition that flexibility always incurs higher costs.

Flexible designs mitigate both risks by allowing incremental investments based on actual demand, thus aligning initial capital expenditures more closely with real-world needs.

De Neufville and Scholtes provide a practical illustration of this concept through a comparison of inflexible and flexible building designs. An inflexible design might require constructing a larger initial structure to benefit from future growth (a five-story building in their example). Conversely, a flexible design allows for a smaller initial structure, like a four-story building, with provisions for future expansions. This approach not only reduces initial costs but also aligns the system's capacity with actual demand, avoiding the pitfalls of both under- and over-design. The cost-effectiveness of flexible designs arises from the ability to build smaller initially and expand only as needed. For instance, the savings from constructing a smaller initial structure can outweigh the additional costs of incorporating features that enable future expansions, such as stronger columns and footings.

The value of flexibility is also evident in the improved expected performance of systems in uncertain environments. By moving the performance curve to the right—toward better performance—flexible designs reduce downside risks and enhance opportunities for upside gains. Monte Carlo simulations and target curves are valuable tools in this context, providing systematic insights into the behaviour of alternative designs under varying conditions.

Understanding and managing complex interdependencies is essential for sustaining adaptability and integrating new technologies into product platforms. The Epoch-Era Analysis method (Ross and Rhodes, 2008b) facilitates this by defining periods of consistent context and expectations (epochs) and sequences of these periods (eras) to depict potential progressions of contexts and expectations over time.

Flexibility becomes increasingly valuable as uncertainty grows (Suh, 2005). The incorporation of flexibility into components, trends in production volumes, and the degree of inherent flexibility are critical considerations when designing flexible product platforms (Suh, de Weck, Kim, *et al.*, 2007). Uncertainty-Oriented Product Platform (UOPP) is a promising approach (Han *et al.*, 2020), which includes flexible product platforms, adaptable product platforms, market-driven product platforms, and sustainable product platforms.

The challenge of selecting adaptable architectures for systems undergoing rapid changes has been addressed using Time-expanded Decision Networks (TDNs). These networks identify future transition pathways, as demonstrated in autonomous driving systems, where optimizing architecture transitions can enhance the system's net present value by 10-20% (Siddiqi *et al.*, 2020). This highlights the necessity of having transition roadmaps for evolving systems.

Other related concepts, such as 'pliability', introduced by Mekdeci *et al.* (2012), describe a system's ability to change without compromising its predefined and validated architecture. This concept enhances system robustness and survivability by enabling voluntary adaptations to evolving contexts, ensuring that even unintentional modifications remain within permissible boundaries. Pliability identifies changes that can be implemented without necessitating further validation or approval, thereby facilitating easier modifications in large and complex systems.

The literature suggests that flexible product platforms can mitigate the effects of both internal (e.g., material changes) and external (e.g., regulatory changes) factors. Suh (2005) and Suh, de Weck, and Chang (2007) demonstrated the value of flexibility in uncertain market conditions, showing how it can suppress change propagation and reduce switching costs. Bauer et al. (2015) and Elezi et al. (2015) proposed methodologies for designing robust product platforms that effectively handle dynamic changes, with promising industrial applications.

Moreover, flexible product platforms can enhance external variety, as suggested by Kim, Wong, and Eng (2005) and Shum (2003).

Cavalliere *et al.* (2019) and Reisinger *et al.* (2021) both propose novel approaches to assessing flexibility in building design. Reisinger introduces four flexibility metrics, while Cavalliere presents six criteria for evaluating the functional flexibility of buildings. Both studies emphasize the importance of these metrics in guiding decision-making towards more sustainable and flexible design choices. Nilchiani (2007) extends this discussion to space systems, proposing a comprehensive framework for measuring the value of flexibility in engineering systems.

Design margins are a critical aspect of product platform development (Eckert *et al.*, 2020). At the system or product level, design margins have been identified as contributors to the provision of opportunities for system change, particularly at the decision variable level (Jacobson and Ferguson, 2023). In parallel work, arguing for the use of appropriate metrics to evaluate different design configurations when specifying design margins to mitigate uncertainty, Juul-Nyholm and Eifler (2023) provide examples of margin specifications, and apply multiobjective robustness indicators to a case example.

These studies collectively highlight the need for and potential benefits of incorporating flexibility metrics in the design and assessment of industrial and engineering systems. These can then be used to explore the trade-off between flexibility and other dimensions of interest for the system stakeholders, to maximize the value the system provides over its lifecycle.

2.3.2 Value-Driven Design

The concept of value in engineering design, particularly within the scope of Value-Driven Design (VDD), emphasizes the paramount importance of aligning design decisions with the creation of stakeholder value (Collopy and Hollingsworth, 2011). VDD represents a strategic departure from traditional design methodologies that primarily focus on meeting predefined performance requirements. Instead, it advocates for maximizing the overall value generated by a system throughout its lifecycle, effectively bridging the gap between technical performance and stakeholder satisfaction. Stakeholders, irrespective of whether changes are deliberate or accidental, expect systems to function efficiently and provide value (Mekdeci *et al.*, 2012).

Fundamentally, VDD is rooted in microeconomic principles, where the objective is to maximize the system's value rather than merely fulfilling a set of static requirements. This approach transforms the design process into an optimization problem, where various design alternatives are evaluated based on their ability to deliver the highest perceived value to stakeholders. The shift towards VDD is particularly significant in complex systems engineering, such as aerospace, where traditional requirements-based approaches often lead to cost overruns and suboptimal performance due to their inherent limitations in handling uncertainty and evolving stakeholder needs (Collopy and Hollingsworth, 2011). Designers of complex, long-lasting projects must learn to abandon fixed specifications and narrow forecasts (De Neufville and Scholtes, 2011).

A key component of VDD is the Value Creation Strategy (VCS), a comprehensive framework that captures and prioritizes stakeholder needs, translating them into rank-weighted objectives and value drivers. This method enables a systematic exploration of design trade-offs early in the conceptual phase, ensuring that the chosen design paths align closely with stakeholder expectations and deliver maximum value (Collopy and Hollingsworth, 2011). The VCS serves as a dynamic blueprint that guides the design process, allowing for iterative refinements and continuous alignment with stakeholder value. For instance, procedures to generate flexibility in engineering systems and improve lifecycle performance, such as using a Generation Variety Index (GVI) and Coupling Index (CI), have been empirically validated to standardize and modularize designs, thereby enabling switching flexibility between product variants (Cardin *et al.*, 2012).

Moreover, VDD promotes the use of quantitative value models, which provide a scalar representation of the system's value based on various attributes such as cost, reliability, and performance. These models facilitate informed decision-making by enabling designers to visualize the impact of different design choices on the overall system value. The probabilistic nature of these models also enhances risk management by quantifying the potential value losses associated with different design risks (Collopy and Hollingsworth, 2011). Additionally, the hybrid real options analysis framework, which integrates product-related and project-related flexibility, allows for the synthesis of both financial and technical analyses within a coherent framework (Jiao, 2012).

The integration of VDD into the acquisition processes, especially in government programs, exemplifies its broader applicability and potential for optimizing large-scale engineering projects. Value-Based Acquisition (VBA) is one such approach where contracts are structured around the value delivered rather than the cost incurred. This incentivizes contractors to adopt VDD principles, thereby aligning their objectives with the overarching goal of maximizing stakeholder value (Collopy and Hollingsworth, 2011). In customizable modular product platforms, understanding the interactions and integration of social and technical factors is crucial for the successful development of complex products (Colombo *et al.*, 2020).

Recent advancements in the field, underscore the effectiveness of VDD in enhancing design optimization and reducing developmental risks and rework. By focusing on value creation from the outset, VDD methodologies enable more agile and adaptive design processes that are better equipped to handle the complexities and uncertainties inherent in modern engineering projects (Collopy and Hollingsworth, 2011; Isaksson *et al.*, 2013). Furthermore, the work by Schwede *et al.* (2022) on modularization methods demonstrates how these methods can impact economic target values like time, costs, quality, and flexibility across all life phases of a product family, using impact chains to model cause-effect relationships.

The adoption of VDD represents a paradigm shift in engineering design, prioritizing stakeholder value over traditional performance metrics. This approach not only drives innovation and efficiency but also ensures that the final product meets or exceeds stakeholder expectations, thereby delivering superior value across the entire lifecycle of the system (Bertoni and Bertoni, 2016).

3 RESEARCH APPROACH

This chapter describes the context in which this thesis was developed, introduces the research approach methodology followed, lists and explains the methods used, and discusses the validity of the research approach.

3.1 RESEARCH CONTEXT

The content of this thesis was primarily developed within the context of the *Value and flexibility Impact analysis for Sustainable Production* (VISP) project, a collaboration between the Chalmers University of Technology, Volvo Cars, and Volvo Trucks Technology Group, with financial support from VINNOVA, the Swedish innovation organization (grant number [2018-02692]).[1] The Systems Engineering Design research group was the host of the author within the division of Product Development, Industrial and Materials Science (IMS) department. Geographically, most of the research activities took place along the west coast of Sweden.

Additional insights were acquired by participating in other projects, such as the Digital Sustainability Implementation Package (DSIP, VINNOVA grant number [2020-04163]),[2] which focused more on the sustainability aspects of product development, and interactions with undergraduate students, either taking product development courses or producing their master's thesis.

3.2 INDUSTRIAL CONTEXT AND PARTNERS

[1] https://www.vinnova.se/en/p/visp---value-and-flexibility-impact-analysis-for-sustainable-production/
[2] https://www.vinnova.se/en/p/digital-sustainability-implementation-package---dsip/

Two automotive companies provided access to use cases and industrial expertise, and closely collaborated with academic researchers in setting up data-gathering events, as well as analysis and dissemination of the results.

3.2.1 Volvo Cars

Volvo Cars, a renowned Swedish automobile manufacturer, has established itself as a leader in safety, innovation, and sustainability. Founded in 1927, the company has grown significantly over the decades and is known for its commitment to quality and forward-thinking design. Volvo Cars has a global presence, with manufacturing plants in Sweden, Belgium, China, and the United States. In 2023, the company sold approximately 700,000 vehicles worldwide, maintaining strong sales growth across key markets including Europe, the United States, and China. Volvo Cars employs around 40,000 people globally.

Volvo Cars offers a diverse range of models, catering to various market segments. Its lineup includes sedans (S60, S90), SUVs (XC40, XC60, XC90), and station wagons (V60, V90). Each model is designed to reflect the company's core values of safety, sustainability, and Scandinavian design. Volvo Cars has adopted a modular platform strategy to enhance flexibility and efficiency in its manufacturing process. The main platforms used are the Scalable Product Architecture (SPA, and SPA2) and the Compact Modular Architecture (CMA). SPA is utilized for larger models such as the XC90, XC60, S90, and V90, allowing for the integration of advanced technologies and diverse powertrain options including plug-in hybrids and fully electric powertrains. The CMA platform underpins smaller models like the XC40, providing similar flexibility and supporting Volvo's move towards electrification.

Volvo Cars is at the forefront of integrating new technologies into its vehicles. Significant innovations include advanced driver assistance systems (ADAS), autonomous driving capabilities, and state-of-the-art connectivity features. The company is also committed to electrification, with a significant portion of its lineup now featuring hybrid or fully electric powertrains. Volvo's commitment to safety continues with the integration of features such as pedestrian detection, lane-keeping assist, and collision avoidance systems.

3.2.2 Volvo Trucks

Volvo Trucks, part of the Volvo Group, is one of the world's leading manufacturers of heavy-duty trucks and transport solutions. Since its founding in 1928, Volvo Trucks has been synonymous with reliability, innovation, and sustainability. Volvo Trucks operates globally, with production facilities in 19 countries and sales operations in over 190 markets. In 2023, the company delivered around 230,000 trucks worldwide, maintaining a strong presence in Europe, North America, and Asia. Volvo Trucks employs approximately 100,000 people across its global operations.

Volvo Trucks offers a wide range of models designed for various transport needs, including long-haul, regional, and urban distribution. Key models include the Volvo FH, Volvo FM, Volvo FMX, Volvo FE, and Volvo FL. Each model is engineered for specific applications, ensuring that Volvo Trucks can meet the diverse demands of the transport industry. Volvo Trucks utilizes flexible and scalable platforms to streamline production and enhance customization. The Volvo Global Truck Concept (GTC) platform supports the development of multiple truck models with varying specifications, allowing for efficient production and rapid integration of new technologies. This platform approach helps Volvo Trucks to adapt quickly to market demands and regulatory changes. The Volvo Group encompasses several other prominent truck brands beyond Volvo Trucks, each catering to different market needs and regional demands. Mack Trucks, based in the United States, is known for its robust and durable heavy-duty trucks, particularly popular in construction and long-haul transport. Renault Trucks, headquartered in France, offers a wide range of commercial vehicles, focusing on efficiency and innovation in urban, regional, and long-haul segments. Together, these brands complement Volvo Trucks' offerings, providing a comprehensive portfolio that meets diverse global transportation needs.

Volvo Trucks is a leader in integrating cutting-edge technologies into its vehicles. Innovations include advanced telematics, connectivity solutions, and autonomous driving systems. Volvo Trucks is also pioneering in the field of electromobility, with electric truck models such as the Volvo FE Electric and Volvo FL Electric designed for urban distribution. Additionally, the company focuses on enhancing safety with features like collision warning systems, lane-keeping support, and adaptive cruise control.

3.3 Design Research Methodology

The research approach methodology used for this thesis is the Design Research Methodology (DRM) (Blessing and Chakrabarti, 2009). DRM is a framework that focuses on aiding in both the creation of support for conducting better design and the process of providing an understanding of design as a scientific subject. The motivation to use DRM was twofold: first, to investigate how design can be used as a tool for change in industrial socio-technical systems and second, to explore how researchers can use design methods in their work. In particular, the author was interested in understanding the potential benefits and challenges of researching engineering design with different types of data (quantitative vs qualitative) and different types of stakeholders (academics vs practitioners). DRM provides a systematic way to plan and conduct design research projects. It also offers a framework for understanding the design problem, exploring possible solutions, and making decisions about which solution to pursue.

In this research, the author incorporated a modification to the traditional DRM methodology by integrating agile principles to accelerate the research process and enhance its impact on industry. This approach was inspired by the need to balance scientific rigour with the practical demands of industrial collaboration, as discussed by Panarotto *et al.*, (2023). This agile adaptation of DRM, referred to as Agile Design Research (Agile DR), focuses on iterative development, early validation, and maintaining flexibility to adapt to changing requirements. By structuring the research process into short, manageable sprints, the author and his collaborators aimed to deliver incremental value to our industrial partners and maintain momentum throughout the project.

