THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Trading Off between Flexibility and Product Platform Constraints for Effective Technology Introduction

A Model-Based Methodology for the Automotive Sector

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ABSTRACT

Developing product platforms is an established method of reducing internal variety costs while delivering variety to customers. A critical aspect of a platform, that is expected to be used and extended for many years, is the ability to introduce new technologies and solutions effectively. Since these technological integration endeavours may challenge platform constraints, it is necessary to be able to assess the trade-off between their expected value and cost of realisation. New technologies can be integrated more easily into products derived from product platforms if they are flexible. However, introducing flexibility early can be wasteful, both in terms of resources used for the development of the platforms and the suboptimal design of products derived from the platform.

In this study, a review of the existing literature is conducted and several case studies in the automotive sector are performed. Both technical and organizational factors are found to limit platform flexibility. This research supports the idea that the flexibility to integrate technology into existing platforms is a valuable property. Consequently, it is important to foster the ability to more objectively assess the value of proposed technology changes in organisations relying on product and production platforms.

Finally, this thesis proposes a model-based methodology to trade off the flexibility of a product platform with the lifetime value it can deliver to its stakeholders. The methodology utilizes technology roadmaps, architectural modelling, value-driven design, and model-based simulations to establish the bandwidth of a product platform. As such, the constraints that the platform introduces for future derived products are balanced against valuable flexibility, which is defined as the flexibility of the platform to allow for more alternative designs, including using new technologies, of higher value in future products. The findings of this thesis have implications for the research of product platforms and their development, as well as for practitioners making decisions about product platforms with consideration to the uncertainty around the ways they will be used and upgraded in the future.

Keywords: Flexibility, Model-Based Design, Product Development, Product Platforms, Technology Integration, Systems Engineering

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Pygmaeos gigantum humeris impositos, plusquam ipsos gigantes videre.

— Didacus Stella (1524-1578)

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In addition, I would like to thank the many students I had the privilege to supervise in the product development courses and their master’s thesis work for their questions and fresh perspectives.

Finally, I could not have gone this far without the support of my family.

Sincerely,

Iñigo Alonso Fernández

Gothenburg, Sweden, October 2022

APPENDED PUBLICATIONS

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

PAPER A

Alonso Fernández, I., Panarotto, M. and Isaksson, O. (2020), “Identification of Technology Integration Challenges at Two Global Automotive OEMs”, *Proceedings of the Design Society: DESIGN Conference*, Vol. 1, pp. 2245–2254.

Distribution of work:
Alonso Fernández conceptualized the paper, performed the literature studies, performed the data collection and analysis, and coordinated the contributions of the other authors. Panarotto and Isaksson also contributed to the empirical data collection and contributed knowledge and critique of the paper’s concept, content, and form.

PAPER B

Alonso Fernández, I., Panarotto, M. and Isaksson, O. (2022). *Trade-off Analysis of Flexible Product Platform Architectures subject to Rapid Technology Introductions* [Manuscript submitted for publication]. Industrial and Material Science Department, Chalmers University of Technology

Distribution of work:
Alonso Fernández conceptualized the paper, developed the theoretical prescriptive contributions, performed the case studies, and coordinated the contributions of the other authors. Panarotto wrote the methodology step related to the value and market models. Isaksson contributed knowledge and critique to the paper's concept, content and form.

PAPER C

Alonso Fernández, I., Panarotto, M. and Isaksson, O. (2022), "Designing Multi-Technological Resilient Objects in Product Platforms", *DS 118: Proceedings of NordDesign 2022, Copenhagen, Denmark, 16th - 18th August 2022, presented at the NordDesign 2022*, pp. 1–12.

Distribution of work:

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

PAPER D

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.

Distribution of work:

Alonso Fernández conceptualized the paper, designed, coded, and run the experimental setup and coordinated the contributions of the other authors. Panarotto and Isaksson contributed with knowledge and critique to the paper's concept, content and form.

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LIST OF ABBREVIATIONS

AR	Augmented Reality
CAM	Change Allocation Model
CCB	Cross Car Beam
CMA	Common Modular Architecture (Volvo Cars)
CPA	Change Propagation Algorithm
DOE	Design Of Experiments
DRM	Design Research Methodology
DSIP	Digital Sustainability Implementation Package
DSM	Design Structure Matrix
DSS	Decision Support System
EOP	End Of Production
FoV	Field of View
FPDP	Flexible Platform Design Process
FUP	Front Underrun Protection
HUD	Head-Up Display
LF	Lower Front
MATE	Multi-Attribute Tradespace Exploration
MDO	Multidisciplinary Design Optimization
MBSE	Model-Based Systems Engineering
MFD	Modular Function Deployment
NPV	Net Present Value
OEM	Original Equipment Manufacturer

PDP	Product Development Process
RQ	Research Question
SBCE	Set-based Concurrent Engineering
SE	Systems Engineering
SOP	Start Of Production
SPA	Single Page Application (web development)
SPA	Scalable Platform Architecture (Volvo Cars)
SV	Surplus Value
TRL	Technology Readiness Level
VISP	Value and flexibility Impact analysis for Sustainable Production
VWFO	Value Weighted Filtered Outdegree

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.