The application of Agile DR involved decomposing complex research problems into smaller, independent tasks that could be addressed within short time frames. This method allowed for rapid feedback and continuous improvement, ensuring that the research remained relevant and aligned with industrial needs. Additionally, it emphasized the importance of practical demonstration and direct communication with stakeholders, which facilitated a more dynamic and responsive research environment. This agile approach not only helped in managing the complexity of the research but also improved the overall efficiency and effectiveness of the design support developed.

In essence, by incorporating agile principles into the DRM framework, we were able to achieve a more flexible and responsive research process that better met the needs of both academic and industrial stakeholders. This innovative approach underscores the potential of combining traditional research methodologies with modern, agile practices to enhance the relevance and impact of design research in industrial contexts.

The DRM framework is divided into four main stages: Research Clarification (RC), Descriptive Study I (DS-I), Descriptive Study II (DS-II), and Prescriptive Study (PS). In Figure 7, those stages are linked to the research methods and key deliverables for this thesis.

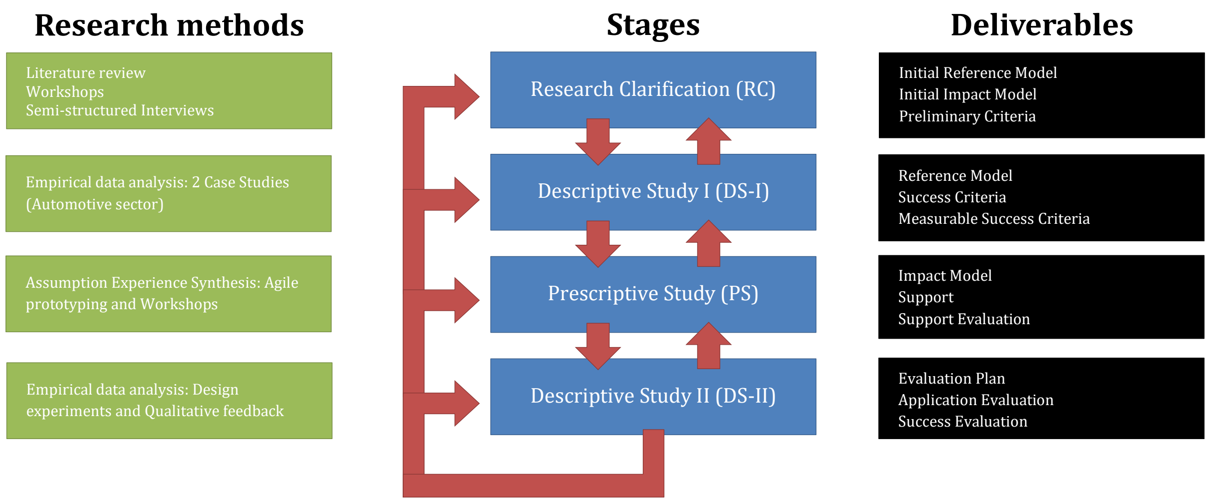

FIGURE 7 DRM FRAMEWORK STAGES.

Table 2 describes the positioning of the papers attached to this thesis within the DRM framework stages and their relative alignment.

TABLE 2 POSITIONING OF THE ATTACHED PAPERS ACCORDING TO THE DRM FRAMEWORK

DRM Stage	Paper A	Paper B	Paper C	Paper D	Paper E	Paper F
Research Clarification	⬤	●	●	⬤	●	○
Descriptive Study I	●	⬤	○	●	○	○
Prescriptive Study	○	⬤	⬤	●	⬤	○
Descriptive Study II	○	○	○	○	●	⬤

Paper A focuses on the Research Clarification (RC) phase and introduces Descriptive Study I (DS-I). Paper B develops DS-I and establishes the theoretical foundation for the Prescriptive Study (PS) stage. Paper C expands on the PS by proposing specific implementation alternatives and offering further theoretical insights. Paper D contributes to the RC by introducing the Field Effects concept and suggesting its application in DS-I and PS. Paper E builds on these suggestions and further develops the PS phase. Finally, Paper F presents an account of Design Study II (DS-II).

3.4 ADOPTED RESEARCH METHODS

3.4.1 CASE STUDIES SELECTION AND IDEALIZATION

Industrial case studies are particularly valuable when the research aims to gain a deeper understanding of real-world phenomena for theory building in qualitative research, necessitating the collection of empirical data (Voss, 2008), despite case studies typically being employed for theory testing (Eisenhardt, 1989).

The selection and idealization of case studies are critical to the research methodology, providing practical insights and validating theoretical models. For this research, the case studies were chosen based on their relevance to the automotive industry and their potential to illustrate the challenges and solutions related to flexible product platform design.

Applying the principles by Yin (2018) ensures that the case studies maintain high standards of **validity** and **reliability** by utilizing multiple sources of evidence, including interviews with engineers and managers, document reviews, and workshops, to achieve construct validity. Internal validity was strengthened through pattern matching and explanation-building techniques to explore causal relationships and validate findings within these specific contexts. Although the findings from Volvo Cars and Volvo Trucks are context-specific, the developed theoretical framework allows for external validity, providing a basis for generalization to other settings. Additionally, careful documentation of research procedures ensures reliability and facilitates replication in future studies.

The primary **selection criteria** for the case studies included the relevance to the research questions, the industry significance, and the availability of data. The case studies needed to address the integration of new technologies into product platforms and the associated flexibility requirements, ensuring they were aligned with the core research objectives. For this reason, mostly mechatronic systems were selected (e.g., steer-by-wire systems, head-up-displays). Focus was placed on leading automotive OEMs known for their innovation and complexity in product development, within an accessible geographical area. Access to detailed data and the willingness of companies to collaborate and share information were critical for conducting in-depth analysis. This access was limited only by commercial confidentiality.

The selected case studies underwent an **idealization process** to ensure they provided clear, actionable insights. This involved developing a comprehensive understanding of the operational context of the OEMs, including their product development processes, technological challenges, and market dynamics. Engaging with key stakeholders within the companies, such as engineers, managers, and decision-makers, helped gather diverse perspectives and validate findings. The scope of each case study was clearly defined to focus on specific aspects of flexibility in product platform design, avoiding overly broad or unfocused analysis. A combination of methods (described in the next section), including workshops, interviews, and document reviews, was employed to collect rich, qualitative, and quantitative data relevant to the research questions. This idealization process was also heavily influenced by the Agile DRM approach, as described earlier.

3.4.2 Data Collection and Analysis Activities

There are many ways to collect data during design research, but the case study approach is one of the most common. Case studies involve investigating a current phenomenon in its real-life context, which can aid in understanding how boundaries between the phenomenon and its context interact (Yin, 2018).

There are some things to consider when using case studies as a research method. First, it is important to make sure that the boundaries between the phenomenon being studied and its context are clear. To do this, experiments may be necessary to isolate the phenomenon from its surroundings. Second, case studies should not be used as a data collection method; rather, they should be used as a setting in which data can be collected. Finally, it is important to remember that case studies provide insights into individual cases and should not be generalized without proper consideration of the limitations and particularities of the cases in question.

In this case, the collection of the data was mainly performed via three main mechanisms, which are described in detail below: literature reviews, workshops, and interviews.

Additional information and inspiration were gathered over the years by attending over two hundred meetings at the partner companies. These ranged from periodic "pulse" meetings, to design reviews, and were attended by a demographic similar to that of the workshops and interviews.

3.4.2.1 Literature Reviews

A literature review of the state of the art of the research was conducted for every article attached to this thesis for its specific areas of interest. To locate the academic publications used in the literature reviews, the SCOPUS database was used. Keywords and backward and forward snowballing (Wohlin, 2014) procedures were used to find the most highly cited and current articles in the field. Article A, as a Research Clarification Study, required more extensive literature review activities, to identify and assess both the current existing areas of research and gaps requiring further research. The entries obtained through SCOPUS and snowballing were filtered by title, abstract, and full-text content based on appropriate inclusion criteria.

Additional tools were used to aid the snowballing, such as *Research Rabbit*[3], *Connected Papers*[4], *Elicit*[5], and *Scite*[6].

3.4.2.2 Digital modelling and experimenting

Tools such as reactive web applications and *Jupyter*[7] notebooks played a crucial role in the development and analysis of the digital experiments. Reactive web applications were coded mainly in *Vue*[8], and allowed real-time interaction with design models, enabling dynamic visualization of changes and their impacts alongside all stakeholders. The Jupyter notebooks provided an interactive coding environment, combining code, visualizations, and narrative text, which facilitated collaboration, exploration of design alternatives, and documentation of insights. The *Python*[9] programming language and the appropriate libraries (e.g., *numpy*[10], *pandas*[11], *matplotlib*[12], *networkx*[13]) were used. As such, the necessary reimplementation of existing algorithms from the literature was performed, and newly proposed methods and metrics were comprehensively built.

For modelling and experimenting with the systems of interest a Model-Based Systems Engineering (MBSE) approach was adopted, leveraging comprehensive models to support the entire lifecycle of complex systems. MBSE was chosen for its ability to integrate models across various domains—requirements, behaviour, architecture, and Verification & Validation (V&V). This approach ensures a cohesive and unified framework, enhancing consistency, traceability, and efficiency throughout the development process.

[3] https://www.researchrabbitapp.com/
[4] https://www.connectedpapers.com/
[5] https://elicit.org/
[6] https://scite.ai/
[7] https://jupyter.org/
[8] https://vuejs.org/
[9] https://www.python.org/
[10] https://numpy.org/
[11] https://pandas.pydata.org/
[12] https://matplotlib.org/
[13] https://networkx.org/

The digital experiments used simple volumes to represent components, such as "space reservations". A similar approach to the use of outer surface "boxes" in the constituent system level architecture models for component placement by Papageorgiou *et al.* (2020), as seen in Figure 6. These are also similar to the concept of Flexible Volumetric Elements (VEs), as discussed by (Popovic *et al.*, 2021). VEs are modular and scalable components used in the industrialized house building (IHB) sector to facilitate high-level mass customization, by enabling the configuration and adaptation of single-family houses to meet specific customer requirements and local contingencies while maintaining production efficiency.

Complementing MBSE, the digital experiments employed Design of Experiments (DOE), a systematic method to determine the relationships between factors affecting a process and the output of that process. DOE's structured approach allowed the identification of critical design variables, optimization of performance, and assurance of robustness. By conducting controlled experiments, the trade-offs in a wide range of scenarios and configurations were explored in the case studies.

To facilitate the development and management of digital models, Object-Oriented Programming (OOP) was utilized. This programming paradigm, centred around objects and data, is particularly advantageous for interfacing with Computer-Aided Design (CAD) and Product Lifecycle Management (PLM) tools. OOP's modular and reusable code structure supports the integration of Knowledge-Based Engineering (KBE) principles, enabling the creation of adaptable and extensible design frameworks.

Version control systems, particularly *Git*[14], were indispensable for managing changes in design models and code. *Git*'s capability to handle multiple contributions simultaneously while maintaining a history of changes ensured traceability and facilitated collaboration. This version control system supports the iterative nature of product development, enabling continuous improvement and refinement of design models.

This collaboration angle was further enriched by the development of libraries containing useful algorithms, essential for enhancing the flexibility and functionality of product platforms. These libraries included algorithms for change propagation, value-weighted filter outdegree, and other flexibility metrics. Recreating and refining algorithms from the

[14] https://www.git-scm.com/

literature allowed the construction of a robust toolkit addressing specific challenges in product platform development.

While alternative approaches such as purely empirical methods or traditional CAD tools without integrated OOP and MBSE frameworks could have been considered, they were not as well suited for this research. Empirical methods alone lack the predictive power and efficiency of model-based approaches, and traditional CAD tools would have resulted in less adaptable and harder-to-manage models.

3.4.2.3 Design experiments

To validate the methods and tools proposed in this research, a series of design experiments were conducted (Montgomery, 2017), focusing on the development and utilization of interactive web applications. These applications serve as both a manifestation of the proposed tools and a platform for testing the underlying methodologies. The web applications incorporate remote real-time telemetry to timestamp and log user interactions, enabling a detailed analysis of user behaviour and decision-making processes.

During the preparatory phase, several prototypes of the web applications were developed and iteratively tested (refer to Paper 1 in the list of additional papers). These prototypes facilitated early detection of potential issues and refinement of functionalities to better align with user needs. The iterative testing process ensured that the final applications were robust and user-friendly.

The core of the design experiments involved detailed tracking of user interactions with the web applications. Real-time telemetry was employed to record the sequence, timing, and nature of decisions made by users engaged in engineering design activities. The teams involved represented a varied set of professional experiences, providing a comprehensive understanding of how different backgrounds influence the use of the tools. This data was then analysed to understand the decision-making process and its impact on the outcomes of the design tasks.

To evaluate the effectiveness of the proposed tools, a comprehensive statistical analysis was conducted (Cohen *et al.*, 2002). This included the use of linear regression models, both with and without interaction terms, to identify significant factors influencing user performance. The assumptions of linear regression—linearity, independence, homoscedasticity, and normality of residuals—were rigorously tested to ensure the validity of the models.

The decisions and their sequences taken by different teams using the tools were compared against the results of their work. Performance metrics were established to assess the relative effectiveness of each team's approach. This comparative analysis provided insights into how different decision-making strategies impacted the final design outcomes, offering a basis for further refinement of the tools and methods.

By integrating interactive web applications with robust data logging and analysis capabilities, these design experiments provided a valuable platform for testing and validating the proposed methodologies. The insights gained from these experiments contribute to the development of more effective tools for flexible product platform design. More details about these experiments can be read in Paper F.

3.4.2.4 Workshops

Workshops provide a space for people to come together and share their experiences and ideas. This can be a valuable method of data collection because it allows for input from a variety of people with different backgrounds and expertise. It might also help build consensus around an issue or topic. However, there are some drawbacks to the use of workshops as a data-collection method. First, this process is time-consuming and expensive. Second, it can be difficult to ensure that everyone who needs to participate does so, which can affect the quality of the data collected. Finally, workshops may not always produce concrete results or recommendations that researchers can use in their work.