Product platforms are an established means of reducing costs while maintaining the capability to deliver variety to customers (e.g., configuration, customization) (Ulrich *et al.*, 2020) and contributing to risk reduction. Automotive product platforms are important because they allow automakers to develop multiple models by using a single original base design. Platforms produce economies of scale by reusing some of the same components in different products and decrease the cost of time and resources when developing new product variants by providing a "template" with most of the architectural and engineering work done in advance. However, the development of a new platform is costly in terms of time and money, as well as engineering resources.

Moreover, the development of product platforms requires a forecast of the future circumstances of the market and technological landscapes in which new products need to be developed. If the product platform requires an extensive redesign to accommodate changes to those circumstances, costs not only increase because of the additional engineering effort required, but a number of the benefits of having a platform strategy are also negated. For example, the production volume of some components is smaller than anticipated if they are replaced with an updated version (Fixson, 2006).

Some sources of change are technological, such as the development of new materials or production methods. The frequency of technology introductions is increasing as more research and development is conducted globally, and novel concepts are made available at a rapid pace. These developments have generated great shifts in the technological landscape, as new generations of means to fulfil needs make their way into the market. This landscape not only increases its range, but also its complexity, because the combination of several technologies into mixed systems can generate even greater results. A salient example is the rise of mechatronics, a discipline in which mechanical systems are enhanced by electrical and electronic systems that require software components (Küchenhof *et al.*, 2022).

Other sources of uncertain shifts are social, such as changes in customer needs or expectations, or economic, such as the rise and fall of prices or the availability of resources. Finally, political factors can impact product design and market trends. Sustainability, for example, shapes all aspects of current discourse and, together with digitalization and servitization, has an outsized impact on the way product development is conducted (Hallstedt *et al.*, 2020).

Managing the uncertainty inherent to the evolution of new technologies and their maturity level supports the development of designs that can accommodate changes later in their lifecycle and meet the needs of all stakeholders.

The purpose of this research project and licentiate thesis is to examine and better understand the definition and assessment of the value of flexibility in product platforms. This value concerns customer needs and the production system, among other stakeholders. Therefore, several open problems in industrial practice and the academic literature are identified and discussed below.

1.1 INDUSTRIAL AND SCIENTIFIC PERSPECTIVES

Automotive industry have successfully developed and produced model variants based on product and platform descriptions (reference).

Since the late 1990s (Siddique *et al.*, 1998), advancements in and increased amount of digital content and digital means in product development and production have resulted in additional features to manage in product platforms. Functionalities and technologies are introduced at a higher frequency (Paunov and Planes-Satorra, 2019), impacting vehicle design, production development, and business models.

The industrial perspective in the automotive sector is characterized by three main contextual factors/trends: (1) platforms are an established way to reduce cost and sustain the capability to generate and deliver variety for customers (e.g., via configuration, customization), as well as reduce risks; (2) the frequency of technology introductions (e.g., Artificial Intelligence, Edge Computing) and shifts in the technological landscape (e.g., Software as a Service) and mixed tech (e.g., mechatronics) is increasing; and (3) sustainability is posing challenges in all aspects and phases (e.g., more stringent limits on emissions for vehicle fleets from the regulation side, and demands for more green and socially responsible alternatives from the market side).

The consequence of these trends is that industrial firms need to violate the constraints of platforms too often to fulfil the needs of new customer demands and adapt them to the use of new technologies. The negotiation of these trade-offs between stakeholders is difficult due to lack of information, great uncertainty about the future, and inputs based solely on the experience of the individuals involved.

The variation of individual differences between middle managers, who tend to be the primary decision-makers when determining architectural decisions (e.g., establishing the aforementioned constraints) for product platforms, have been found to impact the performance of the organization, especially during innovation tasks (Mollick, 2012). Decision Support Systems (DSS), that enable designers and decision makers to leverage their experience while strengthening objectiveness and fact-based systematic assessments, have the potential to improve the performance of the organizations developing product architectures. Consequently, modelling approaches to introduce this way of thinking into existing decision-making structures might have significant positive effects. However, experienced operators can be threatened, so a soft inclusive approach is needed to successfully introduce a new way of working.

The research problem can be described by the difficulty of assessing the impact of the introduction of new technologies into product platforms. This difficulty translates into an inability to make trade-offs on value and costs in decision situations where knowledge about technology performance and adaptations needed from the platform are uncertain. Additionally, assessing the impact of such introductions on the level of fulfilment of customers' needs, and thus on the market demand, is also challenging.

The exploitation of the insights generated by this research faces the challenge of translating theory into practice, including the lack of tool implementations to be validated. This issue impacts the chances of performing meaningful benchmarking among methods and inhibits the diffusion of findings back to practitioners.