In this case, participants were selected by requesting candidates from the network of industry representatives and their subsequent networks to ensure coverage of all relevant disciplines and stakeholders. Owing to the interesting nature of the research, many senior experts (i.e., with decades of experience) and decision-makers at several decision levels participated in the workshops.

In the context of this thesis, in total twelve workshops were held over a four-year timespan, with around 120 unique participants.

3.4.2.5 Interviews

Interviews are a common method of collecting data in case studies. There are three different types of interviews: the fully structured interview, the semi-structured interview, and the unstructured interview. A fully structured interview is distinguished by questions that are precisely worded and posed in a particular and consistent order.

The semi-structured interview provides greater flow to the interview by allowing more room for improvisation, so while the questions are predefined, their phrasing and order are open to adaptation by the interviewer. Further explanation of certain questions or their exclusion altogether is also possible if they are found to be irrelevant in a particular interview. Finally, the unstructured interview is closer to a conversation without predetermined questions and only a general topic to guide the discussion.

Over twenty in-depth semi-structured interviews were conducted concerning this thesis. They were conducted primarily as a complement to the workshops to work around scheduling conflicts and ensure a wide representation of concerns and perspectives. The profile of the participants was, thus, very similar to that described in the workshop section, with a small bias toward more senior people with more complex scheduling issues.

To analyse the transcribed data collected in workshops and interviews, *nVivo* was used. It allowed for a coherent thematic analysis (Braun and Clarke, 2006) and management of quotes from participants, and it also enabled efficient collaboration between researchers.

3.5 Research validity

Establishing the validity of research is a cornerstone of rigorous academic inquiry, especially in the field of design research, where contributions often straddle both theoretical advancements and practical applications. This section outlines the methodologies employed and the steps taken to ensure the validity of the research presented in this thesis, which encompasses workshops, interviews, design experiments, and case studies.

The research methods chosen for this study are validated based on established practices within the field of design research. Workshops and interviews were conducted to gather qualitative data, offering in-depth insights into participant experiences and perspectives. Design experiments provided a controlled environment to test specific hypotheses, while case studies offered contextual depth by examining real-world applications. Triangulation was employed to enhance the credibility of the findings. This approach involves using multiple methods or data sources to cross-verify the results. By integrating data from workshops, interviews, design experiments, and case studies, the research mitigates the risk of bias and provides a more comprehensive understanding of the phenomena studied.

The sampling strategy was carefully designed to ensure representativeness and relevance. According to Cash *et al.* (2022), defining a research sample is crucial in shaping the study's impact on both theory and practice. Diverse sampling methods were used to capture a wide range of perspectives, thereby enhancing the generalizability of the findings. This included purposive sampling for workshops and interviews to ensure that participants had relevant experience and expertise, and case selection for experiments and case studies based on specific criteria (see Section 3.4.1) relevant to the research questions.

Several validation techniques were employed to ensure the robustness of the research findings. Construct validity was ensured through the use of multiple sources of evidence, as recommended by Yin (2018). This involved corroborating interview data with observational data from workshops and experimental results. Internal validity was achieved by identifying and testing causal relationships within design experiments, ensuring that the outcomes can be attributed to the variables under study rather than extraneous factors. External validity was addressed by conducting case studies across different contexts (different systems, technologies, and companies) to examine the applicability of the findings beyond the initial study settings. Reliability was ensured through the development of a detailed research protocol and maintaining a consistent approach across all phases of data collection and analysis.

The research's practical contribution to industry was validated through close collaboration with industrial partners. This involved iterative feedback loops where findings were continuously tested and refined in real-world settings. As highlighted by Isaksson *et al.* (2020), validation in industrial contexts requires ensuring that the research outcomes are both relevant and applicable to industry partners, who often serve as the primary customers of the research.

Ethical considerations were carefully addressed throughout the research process. Informed consent was obtained from all participants, and confidentiality was maintained to protect sensitive information. The ethical guidelines followed align with those established in the field of design research, ensuring the integrity and ethical soundness of the study.

The validity of this research is underscored by a rigorous methodological framework, the use of triangulation, and robust validation techniques. The combined use of workshops, interviews, design experiments, and case studies provided a comprehensive and credible foundation for the research findings. Through careful sampling, validation, and ethical practices, the study ensures both theoretical contribution and practical relevance, adhering to the highest standards of research integrity in the field of design research.

4 Summary of Appended Publications

This chapter summarises the six appended papers and their contributions to the research questions.

4.1 Paper A: Identification of Technology Integration Challenges at Two Global Automotive OEMs

In Paper A, we conducted an in-depth investigation into the integration of new technologies within established product platforms at two major automotive Original Equipment Manufacturers (OEMs): Volvo Car Group and Volvo Group Truck Technology. This study specifically addressed the internal challenges and decision-making processes that these OEMs encounter when adapting their product platforms to incorporate technological advancements.

The research identified several critical challenges related to technology integration, which were categorized into strategic, operational, technical, and market-related issues. These findings were crucial in highlighting the inherent complexities and barriers faced by OEMs in this domain.

The strategic challenges of integrating new technologies into product platforms include managing uncertainty, aligning with brand strategy, acquiring necessary competencies, and ensuring regulatory compliance. Predicting future technological trends and market demands is inherently difficult, complicating the planning process (Harmel *et al.*, 2006). Additionally, integrating new technologies must be consistent with the brand's long-term strategy and image, necessitating a careful alignment to maintain brand integrity (Lundbäck, 2002). The acquisition of new skills and knowledge is critical, as technological integration often requires expertise that may not currently exist within the organization (Batchelor, 2006; Patel and Pavitt, 1997). Furthermore, companies must continuously adapt to stringent and evolving regulatory requirements, which can significantly impact the integration process (Clark and Paolucci, 2001).

Operational challenges focus on the practical aspects of technology integration, such as development lead time, interface management, and production integration. The process of integrating and validating new technologies within existing platforms often requires extended periods, delaying time-to-market (Parslov and Mortensen, 2015). Ensuring seamless interaction between new and existing components is crucial, necessitating effective interface management (Parslov and Mortensen, 2015). Additionally, modifying existing production systems to accommodate new technologies without causing significant disruptions presents a significant operational hurdle (Michaelis and Johannesson, 2011).

From a technical perspective, challenges include technology maturity, change propagation, and verification complexity. Emerging technologies may not be fully mature, posing risks when attempting integration (Coronado Mondragon and Coronado Mondragon, 2018). Managing the ripple effects of changes across the platform is essential to prevent adverse impacts on existing systems, necessitating careful change propagation management (Clarkson *et al.*, 2004). Moreover, the complexity of verifying and validating integrated technologies to meet quality and performance standards adds another layer of difficulty (Borgue, Paissoni, *et al.*, 2021; Scheidemann, 2006).

Market-related challenges involve ensuring customer satisfaction and achieving economies of scale. Integrated technologies must meet or exceed customer expectations to maintain satisfaction and loyalty (Richter *et al.*, 2016). Achieving cost efficiencies while incorporating advanced technologies into the production process is crucial for maintaining competitiveness and profitability (Fixson, 2006). These challenges highlight the need for a comprehensive approach to managing technology integration in product platforms.

The case studies from Volvo Car Group and Volvo Group Truck Technology provided valuable insights into the practical aspects of these challenges. The studies highlighted specific instances where technology integration efforts faced significant hurdles, illustrating the need for more robust and flexible decision-making frameworks.

The findings of Paper A underscore the necessity for improved methods to facilitate early decision-making in platform development. The study advocates for a more nuanced and adaptable approach to decision-making, considering the diverse array of internal challenges identified. By adopting a more varied elicitation process, automotive OEMs can better navigate the intricacies of technological integration.

This paper contributes significantly to the overarching thesis by providing empirical evidence on the challenges of integrating new technologies into existing product platforms. It lays the groundwork for subsequent research aimed at developing methodologies and tools to assess and enhance the flexibility of product platforms. One of the key insights of this paper is the differentiation between needs related to external stakeholders, such as functionality, and those related to internal stakeholders, such as integration risk. This distinction and the other insights gained from this study are instrumental in informing the development of new strategies and frameworks that can better support the integration of emerging technologies in the following papers.

4.2 Paper B: Reconciling Platform vs. Product Optimisation by Value-Based Margins on Solutions and Parameters

In Paper B, we explore the reconciliation of platform and product optimization through the application of value-based margins on solutions and parameters. This study proposes a value-based modelling method to integrate both internal and external variety within the manufacturer, using a case study of an automotive Head-Up Display (HUD) to demonstrate the practical application of this approach.

The study addresses key challenges faced by engineering companies in optimizing margins within product platforms, which include organizational silos, diverse design variables, design space allocation, and varying time perspectives. The method proposed facilitates a balanced approach to platform and product optimization, enhancing long-term system value by maximizing technological variety while minimizing internal variety.

Three platform alternatives (Platform A, B, and C) with varying levels of maturity and space reservations for the HUD were evaluated. Platform A represents a high-maturity platform with limited space, Platform B is an intermediate solution with moderate constraints, and Platform C is a low-maturity, conceptually flexible platform. The study compared three HUD technologies, each differing in volume, field of view (FoV), cost, and maturity. Technology 1, a traditional 2G HUD, features moderate cost and space requirements. Technology 2, an augmented reality 2G AR-HUD, entails higher costs and greater space needs. Finally, Technology 3, a 3G holographic wave guide AR-HUD, is an advanced option offering lower space requirements and high performance, although it is the least mature among the three. The study employed NPV models to evaluate the economic impact of different platform-technology combinations under various future scenarios. These scenarios encompassed changes in manufacturing costs, customer demand, and potential architectural changes. In Figure 8, the relationship between the volume of the component and its performance in terms of FoV(%) are compared to the limits set by the platforms on the volume of the component.

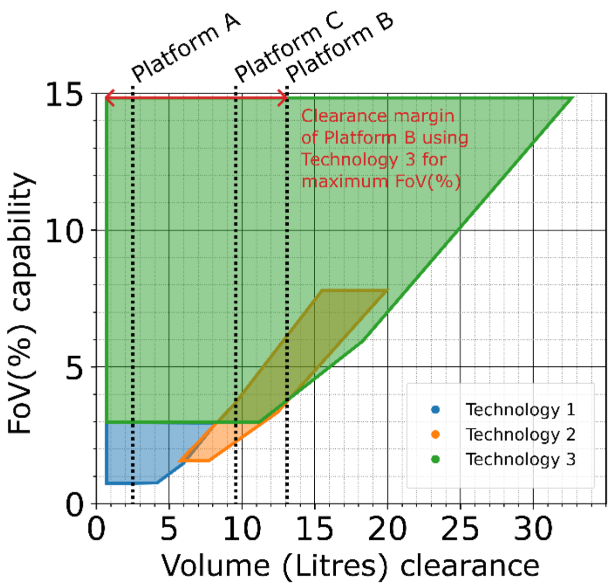

FIGURE 8 PLATFORM CONSTRAINTS AND ASSOCIATED PERFORMANCE IN TERMS OF FOV(%) FOR THE TECHNOLOGIES CONSIDERED IN THE HUD CASE STUDY.

The analysis aimed to maximize external variety within the constraints of the platform margin, showing that understanding margins allows for a diverse range of product variants without compromising cost efficiency. The optimal number of variants was determined by balancing economies of scale and customer demand, as shown in Figure 9, which compares sorting-by-margin and sorting-by-value algorithms for selecting the set of variants to create the product family.

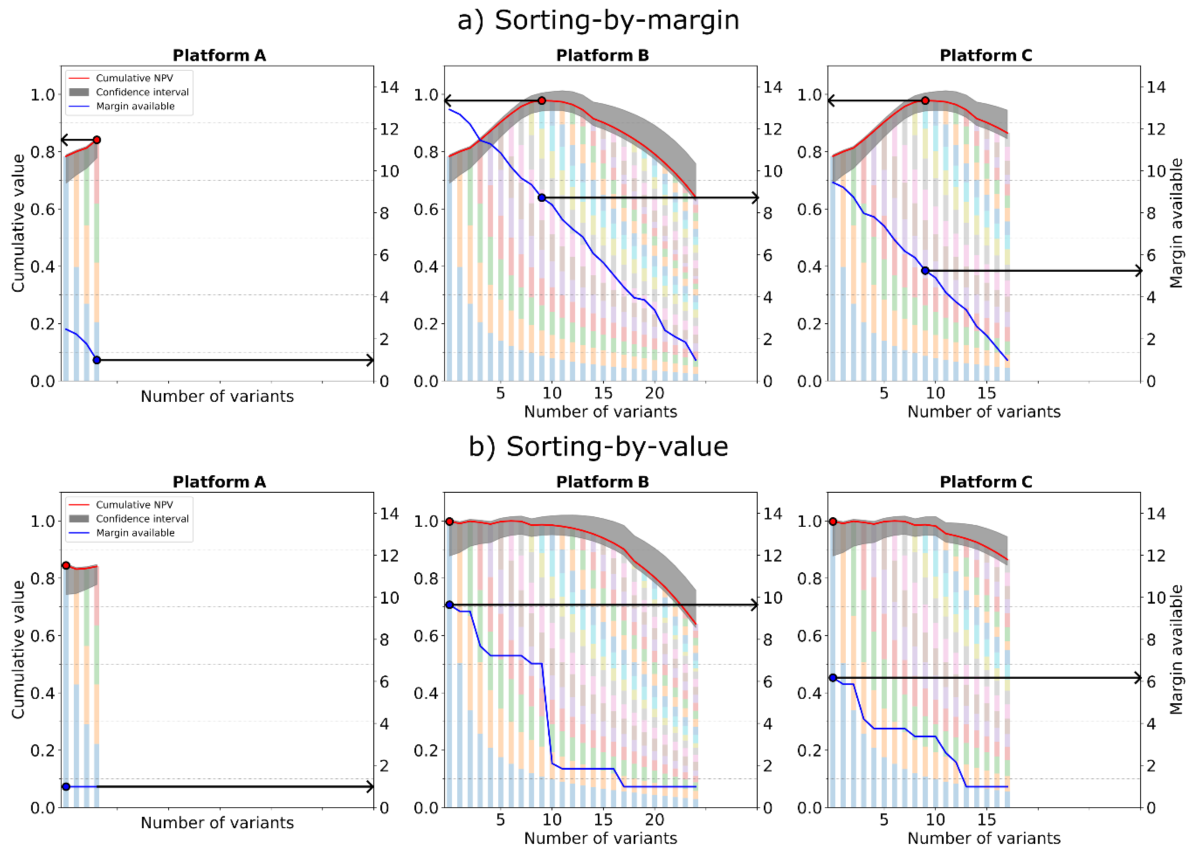

FIGURE 9 (A) SORTING-BY-MARGIN AND (B) SORTING-BY-VALUE OF THE VARIANTS.

Paper B concludes that a value-based margin approach effectively reconciles platform and product optimization by integrating discrete and parametric variables. This method provides a comprehensive framework for evaluating and allocating platform margins, ensuring long-term system value. The automotive HUD case study demonstrates the practical implications of this approach, highlighting the importance of balanced margin delimitation to accommodate both current and future technological needs.

This paper contributes to the Thesis in several important ways. It introduces a novel **framework for margin optimization** through a value-based modelling approach, integrating both internal and external variety within product platforms (Figure 5). The **empirical validation** provided by the case study on automotive HUDs demonstrates the practical applicability of this method, showing how value-based margins can enhance decision-making processes in platform planning and product development. Furthermore, the study emphasizes the necessity of **balancing trade-offs** associated with short-term product-specific optimizations with long-term platform sustainability, which aligns with the thesis's focus on flexible product platforms. Additionally, the findings highlight the significance of margin optimization in **strategic decision-making** and maintaining a competitive advantage and responsiveness in dynamic market conditions, thereby directly supporting the thesis's emphasis on flexibility and adaptability.

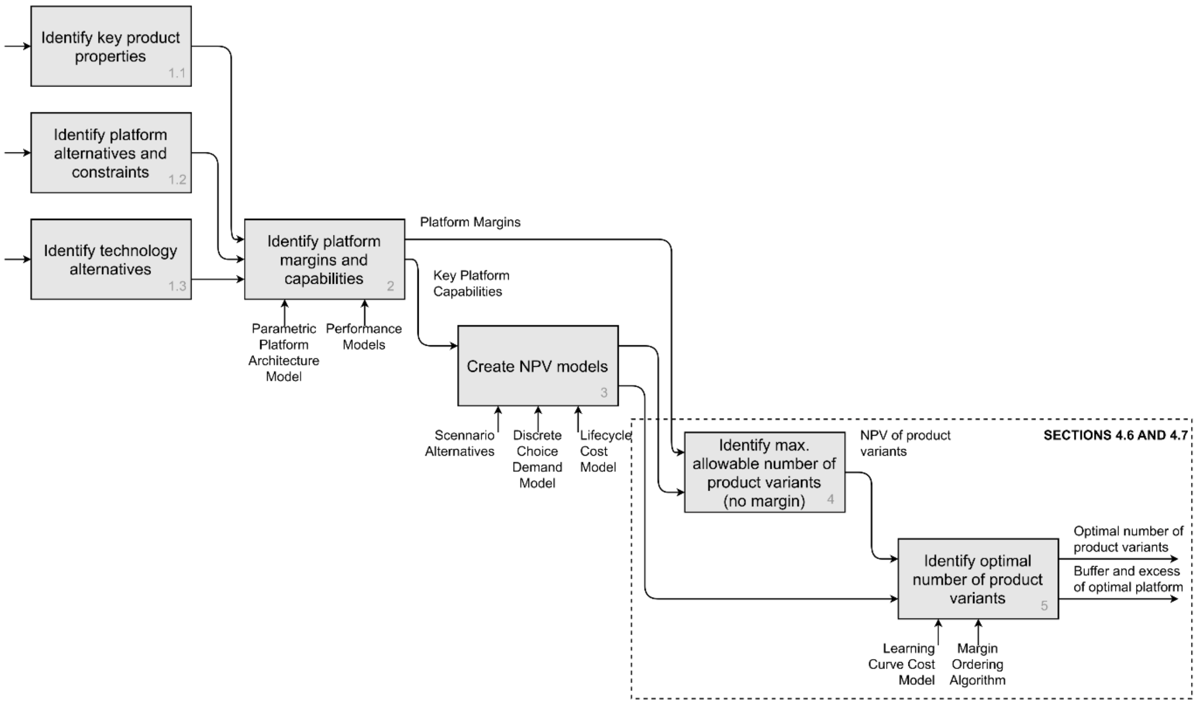

FIGURE 10 OVERALL VALUE-BASED MARGIN APPROACH FROM PAPER B USING AN IDEF0 REPRESENTATION.

Paper B advances the understanding of platform margin optimization, providing valuable insights for engineering companies aiming to balance conflicting objectives in a dynamic market environment. The integration of this method into the broader context of the thesis reinforces the significance of flexibility in product platforms and their ability to efficiently integrate new technologies over time.

4.3 Paper C: Designing Multi-Technological Resilient Objects in Product Platforms

In Paper C, the focus is on enhancing product platforms to manage uncertainty with minimal structural change. The paper examines various design approaches to handle uncertainties, advocating for resilience over flexibility. The primary innovation introduced is the concept of 'resilient objects'—components designed to absorb changes and disruptions without necessitating significant alterations to the platform's overall structure.

The paper provides practical examples, including the use of jaw couplings in mechanical power transmission systems (Figure 11), to demonstrate how resilient objects function. These examples show how resilient objects can absorb changes such as increased torque requirements or misalignments, thereby protecting other components and maintaining system integrity. This approach leads to improved cost efficiency and sustainability, as it minimizes the need for frequent modifications and replacements.

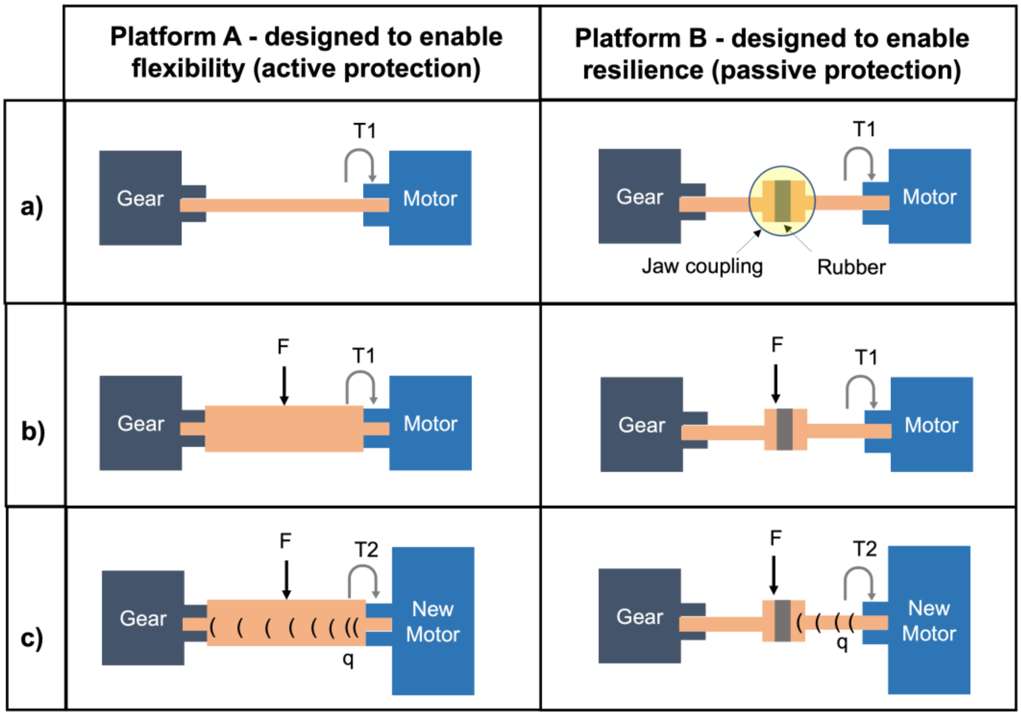

FIGURE 11 COMPARISON BETWEEN A PRODUCT PLATFORM DESIGNED TO ENABLE FLEXIBILITY (ACTIVE PROTECTION AGAINST UNCERTAINTY) AND A PRODUCT PLATFORM DESIGNED TO ENABLE RESILIENCE (PASSIVE PROTECTION AGAINST UNCERTAINTY) USING A JAW COUPLING AS 'RESILIENT OBJECT'.

The study outlines a systematic method for designing, selecting, and evaluating resilient objects for specific areas of the product platform. This method includes constructing a platform model, anticipating changes in requirements, identifying regions most affected by change, and implementing resilient design objects to absorb these changes. This approach is supported by a morphological matrix categorizing resilient objects across different domains—mechanical, hydraulic, electric, and software—to provide comprehensive design solutions. This is achieved through a structured four-step approach:

1. **Construct Product Platform Model:** Use the Enhanced Function-Means (E F-M) tree modelling approach to represent functions, design solutions, interactions, and constraints within the platform (Müller *et al.*, 2019).
2. **Introduce Changes in Requirements and External Environment:** Anticipate and model changes in customer requirements and their effects, identifying unwanted functions such as heat generation and misalignment.
3. **Identify Regions Most Affected by Change:** Evaluate the impact of these changes using Change Propagation Algorithms, highlighting areas of the platform that are most susceptible to negative effects.
4. **Make Design Improvements with Resilient Objects:** Introduce resilient design objects, such as jaw couplings, to absorb changes and break the chain of propagation, ensuring stability and functionality within the platform.

The conclusion of Paper C emphasizes the importance of achieving robustness in product platform design to minimize the impact of uncertainty. By focusing on resilience, the paper contributes to creating platforms capable of efficiently integrating new technologies and adapting to market shifts without extensive modifications. This strategic shift from flexibility to resilience aligns with the thesis's broader objectives of enhancing adaptability and sustainability in product platform development.

The findings from Paper C significantly contribute to the thesis by expanding the conceptual framework for adaptability in product platform design. The introduction and detailed examination of resilient objects provide a novel perspective on designing components to withstand technological and market uncertainties. This approach supports the aim of the thesis of proposing methodologies for evaluating and assessing product platform alternatives that can meet future market expectations while maintaining efficiency in the production system. The practical examples and systematic methods presented enhance the thesis’s relevance and applicability to real-world scenarios, ensuring that the proposed solutions are both theoretically sound and pragmatically viable.

4.4 Paper D Incorporating Field Effects into the Design of Modular Product Families

In Paper D, the focus is on integrating field effects such as electromagnetic and thermal fields into the design of modular products. This integration is essential for managing the complexities introduced by advanced digital components in modern product systems. By using vacuum cleaner robots as a case study, the paper emphasizes the importance of considering these fields at the component level (Figure 12). This approach aids in visualizing and analyzing their impact on product architecture, enabling more informed and innovative design decisions. The relevance of this paper to the thesis lies in its potential to inform methodologies for developing flexible and resilient automotive platforms that can seamlessly integrate new technologies and respond to changing market demands.

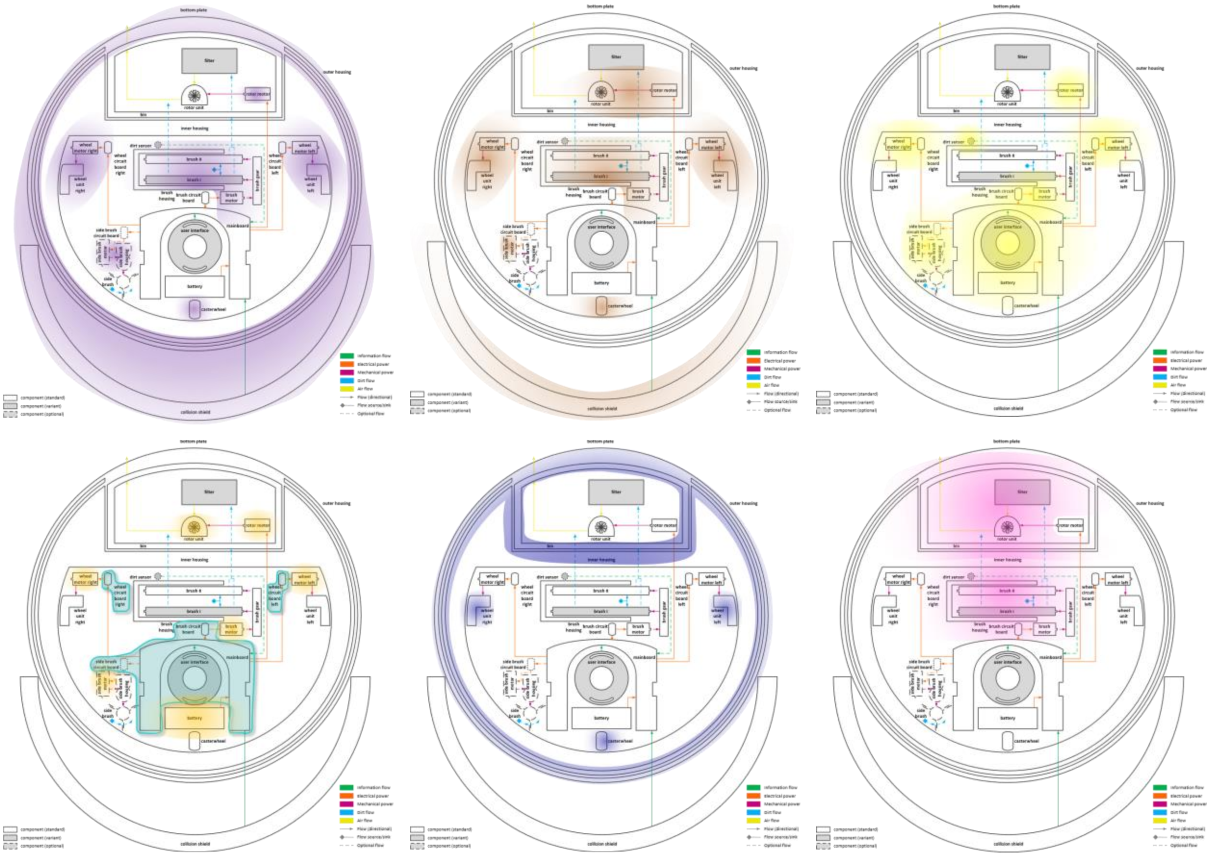

FIGURE 12 MIGS OF THE VACUUM CLEANER ROBOT AND IDENTIFIED FIELDS AND FIELD-SENSITIVE COMPONENTS.