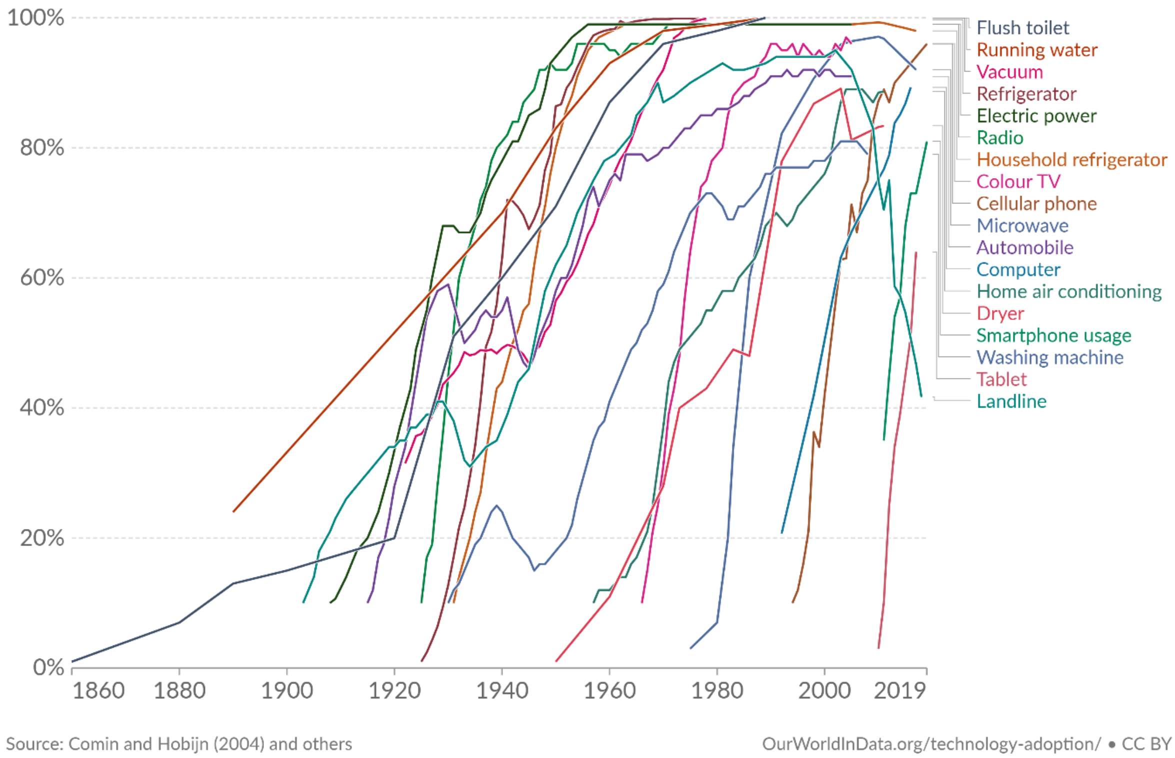
An additional challenge from the scientific or academic perspective is that the design of product platforms is a multidisciplinary research problem, where the different disciplines provide various perspectives.

1.2 CHANGE DRIVERS FOR NEXT GENERATION PRODUCT PLATFORMS AND THE NEED TO DESIGN FOR FLEXIBILITY

Some drivers of change justify and support the development of a product platform strategy. Specifically, such drivers for the development of automotive platforms have been identified among three main categories: internal changes, external changes, and technological developments particular to the automotive sector. Internally initiated changes are those originating within the boundary of the system or firm, and externally initiated changes are those originating from outside (Ross, 2006). Technological developments are an example of external changes of particular interest to this study.

For the internal changes that most prominently drive product platform development, it has been found that the overall planning of the portfolio of products to be marketed and the associated services to complement them is of major concern. The main external change drivers identified are changes in legislation and regulations and changes in customer preferences. Additional changes, such as the offerings of competitors and the overall economic landscape, have been mentioned by some stakeholders.

Technological development megatrends in the automotive sector include the introduction of now mature technology (e.g., digitalization of functions, high-performance materials, new production setups), the electrification of powertrains, and the introduction of autonomous driving features, including intermediate steps like advanced driver assistance systems. The development of new technologies both creates a “technology push” effect, where the potential for the new technology to improve the product or the production side drives the introduction of the new technology, and catalyses the “market pull” effect, where consumers think of and demand new functions and performance levels to be delivered by new products. The pace of adoption for new technologies has also been accelerating, as shown in Figure 1.



Source: Comin and Hobijn (2004) and others

OurWorldInData.org/technology-adoption/ • CC BY

FIGURE 1 SHARE OF US HOUSEHOLDS USING SPECIFIC TECHNOLOGIES, 1860 TO 2019 (DATA FROM COMIN AND HOBIJN [2004] AND OTHERS)

Thus, the increased pace of technological development creates a high-pressure environment for the lifecycle of product platforms. As illustrated in Figure 2, an ever-increasing number of new technologies (represented as red markers in the year of their introduction) must be integrated into more modern automotive platforms (represented by lines spanning from Start of Production [SOP] to End of Production [EOP], of the first and the last products derived from it, respectively). For each of these integrations, a conscious decision must be made that considers the potential violations of the platform and other trade-offs. It is also important to note that for each new technology that is finally integrated, many others have been proposed and rejected. However, there is clear evidence that systematic trade-off support is lacking in practice (see Paper A).