The method proposed in Paper D involves several key steps, each contributing to a comprehensive approach for integrating field effects into product design:

1. **Identification of Fields:** Different fields such as electromagnetic and thermal fields are identified within the product architecture. Recognizing these fields is crucial because they can significantly influence the performance and reliability of the product components. For instance, electromagnetic fields can interfere with electronic circuits, while thermal fields can affect material properties and cause overheating issues.

2. **Visualization of Fields:** These fields are visualized using color codes in the Module Interface Graph (MIG), as in Figure 12 (purple for force, brown for kinematic joints, yellow for electrical, orange for heat, aquamarine for sensitivity to heat, blue for gravity, and pink for pressure). This visual representation helps in understanding the spatial influence of fields on the product layout, making it easier to identify potential conflicts and synergies. The MIG serves as a powerful tool for mapping out the interactions between different components and their respective fields, facilitating better design decisions.
3. **Development of Structural Alternatives:** By shifting module boundaries and redefining interfaces, new structural alternatives are developed that consider the identified field effects. This step involves exploring various configurations to find the optimal arrangement of components that minimizes negative field interactions and enhances overall system performance. The flexibility to alter module boundaries is particularly valuable in the iterative design process, allowing for continuous refinement and improvement.
4. **Evaluation of Alternatives:** The structural alternatives are evaluated for their functional performance and market value using frameworks like Clark and Henderson's innovation framework (Henderson and Clark, 1990). This evaluation helps in determining the most viable design solutions that offer the best balance between functionality, manufacturability, and cost-effectiveness. It also ensures that the final product meets both technical requirements and market expectations.
5. **Creation of Final Layout:** A final product layout is created that incorporates the best structural alternatives, balancing field effects and functional requirements. This layout represents the culmination of the design process, integrating all the insights gained from the previous steps. The final design is optimized for performance, reliability, and ease of manufacturing, ensuring that the product is both innovative and practical.

The study concludes that incorporating field effects into the design process leads to more efficient and adaptable modular product families. This approach not only enhances the functionality and performance of the products but also potentially reduces costs and accelerates product development. By understanding and managing field interactions at the component level, designers can create innovative product structures that are better suited to handle complex environments. This capability is crucial for developing next-generation automotive platforms that must integrate diverse technologies such as electrification, automation, and connectivity.

Paper D significantly contributes to the thesis by providing a novel method for integrating field effects into modular design, aligning with the thesis's focus on enhancing adaptability and efficiency in product platforms. The findings underscore the importance of modular design in accommodating technological advancements and improving product architecture. This approach offers valuable insights for the thesis's analysis of automotive platforms, highlighting the critical role of modular design in integrating new technologies effectively. By applying the principles and methodologies discussed in Paper D, the thesis aims to propose robust solutions for developing flexible product platforms that can adapt to future technological and market changes. This integration of field effects into the design process ensures that automotive platforms remain resilient and capable of sustaining high performance in dynamic environments.

4.5 Paper E: Modeling Technical Risk Propagation Using Field-Effects in Automotive Technology Infusion Design Studies

The integration of new technologies into existing automotive systems often introduces significant technical risks due to the unpredictable and complex field effects. Traditional methods for managing these risks can struggle to accurately predict and mitigate higher-order effects. To address this challenge, Paper E presents a novel Design Structure Matrix (DSM)-based approach that utilizes the inverse-square law to model and mitigate field effects with a high degree of precision.

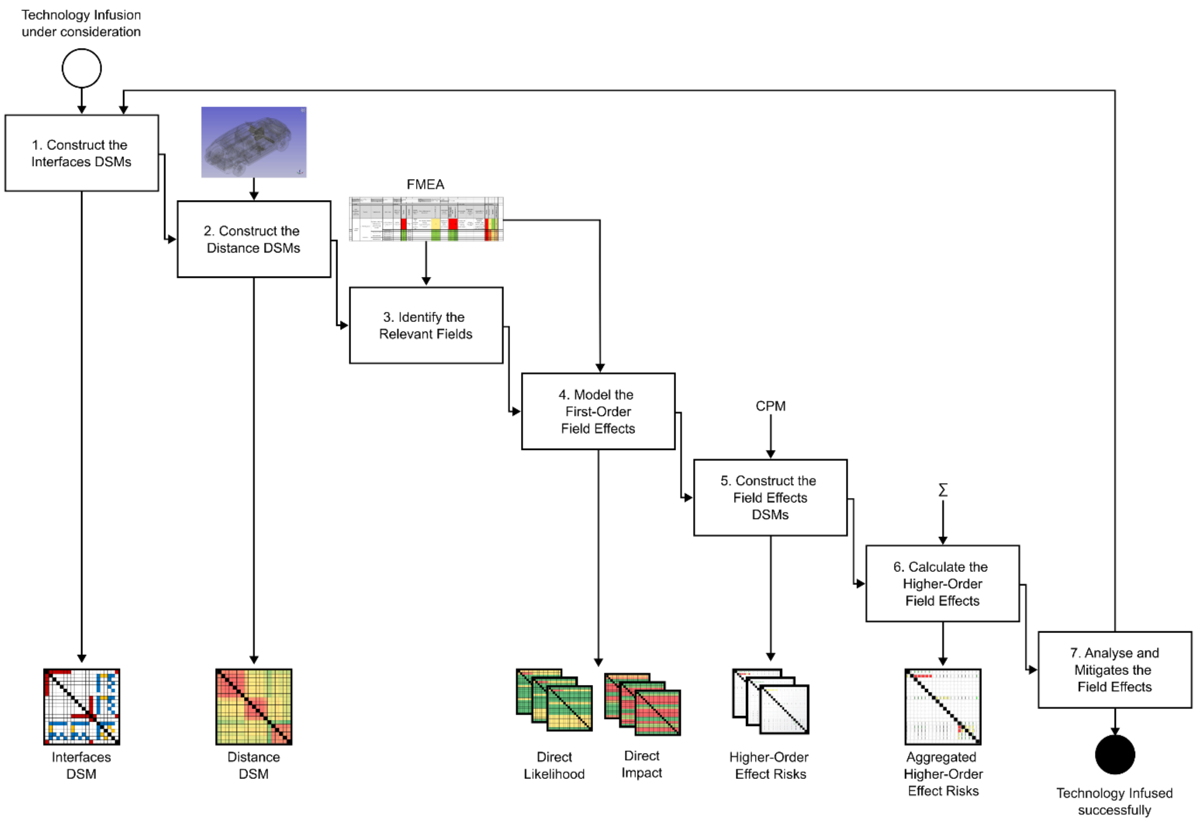

FIGURE 13 THE METHOD FOR MODELING HIGHER-ORDER (HO) FIELD EFFECTS (FE) CAUSED BY NEW TECHNOLOGIES.

The proposed method (Figure 13) employs a DSM to capture the relationships and interactions between system components. By applying the inverse-square law, the method quantifies how field effects attenuate over distance, thereby providing a detailed analysis of potential impacts on the system architecture. This approach is validated through a case study on the integration of a Steer-by-Wire (SbW) system in automotive design.

In the case study, the integration of SbW technology was examined. The SbW system replaces the traditional mechanical linkage between the steering wheel and the wheels with electronic controls, which introduces new field effects, particularly electromagnetic and thermal fields. The study identified key areas where these fields could propagate and potentially disrupt other components in the system.

Paper E presented several key findings:

1. **Identification of Critical Components:** The DSM-based method effectively pinpointed components most susceptible to field effects. For instance, in the SbW

system, sensors and control units were identified as vulnerable due to their proximity to high-field-emitting elements like actuators and power supplies. This precise identification allows for targeted risk management strategies. Detailed analysis showed that certain sensors near the steering wheel and feedback actuators were at high risk for electromagnetic interference, which could lead to inaccurate data readings and compromised system performance.

2. **Mitigation Strategies:** Based on the identified risks, several mitigation strategies were proposed:
    a. **Shielding:** Implementing electromagnetic shielding around sensitive components such as sensors to protect them from interference. For example, enclosing the feedback actuator in a shielded casing significantly reduced electromagnetic emissions, protecting adjacent sensors.
    b. **Spatial Rearrangement**: Increasing the physical distance between high-field-emitting components and susceptible components to reduce the likelihood of interference. By relocating the power supplies away from the primary sensor arrays, the risk of thermal and electromagnetic interference was minimized.
    c. **Redundancy:** Introducing redundant systems and fail-safes to ensure continued functionality in the event of component failure. Incorporating dual redundant ECUs ensured that if one unit failed due to field effects, the other could maintain operational integrity.
3. **Higher-Order Effects:** The study highlighted the significance of considering higher-order field effects, which can lead to cascading failures across the system. By propagating the first-order effects through the DSM, the method provided insights into potential second and third-order impacts, enabling a more comprehensive risk assessment. For instance, it was discovered that electromagnetic interference from the feedback actuator could not only affect nearby sensors but also propagate to influence the performance of distant control units through indirect pathways, underscoring the necessity for holistic mitigation strategies.

This paper contributes to the thesis by demonstrating a practical application of advanced risk modelling techniques in automotive engineering. The proposed DSM-based method enhances the understanding of technical risk propagation due to field effects, providing a robust framework for technology infusion in product platforms. The ability to predict and mitigate higher-order effects supports the thesis' emphasis on flexibility in product platforms, ensuring that new technologies can be integrated efficiently and reliably.

4.6 Paper F: Design Support Efficacy in Risk Perception and Mitigation: Quantitative Evaluation of Design Interactions

Integrating new technologies into existing systems poses significant challenges, particularly in managing risks associated with proximity effects—interactions between components influenced by fields such as magnetic, vibrational, and thermal. Traditional risk management methods, like Failure Mode and Effects Analysis (FMEA), often fall short in addressing the non-linear and complex nature of these interactions. Paper F presents an experimental approach to understanding risk perception and mitigation in complex systems, focusing on field effects in technology infusion scenarios.

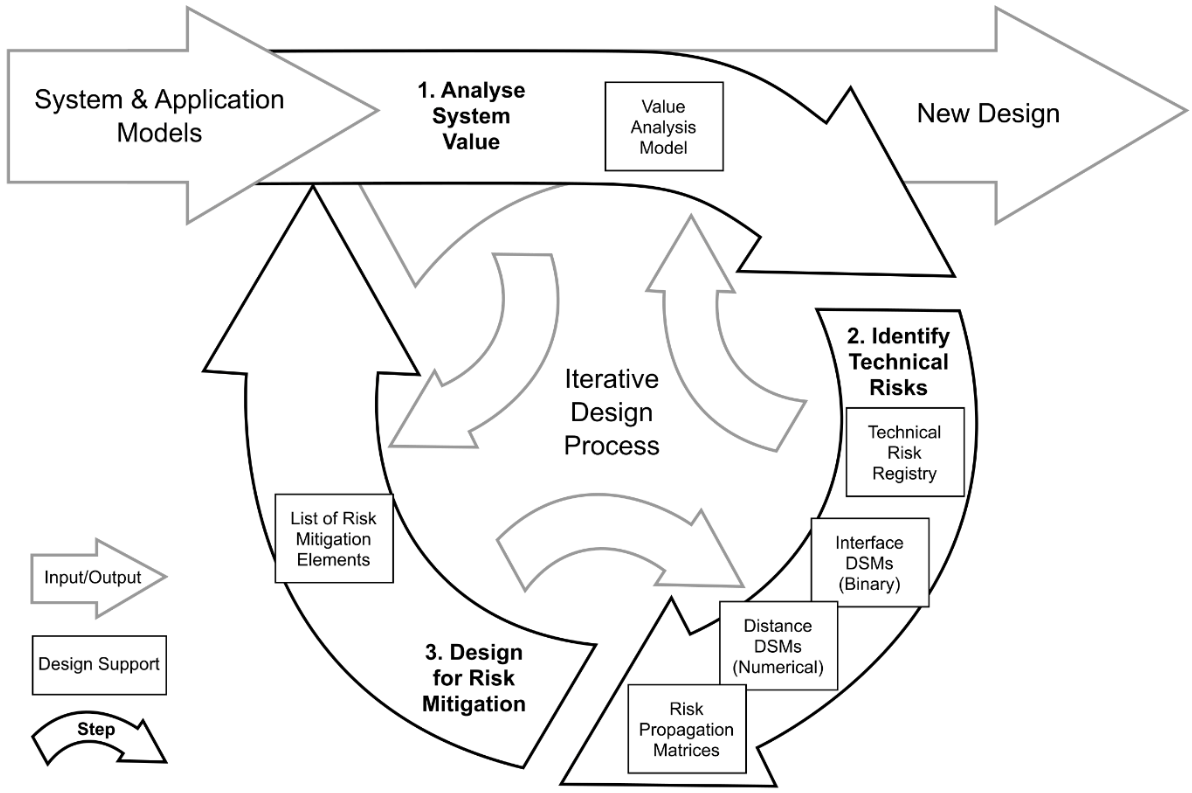

FIGURE 14 ITERATIVE DESIGN WORKFLOW EXERCISED BY THE TEAMS.

The study involved evaluating five design supports: Interface Design Structure Matrices (DSM), Change Propagation Matrices (CPM), Technical Risk Registry, Numerical DSM with spatial distances, and a List of Mitigation Elements. Sixty-eight participants, including industry experts and university researchers, were divided into fourteen teams to assess and manage risks in a simulated design session for truck multi-axle steering systems. The experiment aimed to replicate real-world decision-making environments to test the effectiveness of these design supports in managing the risks associated with proximity effects (Figure 14).

Based on the findings in Paper F, it was evident that these design supports significantly improved the management of proximity effects. For instance, the Numerical DSM with spatial distances enabled teams to effectively identify components at risk of non-contact interactions, such as electromagnetic interference between electronic control units (ECUs) and sensors. Additionally, the Risk Propagation DSM provided insights into higher-order risk effects, allowing for a more comprehensive risk assessment. The study highlighted a strong correlation between the early and intensive use of these supports and improved risk mitigation outcomes. Teams that engaged with these tools early in the design process were more successful in identifying and mitigating risks, particularly in scenarios involving complex field interactions where traditional methods might have underestimated the risks. Furthermore, these supports facilitated more balanced design decisions, helping teams avoid both under-design and over-design. For example, by utilizing the Risk Propagation DSM, teams could accurately determine which components required additional shielding or redundancy without overdesigning the entire system. This approach optimized resource allocation and enhanced system reliability.