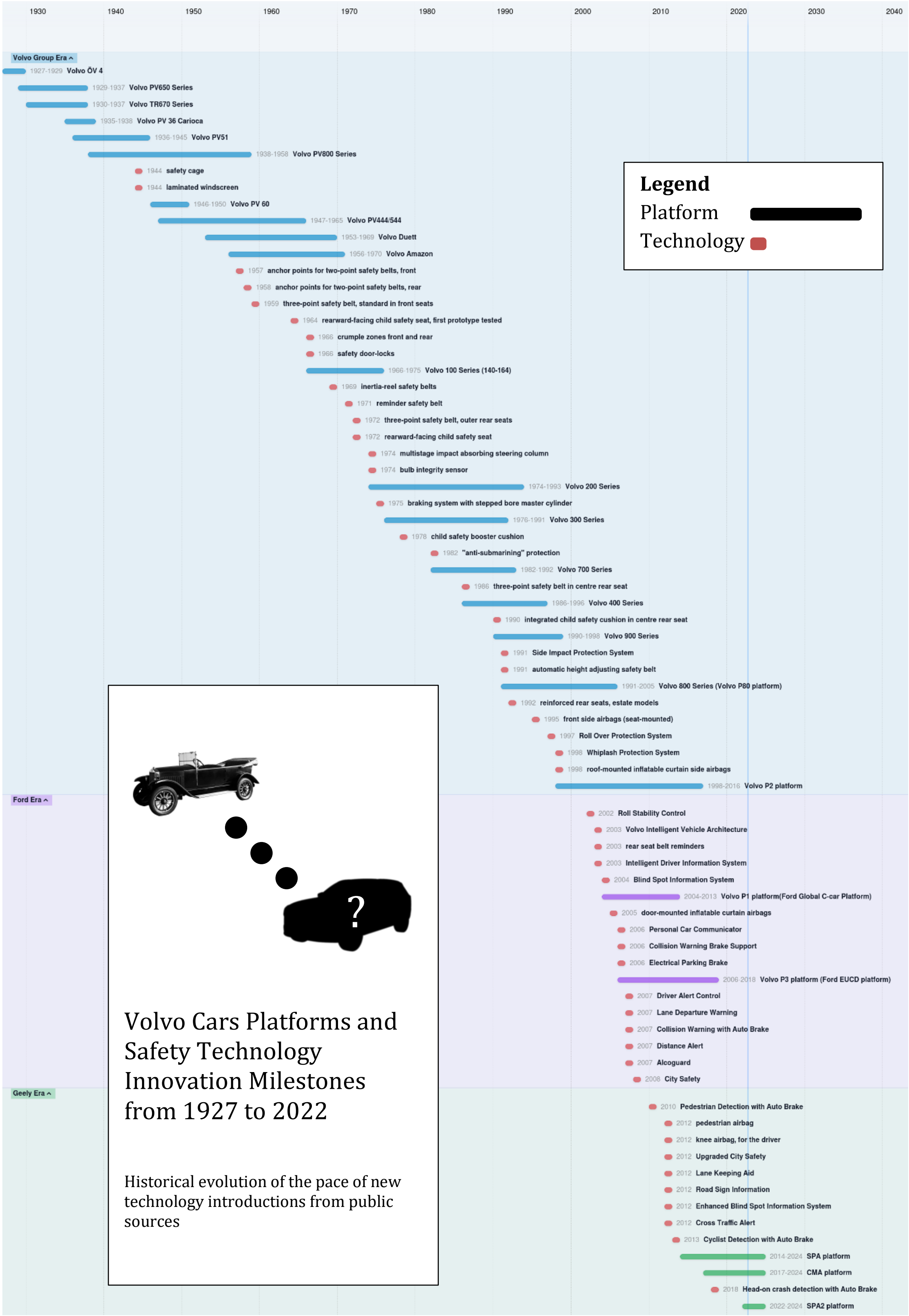


FIGURE 2 VOLVO CARS PLATFORMS AND SAFETY TECHNOLOGY INNOVATION MILESTONES

An example of a single product platform is shown in Figure 3, where the development time of the platform is also represented as a block of time from the beginning of the development to the SOP. At the EOP, the product platform still continues. The products produced up until that point remain in use, potentially for a much longer time, and require maintenance, access to spare parts, and consideration for potential issues that might necessitate a recall.

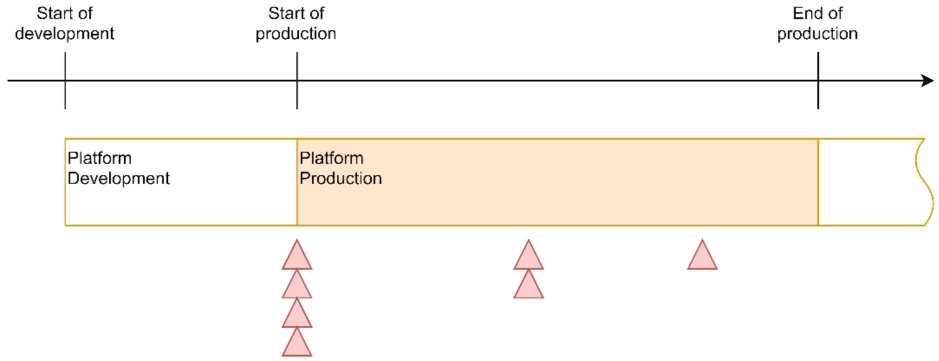


FIGURE 3 PRODUCT PLATFORM LIFECYCLE AND TECHNOLOGY INTRODUCTIONS

Both Figure 2 and Figure 3 highlight the importance of considering the whole lifecycle of product platofrms, as well as the interplay between them for presenting a robust market offering. Planning of product families and the complete portfolio of the company is key when pursuing a product platform strategy (Meyer and Lehnerd, 1997).

All the drivers mentioned above justify the changes and updates that platforms require over their lifecycles, but these changes do not come without drawbacks. These negatives include the additional engineering effort of designing solutions for all components affected downstream of the change and dealing with those changes, both in terms of time and economic resources, as well as other accommodations in production setups, logistic flows, and aftersales support.

1.3 PURPOSE

The purpose of this research project and licentiate thesis is to explore the introduction of new technologies into product platforms. This goal necessitates the definition and assessment of the value of the flexibility of product platforms. This value is defined as stakeholders' value in terms of customer needs and the production system. The project aims to better understand the impact of changes to the product platform, and adaptations within it to deal with changes, on stakeholders' value. Finally, it examines the impact of introducing different degrees of flexibility concerning time, cost, complexity and other relevant attributes on the development of the product platform itself. The main phenomenon studied in this thesis is *the use of flexibility as a parameter in decision-making during the introduction of new technologies into product platforms*.

1.4 RESEARCH QUESTIONS

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

RQ1 *What are the challenges of designing flexible product platforms that can efficiently integrate new technologies?*

The answer to RQ1 is important to manage the uncertainty inherent in the evolution of new technologies. Their maturity level supports the development of designs that can accommodate changes later in their lifecycle and continue to meet the needs of all stakeholders.

RQ2 *How can decisions about the integration of new technologies and flexibility trade-offs in the early phases of platform development be supported by tools and methods for product platform architects?*

The interdisciplinary teams who develop new platforms make decisions that consider both the current situation and future forecasts, thus determining the long-term value of the platform. The better both factors can be tracked over time, the more effective the outcome of decisions regarding the integration of new technologies will be.

RQ3 *How should the value of flexibility in product platforms concerning customer needs and the production system be defined, modelled, and assessed?*

To quantify and analyse the flexibility embodied by alternative platform architectures and definitions, it is necessary to assess the impact of the level of flexibility on the overall value that the product platform can help deliver over its lifecycle. This will be the basis for an analysis of the potential trade-offs that platform designers face.

1.5 THESIS STRUCTURE

The chapters of this licentiate 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 Design Research Methodology followed in the research.

Chapter 4 compiles the summaries of the appended papers.

Chapter 5 details the findings from the studies and logically link them together.

Chapter 6 discusses the results from Chapter 5 as they relate to the goals stated in Chapter 1.

Lastly, **Chapter 7** summarizes the previous chapters and outlines possible future work to be pursued.

Appendices collate the full-text versions of the four papers published during the research.

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

Paper B Trade-off Analysis of Flexible Product Platform Architectures subject to Rapid Technology Introductions

Paper C Designing Multi-Technological Resilient Objects in Product Platforms

Paper D Interactive model-based decision-making tools in early product platform design

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 Product Development Process (PDP). The concepts of flexibility and value assessment are presented, and an introduction to product platforms is given. The chapter also highlights the identified gaps in the current state-of-the-art.

2.1 PRODUCT DEVELOPMENT PROCESS

According to (Ulrich *et al.*, 2020), the Product Development Process (PDP) is the sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product. A well-defined process is useful because it provides phases and checkpoints to ensure quality, offers a basis for coordination among teams and individuals, simplifies the planning process, enables effective management of resources, and leads to improvements in the process itself via documentation and reflection on the results. A generic PDP consists of six phases: (1) planning, (2) concept development, (3) system-level design, (4) detail design, (5) testing and refinement, and (6) production ramp-up.

2.1.1 PRODUCT PLATFORMS

A product platform is a collection of assets (e.g., components, processes, knowledge, people and relationships) that are shared by a set of products (Robertson and Ulrich, 1998). Other definitions focus on simple architectures based on modules with defined interfaces between them (Meyer and Lehnerd, 1997). The PDP of platform products is characterized by a concept development phase that presumes a proven technology platform, so the team assumes that the new product will be based on the use of an existing technological subsystem (Ulrich *et al.*, 2020).

Platform research has traditionally focused on firms' internal concerns, such as innovation, modularity, commonality, and mass customization (Facin et al., 2016). New research themes, including managerial questions related to capability building, strategy, and ecosystem building based on platforms are more recent additions to the literature (Pirmoradi *et al.*, 2014).

The platform bandwidth is the range of customer requirements it is designed (selected and sized) to meet (Levandowski *et al.*, 2014). The bandwidth then limits the number and type of features that can be included in a product derived from it. This constraint is necessary to ensure that products are efficient and effective. Without these constraints, companies would produce bloated and ineffective products. By limiting the range of possible products, companies are forced to focus on creating quality items that will appeal to consumers. This focus on quality results in better products for consumers and increased profits for businesses.