This paper contributes significantly to the thesis by demonstrating how advanced risk management tools can improve the integration of new technologies into existing systems. The findings validate the hypothesis that effective risk management, particularly concerning field effects, can prevent system failures and enhance overall system design. The use of DSM and CPM, along with other supports, aligns with the thesis' emphasis on flexible and reliable product platforms, ensuring that new technologies can be integrated efficiently and sustainably. These results provide a robust framework for future research and practical applications in complex system design, supporting the overarching goal of developing adaptive and resilient engineering solutions.

5 SYNTHESIS OF THE RESULTS

This chapter then synthesises the findings relevant to this thesis into a coherent starting point for an informed discussion and for drawing up conclusions and future research plans.

The purpose of this section is to synthesize the findings from the appended papers, integrating them into a cohesive argument that supports the aim and objectives of this thesis. By examining the results through the lens of flexibility in product platforms, this synthesis will prepare the groundwork for addressing the research questions posed in Section 1.4 and set the stage for the discussion in Section 6.

5.1 CHANGE DRIVERS FOR NEXT-GENERATION PRODUCT PLATFORMS AND THE NEED TO DESIGN FOR FLEXIBILITY DESIGN SUPPORT

The evolution of automotive product platforms is driven by a multitude of factors that necessitate an increased focus on flexibility and adaptability. Key change drivers include the rapid advancement of new technologies, shifting market demands, regulatory pressures, and the need for sustainable production practices. These factors collectively create an environment where traditional, rigid product platforms are insufficient, and there is a critical need to design flexible product platforms supported by robust design methodologies.

Technological Advancements (Technology Push): The automotive industry is experiencing unprecedented technological growth, particularly in areas such as electrification, autonomous driving, and connectivity. The integration of electric drivetrains, advanced driver assistance systems, and smart vehicle technologies requires platforms that can accommodate frequent and substantial technological upgrades (Braha *et al.*, 2006). Traditional platforms, which are often designed for a specific set of technologies, lack the adaptability needed to incorporate these innovations efficiently, leading to increased costs and longer development cycles (Kamrad *et al.*, 2013).

Market Dynamics (Market Pull): Consumer preferences are continually evolving, driven by the desire for more personalized and technologically advanced vehicles. Customers now expect a higher degree of customization and quicker turnaround times for new models. This demand for variety and speed necessitates platforms that can support a wide range of configurations without extensive re-engineering (Jiao *et al.*, 2007). A flexible platform approach allows manufacturers to quickly respond to market changes and introduce new models with minimal disruption (Thomas *et al.*, 2014).

Regulatory Pressures: Stringent regulations aimed at reducing emissions and improving vehicle safety are compelling manufacturers to innovate continuously. Compliance with these regulations often requires integrating new technologies and redesigning existing components, which can be challenging with inflexible platforms (Ross *et al.*, 2008). Flexible platforms enable automotive companies to adapt to new regulations more efficiently, ensuring compliance while maintaining production efficiency (Daaboul *et al.*, 2011).

Sustainability Considerations: Sustainability is a growing concern in the automotive industry, influencing both product design and manufacturing processes. There is an increasing emphasis on developing environmentally friendly vehicles and adopting sustainable production methods. Flexible product platforms support this by allowing the integration of green technologies and optimizing resource use throughout the vehicle's lifecycle (De Neufville and Scholtes, 2011). This adaptability not only meets regulatory demands but also aligns with consumer expectations for sustainable products (Cardin, 2014).

The Need for Design Support: Given these drivers, there is a pressing need for methods and tools that support the design of flexible product platforms. This approach would allow for the assessment of multiple platform configurations, considering both technological integration and production constraints (Raudberget *et al.*, 2015). The result would be a more informed decision-making process that reduces the risk of late-stage changes and enhances the ability to introduce new technologies seamlessly, increasing the value delivered to all stakeholders (Kipouros and Isaksson, 2014).

The dynamic nature of the automotive industry, influenced by rapid technological advancements, market demands, regulatory requirements, and sustainability goals, underscores the necessity of flexible product platforms.

5.2 Flexibility in Technology Integration

One of the primary challenges identified in integrating new technologies into automotive platforms is the inherent rigidity of traditional platform designs. Paper A highlights several critical barriers, including compatibility issues with existing systems, the complexity of incorporating advanced technologies, the involvement of a diverse array of stakeholders, and the need for substantial modifications to core architectures. These challenges underscore the necessity for platforms that are inherently flexible and capable of accommodating frequent and substantial technological upgrades.

External stakeholders such as customers and suppliers play essential roles. Customers demand the latest technological advancements and greater product flexibility, influencing OEMs to prioritize adaptability. Suppliers, on the other hand, provide the essential components and technologies that must seamlessly integrate with the existing platform. Internally, departments such as design, production, and marketing are crucial. The production team must adapt manufacturing processes to accommodate new technologies, ensuring efficiency and cost-effectiveness. Meanwhile, the marketing team must effectively communicate the benefits of technological advancements to consumers, aligning product features with market demands.

Strategically, these findings emphasize the importance of adopting flexible design methodologies that can adapt to rapid technological changes. By prioritizing flexibility from the early stages of platform development, automotive OEMs can mitigate the risks associated with technology integration, reduce development cycles, and maintain competitive advantage in a fast-evolving market.

5.3 Value-Based Optimization

The findings from Paper B provide significant insights into value-based optimization techniques that balance platform flexibility with product-specific goals. These techniques involve assessing the value margins of various design solutions, allowing for an optimization process that aligns both economic and performance considerations.

The key trade-offs identified include balancing short-term performance gains against long-term flexibility and adaptability. The benefits of this approach are evident in the ability to develop product platforms that not only meet current market demands but are also equipped to evolve with future technological advancements. This optimization framework is crucial for creating platforms that can sustain technological integration over time, enhancing both their economic and operational viability.

5.4 Design of Resilient Objects

Paper C introduces the concept of designing multi-technological resilient objects within product platforms. These resilient objects are designed to absorb and adapt to technological changes without compromising the overall system's integrity and performance.

The impact of incorporating resilient objects into product platforms is profound. They significantly enhance the platform's robustness, allowing it to withstand and adapt to various technological shifts. This approach not only improves the immediate flexibility of the platform but also ensures long-term resilience, making the platform more sustainable and adaptable in the face of ongoing technological evolution.

5.5 Incorporation of Field Effects

Paper D's exploration of field effects in modular product family design provides a critical method for integrating various physical and environmental considerations into platform development. Field effects, such as electromagnetic and thermal influences, play a crucial role in determining the placement and interaction of components within a system.

By incorporating these field effects into the design process, platforms can achieve greater modularity and adaptability. This method enhances the platform's ability to accommodate a wide range of technological integrations, ensuring that new technologies can be seamlessly incorporated without extensive re-engineering. This approach is vital for maintaining the flexibility and sustainability of product platforms.

5.6 Risk Propagation and Management

Advanced risk modelling techniques, as discussed in Paper E, are essential for predicting and mitigating the impacts of technical risks on platform flexibility. These techniques involve the use of probabilistic models and simulations to understand how risks propagate through complex systems.

The contribution of these risk management strategies to the overall framework for flexible product platforms is significant. They provide a structured approach to identifying and addressing potential risks early in the design process, ensuring that platforms can be developed with a clear understanding of the potential challenges and their implications. This proactive approach to risk management is crucial for maintaining the flexibility and robustness of product platforms.

5.7 Experimental Findings on Risk Management

The experimental findings from Paper F provide empirical evidence of the effectiveness of various design supports in managing risks associated with new technology integration. These experiments demonstrate how different strategies can be applied to mitigate proximity effects and other risk factors in complex system design.

The evaluation of these design supports reveals their critical role in enhancing platform flexibility. By effectively managing risks, these supports ensure that new technologies can be integrated without compromising the platform's overall performance and integrity. This empirical validation underscores the importance of incorporating robust risk management strategies into the design and development of flexible product platforms.

5.8 Integrative Framework for Platform Flexibility

The synthesis of findings across the six papers reveals several common themes, including the importance of flexibility, value-based optimization, and robust risk management. These themes are integrated in Figure 15 into a cohesive design support framework that provides a comprehensive approach to enhancing flexibility in product platforms.

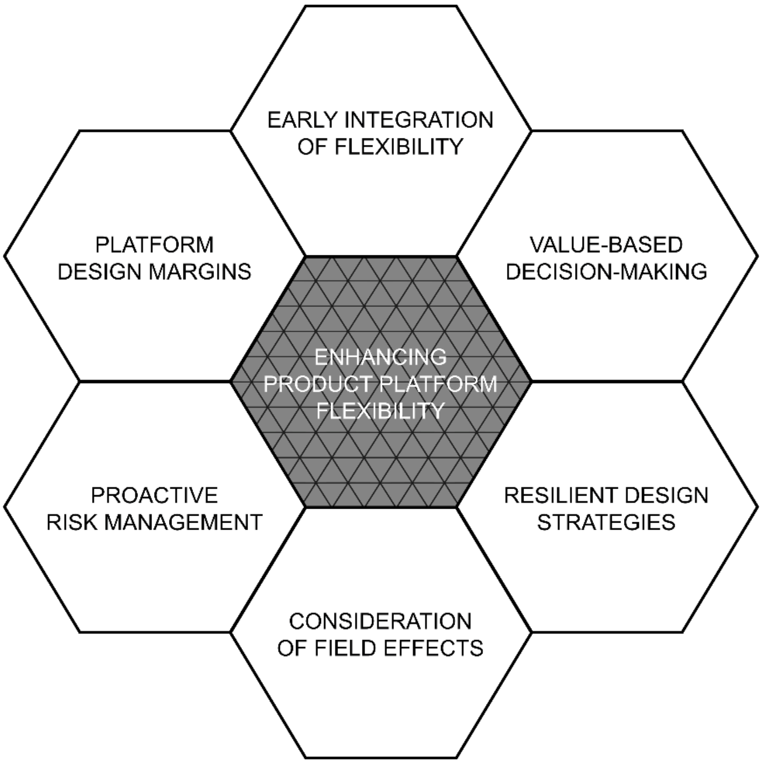

FIGURE 15 FRAMEWORK FOR PLATFORM FLEXIBILITY

This integrative and iterative framework emphasizes the need for:

Early Integration of Flexibility: Prioritizing flexibility in the initial stages of platform design to accommodate future technological changes. As discussed in Sections 2.1 and 2.3.1, incorporating flexibility early allows for seamless adaptation to new technologies, minimizing redesign costs and time-to-market delays. For example, integrating modular components that can be easily upgraded ensures that as new technologies emerge, they can be incorporated with minimal disruption. This early flexibility sets the stage for the other elements of the framework to function effectively, as it provides a foundation upon which value-based decision-making and resilient design strategies can build.

Value-Based Decision-Making: Utilizing value-based optimization techniques to balance short-term and long-term goals. This approach, detailed in Section 5.3, based on Sections 2.3.2 and 4.2 (Paper B), ensures that immediate needs do not overshadow future potential benefits. By aligning decisions with overall value creation, platforms can sustain their relevance and competitiveness over time. For instance, decisions about which technologies to integrate should consider both their current market value and potential future advancements. This value-based approach directly interacts with the early integration of flexibility by ensuring that initial design choices are made with a clear understanding of their long-term impact on the platform's adaptability and overall value.

Resilient Design Strategies: Incorporating resilient objects to enhance robustness and adaptability is described in Section 5.4. Section 4.3 (Paper C) highlights the development of resilient objects, which can absorb and adapt to changes, ensuring that platforms remain functional and efficient despite evolving requirements. Resilient design strategies, such as creating adaptable chassis or interchangeable power units, complement value-based decision-making by providing physical and structural means to implement those decisions effectively. By designing components that can handle future changes, the platform maintains its value over time, integrating seamlessly with the initial flexibility designed into the system.

Consideration of Field Effects: The benefits of integrating field effects to ensure seamless incorporation of new technologies have been noted in Section 5.5. For example, when integrating a new battery technology into an electric vehicle platform, considering the thermal and electrical field effects ensures that the new component works harmoniously with existing systems. Section 2.2.2 discusses how understanding and managing field effects can lead to better integration outcomes, reducing the risk of incompatibilities and performance issues. Paper D expands on this theme, and Paper E proposes a method of considering the impact of FEs using change propagation. This consideration is crucial for both resilient design and value-based decision-making, as it ensures that new technologies do not disrupt existing value propositions or compromise the resilience of the platform.

Proactive Risk Management: Employing advanced risk modelling techniques to predict and mitigate potential risks is essential. Section 5.6 emphasizes proactive risk management as a means to foresee and address challenges before they escalate, ensuring smoother platform evolution. For instance, using predictive analytics to foresee potential supply chain disruptions or technological failures allows for timely interventions. Proactive risk management ties closely with all other aspects of the framework—early integration of flexibility provides the means to adapt to identified risks, value-based decision-making ensures that risk mitigation strategies are economically viable, and resilient design strategies offer the physical robustness needed to withstand potential issues. Section 5.7 (Paper F) explores the perceptions of teams of designers when identifying and mitigating technical risks using design supports based on the propagation of field effects.

Platform Design Margins: Implementing value-based margins on solutions and parameters to optimize internal and external variety, ensuring both current and future technological needs are met. Paper B discusses how these margins can be used to balance current and future technological needs, providing a buffer that allows for gradual and controlled platform adjustments. Design margins ensure that there is enough leeway within the platform to incorporate future changes without significant redesign. This concept interacts with the early integration of flexibility by defining the extent of adaptability, with value-based decision-making by ensuring economic feasibility, and with resilient design strategies by providing the necessary buffers for resilience.

The framework presented by this thesis merges the approach of design for future flexibility (Jankovic and Eckert, 2016), into the product platforms approach. This integration acknowledges the inherent differences between the two methodologies: product platforms focus on achieving economies of scale through component standardization and modularity across a range of products, while design for future flexibility emphasizes the capacity of products to adapt to evolving requirements and technologies over their lifespan. Future flexibility products are distinct in that they are likely to undergo one or more cycles of system architecture revision throughout their life cycle, ensuring they remain relevant and functional amidst changing demands. By combining these approaches, the framework aims to create product platforms that are not only cost-effective and efficient in the present but also robust and adaptable to future technological advancements and market needs. This hybrid approach leverages the strategic planning and modularity of product platforms while incorporating the foresight and adaptability required for future flexibility, ultimately providing a comprehensive solution for developing resilient and adaptable product platforms.

The findings presented in this chapter highlight the critical factors that influence platform flexibility and offer practical insights into developing more adaptable and resilient product platforms. These results also indicate potential areas for future research, such as further exploration of value-based optimization techniques and the development of more sophisticated risk management models, further discussed in Section 7.2.

6 DISCUSSION

This chapter uses the results and findings from previous chapters, in contrast with the existing literature, to address the research problem and answer the research questions. It also explores the novelty of the findings compared to the current state of the art, assesses research quality, considers the validation of the results, and discusses the scientific and industrial contributions of this thesis.

The research problem was expressed in Section 1.2 as the difficulty of assessing the impact of the introduction of new technologies into product platforms, and how it hindered the decision-making process. To address this problem, the research questions are answered here.

The core research problem identified in this thesis is the inadequacy of current platform development practices in enabling designers to comprehensively model and evaluate the flexibility of product platforms from the early stages of development. This shortcoming often leads to under-designed platforms that lack necessary flexibility or over-designed platforms that waste resources. To address this issue, the research has introduced a novel framework that prioritizes flexibility from the initial design stages, ensuring that product platforms can adapt to rapid technological changes and evolving customer demands.

A significant contribution of this research is the development of a model-based framework that integrates flexibility, value-based decision-making, resilient design strategies, and proactive risk management (see Section 7.1 Research Contributions and Claims). This framework facilitates the early identification and incorporation of design margins, providing buffers for future modifications without extensive redesigns. Additionally, the concept of resilient objects, which are platform components designed to absorb or adapt to changes, has been introduced to enhance platform adaptability. These methods were validated through real-world tests involving experienced practitioners from Swedish automotive OEMs, demonstrating their practical applicability and effectiveness. This proactive approach optimizes the balance between internal and external variety, ensuring that platforms are efficient today and adaptable to future technological advancements. As expressed by Clark (2015), "*For knowing the world, in the only sense that can matter to an evolved organism, means being able to act in that world: being able to respond quickly and efficiently to salient environmental opportunities.*"

6.1 Answering Research Question 1

RQ1 *What are the barriers and enablers in deciding to introduce* ***new technology*** *into* ***product platforms****?*

The decision to introduce new technology into product platforms is influenced by a range of barriers and enablers. These factors can significantly impact the success of technology integration, affecting organizational strategy, technological compatibility, financial viability, supply chain efficiency, and regulatory compliance.

Paper A identifies the critical challenges faced by OEMs in integrating new technologies into existing platforms, emphasizing the importance of early-stage flexibility modelling.

Organizational barriers such as resistance to change, lack of strategic alignment, and insufficient communication are significant obstacles (Hassannezhad *et al.*, 2019). Resistance to change often arises from a lack of understanding or fear of the unknown, hindering the adoption of new technologies. A lack of strategic alignment between different departments can lead to conflicting priorities, making it difficult to integrate new technologies seamlessly. Insufficient communication within and between teams further exacerbates these issues, as crucial information may not be effectively disseminated (Paper A).

Organizational enablers include strong leadership, clear strategic vision, and effective change management practices (Krause and Gebhardt, 2023). Strong leadership is essential for driving technology integration initiatives and overcoming resistance to change. A clear strategic vision aligns the organization's goals with the integration of new technologies, ensuring all departments work towards a common objective. Effective change management practices facilitate smooth transitions and minimize disruptions, enhancing the organization's ability to adopt new technologies (Paper A). Integrated Product Development (IPD) aligns design and production through coordinated decision-making and early collaboration (Areth Koroth *et al.*, 2024). IPD enhances producibility, manages uncertainties, and reduces late-stage changes by fostering communication between departments throughout the product lifecycle.

Technological barriers include compatibility issues, technology maturity (de Weck, 2022), and integration complexity (Parslov and Mortensen, 2015). Compatibility issues arise when new technologies are not easily integrated with existing systems, leading to increased complexity and potential disruptions. Technology maturity, or Technology Readiness Level (TRL), is a critical factor; technologies at lower TRLs may require significant development before they can be effectively integrated. Integration complexity is another challenge, as incorporating advanced technologies often involves significant changes to the product architecture (Paper E).

Technological enablers include modular design (Otto *et al.*, 2016), robust testing protocols (Borgue, Paissoni, *et al.*, 2021), and scalable architectures (Simpson *et al.*, 2014). Modular design allows for the easy integration of new technologies by enabling components to be developed and tested independently before being combined into the final product. Robust testing protocols ensure that new technologies perform as expected, reducing the risk of failures and rework. Scalable architectures support the gradual integration of new technologies, allowing for incremental improvements rather than large-scale overhauls.

Financial barriers such as high costs, uncertain return on investment (ROI), and budget constraints can impede technology integration. New technologies often entail substantial upfront costs, which can be prohibitive for organizations with limited financial resources. The ROI on new technologies can be uncertain, making it difficult to justify the investment to stakeholders (Jiao, 2012). Additionally, budget constraints may limit the ability to allocate sufficient resources for technology integration projects (Paper B).

Financial enablers such as strategic investment, cost-benefit analysis, and financial incentives can support technology integration. Strategic investment in new technologies demonstrates a commitment to innovation and can drive long-term growth. Cost-benefit analysis helps to quantify the potential returns on investment, providing a solid basis for decision-making . Financial incentives, such as tax breaks or grants, can offset some of the initial costs associated with technology integration.

Supply chain barriers include supplier readiness, logistics challenges, and the complexity of coordinating multiple tiers of suppliers. Supplier readiness is critical; if suppliers are not prepared to support the new technology, integration efforts can be delayed. Logistics challenges, such as transporting and handling new components, can also pose significant obstacles. The complexity of coordinating multiple tiers of suppliers adds another layer of difficulty, as it requires effective communication and collaboration across the supply chain.

Supply chain enablers include strong supplier relationships, integrated logistics systems, and adaptive supply chain management. Strong supplier relationships facilitate better collaboration and coordination, ensuring that suppliers are prepared to support new technologies. Integrated logistics systems streamline the movement of components, reducing delays and increasing efficiency. Adaptive supply chain management practices allow for quick responses to changes and disruptions, maintaining supply chain continuity.

Regulatory barriers such as compliance with evolving standards and legal requirements must be navigated carefully. Automotive companies must continuously adapt to new regulations, which can require significant modifications to existing platforms. Ensuring compliance with these regulations is essential to avoid legal repercussions and maintain market access. This need for continuous adaptation can be a substantial barrier to integrating new technologies.

Regulatory enablers include proactive compliance strategies, collaboration with regulatory bodies, and continuous monitoring of standards. Proactive compliance strategies involve anticipating regulatory changes and preparing in advance, reducing the impact of new regulations. Collaboration with regulatory bodies can provide insights into upcoming changes and facilitate smoother compliance processes. Continuous monitoring of standards ensures that the organization remains compliant and can quickly adapt to new requirements.

The findings of this thesis highlight the interplay between barriers and enablers in technology introduction into product platforms. Organizational, technological, financial, supply chain, and regulatory factors all play critical roles. By addressing barriers and leveraging enablers, organizations can create flexible product platforms that are resilient to change and capable of integrating new technologies efficiently.

The decision to introduce new technology into product platforms is shaped by a complex interplay of barriers and enablers. Addressing organizational, technological, financial, supply chain, and regulatory challenges while leveraging the corresponding enablers can significantly enhance the flexibility and adaptability of product platforms. This approach ensures that automotive companies can stay competitive and responsive in a rapidly evolving technological landscape.

6.2 Answering Research Question 2

RQ2 *How can a flexible product platform be modelled from an early stage of development, so its **flexibility** may be traded against stakeholder needs?*

Defining flexibility in product platforms is crucial for maintaining competitiveness and responsiveness in dynamic market conditions. Flexibility in this context refers to the ability to accommodate changes in design, technology, and features without significant re-engineering (Suh, de Weck, Kim, *et al.*, 2007). This capability enables platforms to adapt efficiently to new technologies, customer preferences, and regulatory requirements.

To assess flexibility, metrics such as modularity, scalability, and adaptability are employed. Modularity allows for the independent development and replacement of components, enhancing the platform's ability to integrate new technologies seamlessly (Schwede *et al.*, 2022). Scalability measures the ease with which a system's capacity can be adjusted, ensuring that the platform can grow or shrink according to market demands. Adaptability evaluates how well the platform can respond to changes in its environment or requirements, thus maintaining its relevance over time (Nilchiani, 2007).

Early-stage modelling techniques are critical in integrating flexibility into product platforms. Model-Based Systems Engineering (MBSE) and Value-Driven Design (VDD) are two key methodologies that provide a robust framework for visualizing and managing the complexities of flexible design. MBSE helps in creating detailed models that capture the interactions and dependencies within the platform, making it easier to anticipate and manage changes (Isaksson *et al.*, 2013). VDD, on the other hand, focuses on maximizing stakeholder value by aligning design decisions with the overall value generated throughout the product lifecycle (Collopy and Hollingsworth, 2011). Paper B introduces value-based margins as a method to balance flexibility and stakeholder needs effectively. This approach aligns with the VDD method, demonstrating how value-driven metrics can guide the early-stage development of flexible platforms, ensuring that design decisions are aligned with long-term stakeholder value.

The use of resilient objects is another critical aspect of enhancing platform flexibility. Resilient objects are designed to absorb changes and uncertainties, ensuring that the platform can maintain its functionality and performance despite external disruptions (Otto *et al.*, 2019). By incorporating resilient objects into the design, platforms become more robust and adaptable, capable of handling a wide range of future scenarios. Paper C discusses the role of resilient objects in enhancing platform flexibility. By integrating resilient objects into the design, platforms can better absorb technological changes and uncertainties, supporting the idea that resilient objects are crucial for maintaining platform functionality and performance.

Balancing flexibility with stakeholder needs involves a comprehensive analysis of stakeholder requirements and expectations. Techniques such as stakeholder mapping and value analysis help capture these diverse needs, ensuring that the platform design remains relevant and valuable (Ross and Rhodes, 2008b). Trade-off analysis further evaluates the implications of design decisions on various stakeholder requirements, balancing flexibility with economic and performance considerations. Methods like multi-criteria decision analysis (MCDA) and probabilistic modelling help quantify these trade-offs, providing a clear rationale for design choices (Cardin *et al.*, 2012).

Paper D highlights the importance of considering field effects from the early stages to enhance the modularity and scalability of product platforms. This approach ensures that platforms remain adaptable and can efficiently integrate new technologies without significant re-engineering (Otto *et al.*, 2019). Paper E provides insights into managing the risks associated with technology integration using field effects. By modelling risk propagation, the paper demonstrates how early-stage flexibility modelling can identify and mitigate potential integration issues, ensuring that platforms can adapt to new technologies while maintaining performance and reliability (Clarkson *et al.*, 2004).

Empirical validation through case studies further underscores the feasibility and benefits of early-stage flexibility modelling. For instance, the integration of advanced driver assistance systems (ADAS) into existing platforms demonstrates the practical challenges and solutions in implementing flexible platforms (Patel *et al.*, 2021). Key lessons from these studies include the importance of early stakeholder engagement, iterative design processes, and the value of modularity in managing complexity.

Incorporating flexibility from the early stages of platform development is essential for creating adaptable, robust, and efficient product platforms. By using model-based approaches and resilient objects, designers can ensure that platforms remain relevant and valuable in dynamic market conditions.

6.3 ANSWERING RESEARCH QUESTION 3

RQ3 *How can the* ***impact*** *of introducing or replacing technologies on the flexibility, risk management, and value optimization of product platforms be effectively* ***assessed****?*

Introducing or replacing technologies on product platforms has multifaceted impacts, primarily affecting platform flexibility, risk propagation, and value optimization.

Impact on Platform Flexibility: The integration of new technologies into automotive product platforms often encounters significant challenges due to the inherent rigidity of traditional platform designs. Findings from Paper A highlight critical barriers such as compatibility issues with existing systems, the complexity of incorporating advanced technologies, and the need for substantial modifications to core architectures. These challenges necessitate designing platforms with inherent flexibility, enabling frequent and substantial technological upgrades. By prioritizing flexibility early in platform development, automotive original equipment manufacturers (OEMs) can reduce development cycles and maintain competitive advantage in rapidly evolving markets.

Risk Propagation and Management: Advanced risk modelling techniques are essential for predicting and mitigating the impacts of technical risks on platform flexibility. Paper E discusses the use of probabilistic models and simulations to understand how risks propagate through a platform when new technologies are introduced. Effective risk management can prevent system failures and enhance overall design integrity, ensuring that platforms can absorb and adapt to technological changes without significant disruptions. The correlation between the use of design supports and improved risk mitigation outcomes underscores the importance of integrating risk management tools early in the design process.

Value Optimization and Strategic Decision-Making: The findings from Paper B emphasize value-based optimization techniques that balance platform flexibility with product-specific goals. This involves assessing the value margins of various design solutions, allowing for an optimization process that aligns economic and performance considerations. The trade-offs between short-term performance gains and long-term flexibility are crucial for developing platforms that meet current market demands while being equipped to evolve with future technological advancements.

Designing Resilient Objects: Paper C introduces the concept of designing multi-technological resilient objects within product platforms, which are components capable of absorbing and adapting to technological changes without compromising overall system integrity. Incorporating resilient objects significantly enhances platform robustness, allowing it to withstand and adapt to various technological shifts. This approach ensures that platforms are not only immediately flexible but also resilient in the long term, making them more sustainable and adaptable to continuous technological evolution.

Incorporating Field Effects: Paper D explores the incorporation of field effects in modular product family design, providing a critical method for integrating various physical and environmental considerations into platform development. By accounting for field effects such as electromagnetic and thermal influences, platforms can achieve greater modularity and adaptability. This method ensures that new technologies can be easily integrated without much re-engineering, maintaining the platform's flexibility and sustainability.

The impact of introducing or replacing technologies on product platforms is profound, influencing flexibility, risk management, and value optimization. The integration of advanced risk modelling, value-based optimization, resilient object design, and field effects into platform development strategies ensures that automotive platforms can efficiently and sustainably adapt to technological advancements.

6.4 Reflection on Research Approach and Methods

Reflecting on the research approach and methods utilized in this thesis reveals both strengths and areas for potential improvement. The use of the Design Research Methodology (DRM) provided a systematic and structured framework. This approach facilitated the development of a robust understanding of the complexities involved in designing flexible and adaptable product platforms.