2.1.2 PRODUCT ARCHITECTURE

Architecture is the foundation of an effective platform design. In its most basic definition, a product platform is the set of assets shared across a set of products. Components and sub-assemblies are often the most important of these assets. However, a more satisfying definition of the architecture of a product approaches it as the scheme by which the functional elements of the product are arranged into physical elements and how they interact (Ulrich *et al.*, 2020).

Product architecture describes the structure and organization of the parts of a product or product family, and it is defined by the significant design decisions that shape them, where significance is measured by the cost of change. Product architecture is important because it yields a product or a class of products that is optimal for its intended use. The architecture of product platforms has proven to be more flexible when being modular (Muffatto and Roveda, 2000).

The architecture is modular when different parts are easily removed or replaced if needed. It can also be scalable such that it can grow with the product as it evolves (Johannesson *et al.*, 2017). The parametric design allows for easy modification of the product based on customer feedback or changing market conditions. Model-Based Systems Engineering (MBSE) ensures that all aspects of the platform are properly coordinated and integrated into one system. By using these techniques, companies can develop products more quickly and efficiently while still maintaining quality control.

A functional model of architecture using the enhanced function-means (EF-M) method is capable of representing the design space and enabling the exploration of the integration of novel solutions into the existing product structure (Müller *et al.*, 2019). It does so by representing not only the functions and design solutions to fulfil them but also the constraints and interactions between design solutions.

2.1.3 PRODUCT PLATFORM PLANNING PROCESS

By providing exactly the features, functions, and performance level desired by each market segment, the variety of derivative products created from a product platform can reach the market faster and with less development effort. An effective platform design will allow for easy modification and extension of the product family, while a bad design can lead to costly rework and delays. There are many factors to consider when designing a product platform, including its architecture, design parameters, and additional support models.

Nonetheless, product platform development projects can take much more time and monetary investment than derivative product development projects. There are downsides to this approach, as architectural decisions are difficult to change later, and knowledge about the product might be lacking at this early stage. It is important to consider what parameters to include in the models and to what level of fidelity the models should be developed. Thus a company cannot afford to develop a new platform too often, and it needs to be decided whether the development of a new product can be achieved by using an existing platform, extending or redesigning the platform, or designing an all-new platform. These decisions are closely related to the maturity of different technologies and whether they are ready for commercial utilization. Another aspect that must be considered is whether different variants of the platform are to be introduced into the market at the same time or in sequence.

Technology platforms have been proposed as means to allow the organization of initiatives regarding high-level functionality to help managing and optimizing technology investments across the development of multiple product platforms (Levandowski *et al.*, 2013).

The emergence of a new platform can have a significant impact on growth due to the network effects that it creates. On the demand side, customers who benefit from the platform standard and make a long-term commitment to using its derivatives create a network effect. On the supply side, suppliers or partners who invest in complementary innovations, such as accessories or services that enhance the value of (and demand for) the platform, also create a network effect. To enable such network effects, developers must pay close attention to designing key features and interfaces while creating both the platform and its derivatives. By doing so, they can ensure that everyone benefits from these positive feedback loops created by network effects.

2.1.3.1 DESIGN OF PRODUCT PLATFORMS

The design of a product platform is an important step in product development. Since the beginning of the century, there has been a flurry of activity to develop methods and tools to facilitate platform-based product family development (Simpson *et al.*, 2006, 2014). In Table 1, a selected set of platform design methodologies are compared against the steps proposed by Suh *et al.* (2007):

TABLE 1 COMPARISON OF PRODUCT PLATFORM DESIGN METHODOLOGIES, ADAPTED FROM (SUH *ET AL.*, 2007)

	Methodologies	**FPDP Suh et al.**	**Simpson et al.**	**Martin & Ishii**	**Li & Azarm**	**Gonzalez-Zugasti et al.**
	Case Example	*Vehicle Platform*	*Electric Motor*	*Water Cooler*	*Cordless Screwdriver*	*Interplanetary Spacecraft*
Design Steps	**Step I** Identify market, variants, and uncertainty	✓	✓		✓	✓
	Step II Determine uncertainty-related key attributes, and design variables	✓	✓		✓	✓
	Step III Optimize product family and platform bandwidth	✓	✓		✓	✓
	Step IV Identify critical platform elements	✓		✓		
	Step V Create flexible platform design alternatives	✓		✓		
	Step VI Determine costs of design alternatives	✓		✓	✓	✓
	Step VII Uncertainty analysis	✓			✓	✓

The design steps described in Table 1 are (I) identify market, variants, and uncertainty, (II) determine uncertainty-related key attributes, and design variables, (III) optimize product family and platform bandwidth, (IV) identify critical platform elements, (V) create flexible platform design alternatives, (VI) determine costs of design alternatives, and (VII) uncertainty analysis. Decisions must be made at each of those steps, and the next section explores how they are made.

2.1.3.2 DECISION-MAKING ABOUT PRODUCT PLATFORMS

Decision makers require a systematic approach to support their design of the architecture of a product due to the complexity, multiple correlations, and lack of transparency in the product portfolios of the firms (Windheim *et al.*, 2016). Product platforms often become overly constraining in a dynamic market environment.