One of the primary strengths of this research lies in its methodical and iterative nature, as prescribed by the DRM framework. This method ensured that the research was grounded in both theoretical and empirical foundations. The combination of literature reviews, workshops, and interviews allowed for a rich collection of qualitative data, providing deep insights into the challenges and opportunities associated with technology integration in product platforms. Additionally, the case study approach, involving collaboration with major automotive OEMs, provided real-world applicability and relevance to the findings.

The use of probabilistic models and simulations, particularly in the context of risk propagation and management, added a quantitative dimension to the research. This allowed for the rigorous testing of hypotheses and the validation of proposed methodologies, ensuring that the recommendations made were both scientifically sound and practically viable. The incorporation of field effects and the concept of resilient objects further enriched the research, providing innovative solutions to the challenges identified.

Despite the strengths, several areas for improvement were identified. Firstly, the reliance on case studies from a specific industry and geographic region (Sweden) may limit the generalizability of the findings. Future research could benefit from a broader range of case studies across different industries and regions to validate the applicability of the proposed methodologies in diverse contexts.

The qualitative data collection methods, while rich in detail, also introduced potential biases. The selection of participants for workshops and interviews, primarily through networks of industry representatives, may have inadvertently led to a concentration of perspectives from certain disciplines or organizational levels. Ensuring a more diverse and representative sample in future studies could mitigate this bias and provide a more holistic view of the challenges and opportunities in technology integration.

Moreover, while the use of probabilistic models and simulations provided valuable insights, the complexity of these models could be a barrier to their practical implementation. Simplifying these models or developing user-friendly tools and interfaces could enhance their usability and adoption by industry practitioners.

The choice of DRM as the overarching framework was instrumental in guiding the research process, from problem identification to the development of practical solutions. This structured approach ensured that the research remained focused and aligned with the overarching objectives. However, the iterative nature of the adapted Agile DRM also meant that the research had to be flexible and adaptive, accommodating new findings and adjusting methodologies as necessary.

The integration of both qualitative and quantitative methods provided a comprehensive understanding of the research problem. The thematic analysis of qualitative data using tools like *nVivo* allowed for the identification of key themes and patterns, while the quantitative models provided empirical validation of these insights. This mixed-methods approach was crucial in addressing the multifaceted nature of technology integration in product platforms.

The research approach and methods employed in this thesis were effective in addressing the research questions and achieving the objectives. The systematic and iterative nature of the DRM framework, combined with the use of both qualitative and quantitative methods, provided a robust foundation for exploring the impact of technology integration on automotive product platforms. However, future research should consider broader case studies, mitigate potential biases in qualitative data collection, and simplify complex models to enhance practical applicability. These reflections provide valuable lessons for future studies in this area, ensuring continuous improvement and refinement of research methodologies.

6.5 LIMITATIONS

While the findings of this research offer insights applicable to various fields of platform development, it is crucial to acknowledge the limitations, particularly the exclusive focus on the automotive sector. The reliance on data from the automobile manufacturing industry gathered through interviews, workshops, and case studies conducted solely in Sweden with visits to local factories, introduces a contextual bias. The location and cultural nuances inherent in this research play a substantial role in shaping the findings and conclusions, limiting the generalizability of the results beyond the automotive sector.

The thesis introduces a flexibility assessment framework designed for the supporting platform architects, yet the extent of the testing performed was circumscribed to a handful of case studies. The framework has been embodied as a tool for the interactive development of platform alternatives, emphasizing collaboration. However, the success of such a solution is contingent on various factors, including the development process and specific decision points at the firm, which fall outside the scope of this thesis. Notably, the thesis concentrated on assessing the value of flexibility of a set of platform architectures concerning a predefined set of future scenarios, the definition of which is a prerequisite before selecting and optimizing an architecture. Applying the framework to existing technology integration projects may incur additional costs, and further tests are imperative to ascertain its effectiveness in diverse scenarios within the automotive sector. Therefore, while the framework provides foundational design support, its practical application and efficacy warrant additional investigation and testing in additional real-world settings.

7 Conclusions and Outlook

This thesis aimed to explore the value of flexibility in product platforms concerning customer needs and the production system, and their ability to efficiently integrate new technology over time. Based on that aim, this thesis supports the value and flexibility impact assessment on the architecture of product platforms when introducing new technologies, by adopting a systematic, structured approach.

This thesis first and foremost investigated the assessment of the value of flexibility in product platforms within the automotive sector. It scrutinized how the characteristics inherent in flexible product platforms align with the diverse requirements of the automotive industry. These platforms offer adaptability, scalability, and ease of reconfiguration. Notably, the empirical investigation underscored challenges such as intuition-based decision-making, descriptive methodologies, and the need for effective flexibility allocations of design margins between components for fostering the optimal utilization of flexible product platforms.

An essential focus of this exploration was the examination of value-based approaches geared towards engineering design trade-offs in the design and implementation of flexible product platforms. The thesis proposed a prescriptive framework, rooted in theoretical and empirical research, integrating the experiential and cognitive capabilities of humans and the platform through defined metrics of flexibility.

The introduction of new technologies into product platforms involves a complex interplay of barriers and enablers, significantly shaping decision-making (Research

Question 1). Organizational barriers like resistance to change hinder technology adoption, while strong leadership and change management drive integration. Technological barriers such as compatibility issues complicate integration, but modular design facilitates smoother incorporation. Financial constraints are mitigated through strategic investments and cost-benefit analyses. Supply chain challenges require strong supplier relationships and adaptive management. Regulatory compliance is navigable through proactive strategies and monitoring.

Modelling flexible product platforms from an early stage ensures these platforms meet stakeholder needs and adapt over time (Research Question 2). Flexibility is defined by modularity, scalability, and adaptability. Modularity enhances integration, scalability adjusts capacity, and adaptability enables response to changes. Model-Based Systems Engineering (MBSE) and Value-Driven Design (VDD) align design decisions with stakeholder value. Resilient objects enhance robustness. Case studies validate the benefits of early-stage flexibility modelling.

Introducing or replacing technologies on product platforms impacts flexibility, risk management, and value optimization (Research Question 3). New technologies face compatibility issues and integration complexity, necessitating flexible platforms. Advanced risk modelling predicts and mitigates technical risks, ensuring adaptation without disruptions. Value-based optimization balances short-term gains with long-term flexibility. Resilient objects maintain integrity despite shifts. Incorporating field effects enhances modularity and adaptability, ensuring seamless integration. These strategies ensure automotive platforms remain competitive and adaptable amid technological advancements.

Jones and Eckert (2023) identify the problem of internal stakeholders stacking margins without a holistic view, leading to either inflated margins or insufficient flexibility for future components. Even with centralized authority, organizations face the challenge of deciding appropriate margins amidst future uncertainties. Erring on the side of minimal margins risks incompatibility with new components, while excessive margins waste resources. These issues highlight two interconnected problems: the need for margins at the platform level due to uncertainty and subsystem teams independently budgeting margins without considering overall system needs. Collaborative decision-making during the early stages of product development is crucial as it sets ambitious yet feasible objectives that align with market demands and requires input from various departments such as marketing, production, and engineering, necessitating effective collaboration to ensure successful outcomes (Jankovic *et al.*, 2010). To address this, this thesis recommends not relying on stacked margins for flexibility but being intentional and proactive in margin management. Emphasizing architecture as a series of decisions with their rationales can support this proactive approach.

7.1 Research Contributions and Claims

As outlined in the research methodology section, the objective of this thesis is to balance its research contributions between theoretical knowledge and practical applications, ensuring that the work is both academically rigorous and practically relevant.

These contributions must be validated differently, with academic contributions focusing on novelty and compliance with existing literature, and practical contributions validated within the specific industrial context (Isaksson *et al.*, 2020).

The ensuing explanation details the nature of these contributions.

7.1.1 Scientific Contribution

This thesis significantly contributes to the academic discourse on the practicalities of assessing the impact of technology introduction on the flexibility of product platforms, offering insights into how to trade-off the benefits the new technology provides versus the disruption to the platform architecture. By integrating a model-based approach with a value-driven design approach supported by a new flexibility metric, the thesis elucidates how platform architects' capabilities can be enhanced, particularly in managing complex decision-making. This contribution is validated through empirical performance validation, where real-world tests and simulations ensure the practical applicability of the proposed methods.

The exploration of the challenges faced by the industry in implementing platform strategies, specifically in the automotive sector, underscores the industry's willingness to leverage decision-support systems to address communication issues in early product development phases. These findings are substantiated by construct validity, ensuring the consistency and reliability of the observed phenomena across different industrial contexts.

The emphasis on interactive modelling within this thesis advocates for a holistic perspective in developing coordinative artefacts for development teams and decision-makers. The introduced new way of measuring flexibility using platform margins serves as a catalyst, providing researchers with a foundational tool to refine and develop flexible platform development frameworks that actively engage discipline experts to collaborate with other disciplines and decision-makers, leveraging their strengths. This approach is validated using theoretical performance validity, ensuring that the proposed models and frameworks accurately represent the underlying theoretical constructs.

As the landscape of automotive technology development evolves with the integration of AI handling routine tasks, this thesis calls attention to the foundational principles of human-in-the-loop design, emphasizing human supervisory control. This contribution is validated through theoretical structural validity, ensuring that the proposed design principles are logically coherent and well-grounded in existing theoretical frameworks. Furthermore, it encourages ongoing research to proactively use and refine the visualization and collaboration tools, thereby avoiding potential pitfalls and paradoxes associated with over-reliance on data-driven automatic decision-making.

In essence, this contribution not only expands the theoretical understanding of the value of flexibility in product platforms but also motivates researchers to further refine frameworks, fostering a symbiotic relationship between experts and their decision-support systems while navigating the evolving landscape of technology integration.

7.1.2 Industrial Contribution

According to (Zielhuis *et al.*, 2022), disseminating engineering design and product development research effectively requires four key strategies: 1) Customize content to address the specific needs and interests of the design practice audience. 2) Promote the sharing and growth of personal knowledge acquired during the project through methods such as workshops and artefacts. 3) Explore collaborative content development between researchers and design professionals within projects. 4) Align research outcome presentations with the preferences of design professionals, providing a variety of formats from practical tools to theoretical insights. During the elaboration of this thesis, all four strategies have been employed.

For industrial practitioners, this thesis delivers valuable insights into leveraging the proposed framework to enhance flexibility, efficiency, and the integration of novel technologies into product platforms. By presenting practical examples via case studies, this work serves as a guide for industry professionals seeking to optimize platform design and empower platform architects through the developed tools and methods. These case studies provide a robust method of validation by demonstrating the real-world applicability and effectiveness of the proposed strategies.

Theoretical and empirical research within this thesis addresses a knowledge gap identified by the industry regarding the assessment of the value of flexibility in product platforms. The model-based approach, rooted in value-driven design, simplifies collaboration in final decision-making. The proposed "platform margins" concept stands as a key contribution, designed to seamlessly integrate concerns about uncertainty and align the performance and capabilities of both the product architecture and the production environment in the design of flexible platforms. This approach is validated through both construct validity, ensuring the consistency and reliability of the concept across different scenarios, and empirical structural validity, confirming its applicability and effectiveness in practical settings.

By employing this approach as a practical tool from the early design phases, industries can enhance the adoption of flexible platforms in their product development processes. The iterative process of validation, involving real-world tests and simulations, ensures that the proposed methods are both theoretically sound and practically viable.

While initially designed with automotive products in mind, the generic nature of the proposed framework and its components extends its applicability to other sectors incorporating the need to plan for uncertain future scenarios and the upswing of new technologies. The versatility of this framework positions it as an asset for industries seeking to implement platform strategies, fostering adaptability across diverse manufacturing domains. This broad applicability can be validated through analytical generalization, demonstrating if the findings and methods can be extended beyond the specific context of the automotive industry to other sectors with similar needs.

7.2 Outlook

The author's recommendation for future research endeavours centres on extending the framework for assessing the value of flexibility to address sustainability concerns more granularly and further integrate production platforms' challenges related to those concerns. Modelling manufacturing operations can serve to improve the integration of product platforms and manufacturing platforms during the early phases of platform development (Landahl *et al.*, 2017). While the flexibility assessment framework design and application were initially informed by automotive platform design contexts, there exists a significant potential for broader application in diverse domains of product development, especially with an emphasis on the circular economy and the digitalization megatrend. Additionally, integrating digital tools and data management systems can enhance the interoperability between product and production platforms, supporting agile and demand-driven product realization (Säfsten *et al.*, 2022).

To enhance the applicability of the developed tools, it is imperative to explore their impact on various types of development processes, support tools, and the collaborative skills of users across different domains. A detailed investigation into the sustainability implications of deploying this framework in diverse collaboration scenarios becomes vital for comprehensive and meaningful insights.

Understanding the evolving role of platform architects in the firm's product lineup definition process is crucial for successful implementation. As technology evolves, the interplay between performance and platform efficiency undergoes transformations that need to be monitored. The proposed metric, when integrated with cutting-edge technologies like AI and machine learning, holds the potential to actively shape collaborative decision-making in platform design. Assessing the flexibility impact within the evolving technological landscape becomes integral to ongoing research in the field, particularly in terms of sustainability and resource efficiency.

Moreover, this thesis advocates for researchers to utilize platform margins as an instrument not only for trade space exploration but also to foster and ensure trust between the stakeholders of the product development process. The emphasis on trust-building aligns with the broader goal of seamless integration and sustainable collaboration between architects, subject matter experts, and supply chain partners in the realm of flexible platforms and decision-support systems development.

The continuous evolution of flexible product platforms presents a dynamic landscape with ongoing research and emerging concepts. The relationship between platforms and technology, akin to the interplay between constraints and innovation, stands poised to revolutionize the automotive sector's approach to early platform design. This thesis, acting as a foundational guide, propels the automotive industry toward a future where the value of flexibility in product platforms is harnessed to its fullest potential, emphasizing the harmonious integration of human and technological elements in the pursuit of innovation.

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9 APPENDICES

Paper A Identification of Technology Integration Challenges at Two Global Automotive OEMs

Paper B Reconciling Platform vs. Product Optimisation by Value-Based Margins on Solutions and Parameters

Paper C Designing Multi-Technological Resilient Objects in Product Platforms

Paper D Incorporating Field Effects into the Design of Modular Product Families

Paper E Modeling Technical Risk Propagation Using Field-Effects in Automotive Technology Infusion Design Studies

Paper F Design Support Efficacy in Risk Perception and Mitigation: Quantitative Evaluation of Design Interactions