Some current approaches from the literature aim to support the design of modular product families to enhance their robustness against future changes by identifying and redesigning the change-critical elements of the product family based on decision-relevant criteria (Greve *et al.*, 2021). The Change Allocation Model (CAM) focuses on making the standard parts of the product family robust against future changes in the market and production environment. Alternatively, (Schwede *et al.*, 2022) discuss a method for the selection of modularization methods (such as Design Structure Matrices [DSM], heuristics, and the Modular Function Deployment [MFD]) based on their economic impact.

More research effort has been allocated to the fact that, during the development of the architecture of a product platform, it is difficult to predict the final aggregate performance of the -ilities in derived variants instantiated from the platform. It has been proposed that some architectural properties can be used as proxies for the -ilities (Salado, 2022). The framework developed by Salado links the -ilities to those architectural properties using computer granular models, engineering- and physics-based models for objective elements and relationships, and expert consensus for the rest.

Another perspective on -ilities suggests categorizing them as extensive attributes (i.e., attributes of the system or product being designed or those of its components, where the system attribute is a function of component attributes) (Collopy and Hollingsworth, 2011). Such a classification can be useful for comparing the -ilities to other extensive attributes like weight or cost.

Architecture decisions are made with many factors in mind, including the need for -ilities such as flexibility. However, this demand for flexibility often comes at the cost of reduced design freedom. For example, a building's layout may be constrained by its location on a site or its relation to other buildings. In addition, certain materials and construction methods may be required to allow for later changes or modifications. While these limitations can be frustrating, they are often necessary to achieve the desired level of flexibility.

2.2 DESIGN FOR ADAPTING TO CHANGE

Many different properties of a system qualify its ability to adapt to different changes (Ross, 2006; Ross *et al.*, 2008). For example, depending on the source of the change, *adaptability* is defined as the ability of a system to be altered by a system-internal change agent with intent, while *flexibility* is the ability of a system to be altered by a system external change agent with intent. *Robustness* is the ability of a system to maintain its level and/or set of specified parameters in the context of changing internal and external forces. An alternative definition of flexibility (Ferguson *et al.*, 2008) describes it as the property of a system that promotes change in both the design and performance space.

Agility is the ability of a system to change in a timely fashion, and *changeability* is the ability of a system to alter its operations or form, and possibly its function as a result, at an acceptable level of resources. *Evolvability* is the ability of a system to have its design inherited and changed across generations over time, while *extensibility* is the ability of a system to accommodate new features after design. *Modifiability* is the ability of a system to change the current set of specified system parameters. *Reconfigurability* is the ability of a system to change its components' arrangements and links reversibly, and *scalability* is the ability of a system to change the current level of a specified system parameter. All these -ilities can be ordered in a means-ends hierarchy (De Weck *et al.*, 2012).

These concepts have been used to describe how a system design can mitigate the likely impact of uncertainties without removing the actual sources of uncertainty (Dwyer, 2020).

Another means of reducing the effort required for future modifications that complements modularity is the use of "system excess" or "over-design" as a system lifecycle attribute (Long and Ferguson, 2017).

Furthermore, additional change-propagation mechanisms identified in recent literature (Brahma and Wynn, 2021) include under-conservative assumptions, insufficient excess capacity, performance violation, constraint violation, and special incompatibility. Some proposed ways to address these issues are the tracking of assumptions during the design process, the selection of oversized parts to absorb future changes, the analysis of the many-to-many mappings between design and performance parameters, the tracking of the constraints introduced during the design process, and the modelling of special incompatibilities early to implement geometrical modularity.

2.3 STATE OF THE ART OF FLEXIBILITY IN ENGINEERING DESIGN

Paper A presents a review of the literature on existing methods for developing product platforms. It shows a wide variety of approaches from different industries (the software industry is the one with the most advanced and tested methods available) with different focuses and levels of adoption in the industry.

Some approaches are “top-down” and start with business needs before addressing consequences to the more detailed phases of a development effort. Others are “bottom-up” and attempt to track the details of an existing or proposed technical implementation into a high-level organization through the concerns of the different technical disciplines involved.

A common aspect of many approaches is that they use models to represent the product platforms. Models of the platforms are, in most cases, developed around the definition of their functions, modules, or general attributes that have been studied for a long time.

2.4 VALUE ASSESSMENT OF FLEXIBILITY IN DESIGN

The introduction of new technology in an automotive platform is an "option" because it provides a right. However, it is not an obligation (i.e., OEM can use it or not) and is acquired at some cost (e.g., loss of space, un-optimal geometry). It also requires taking some action (e.g., to change or add new components to the architecture) which may occur in the present, or the future whenever it is desired with the maturity of the technology allowing). For example, it might transpire when a predetermined condition (e.g., "strike" price, time, the effort of updating production setup, or price of a license) is met.

Value-Driven Design (VDD) (Collopy and Hollingsworth, 2011; Isaksson *et al.*, 2013; Ross *et al.*, 2010) is an established framework for dealing with extensive attribute such as the -ilities described above, during design. VDD approaches to product family design have also been compared to “traditional” multidisciplinary design optimization (MDO) (Jung *et al.*, 2021).

The Value Weighted Filtered Outdegree (VWFO) (Viscito and Ross, 2009) has been proposed as a metric to identify valuably flexible designs in a Tradespace. This metric is based on the Multi-Attribute Tradespace Exploration (MATE) framework and uses computer models to evaluate the performance of many different designs in utility-cost space. MATE uses Tradespace modelling and multi-attribute utility theory for the aggregation of decision makers' preferences. Doing so creates a common metric for evaluation in those models to generate and evaluate a multitude of system designs (Ross *et al.*, 2004). For this study, a derided metric was developed based on the concept of VWFO (see section 0).

3 RESEARCH APPROACH

This chapter describes the research approach methodology used in this thesis and the motivation for doing so.

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 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.

Additional knowledge was attained 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 producing their master's thesis.

3.2 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

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[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/

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.

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 4, those stages are linked to the research methods and key deliverables for this thesis.

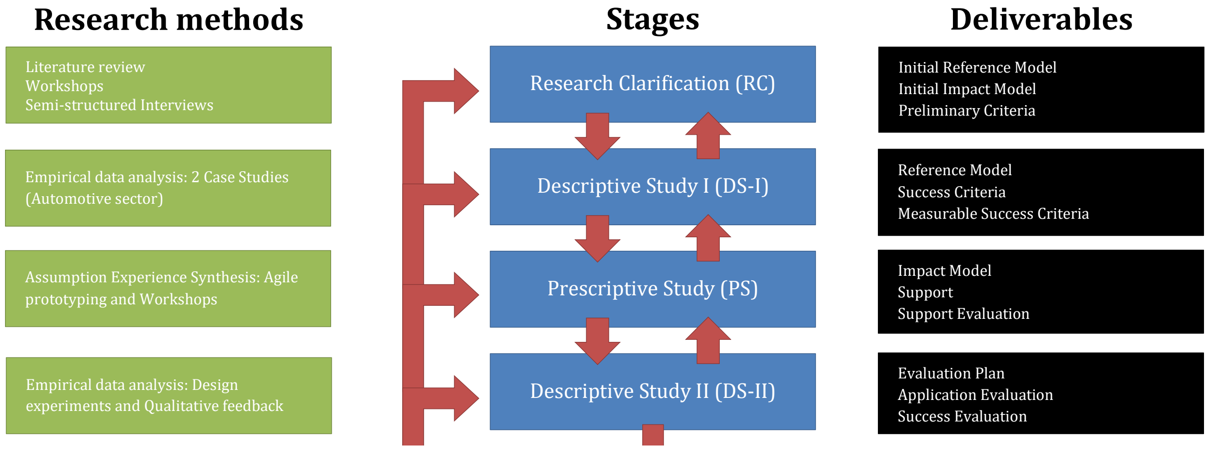

FIGURE 4 DRM FRAMEWORK STAGES

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 THESIS ACCORDING TO THE DRM FRAMEWORK

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

Paper A focuses on the Research Clarification phase and introduces Descriptive Study I. Paper B develops Design Study I and provides the theoretical basis of the Prescriptive Study stage. Paper C further expands the Prescriptive Study by proposing specific implementation alternatives and further theoretical background. Paper D provides additional input for the future Description Study II, which requires additional input from the Research Clarification stage. The knowledge gained from this study also informed the development of support material during both the DS-I and PS stages.

3.3 DATA COLLECTION 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 an understand of 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 performed via three main mechanisms, which are described in detail below: literature reviews, workshops, and interviews.

3.3.1 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] and Elicit.[5]

3.3.2 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.

3.3.3 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.

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[3] https://www.researchrabbitapp.com/

[4] https://www.connectedpapers.com/

[5] https://elicit.org/

The interviews were conducted primarily as a complement to the workshop 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.

3.4 DATA ANALYSIS

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.

For the quantitative part of the data as well as the modelling and simulation studies, the *Python* programming language and the appropriate libraries (e.g., *numpy*, *pandas*, *matplotlib*, *networkx*) were used. As such, the necessary reimplementation of existing algorithms from the literature was performed, and newly proposed methods and metrics were comprehensively built.

4 SUMMARY OF APPENDED PAPERS

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

As part of the research that led to this thesis, four papers were published in high-quality peer-reviewed scientific fora and are included in the Appendix.

4.1 PAPER A: IDENTIFICATION OF TECHNOLOGY INTEGRATION CHALLENGES AT TWO GLOBAL AUTOMOTIVE OEMS

4.1.1 ARTICLE SUMMARY

This study reviews the existing approaches to modelling product platforms and showcases the challenges faced by OEMs when introducing new technological innovations to their platforms. A gap was identified in the methods used to assess the ability of existing platforms to integrate new technologies whenever they become available.

4.1.2 CONCLUSIONS

The challenges found in the integration of new technologies into product platforms were investigated in this paper. The findings highlight a normative gap in the current automotive literature on how to approach this process and overcome some of the current challenges. These include, for example, the early availability of value models to assess the impact of flexibility and other 'ilities' in the lifecycle value of product platforms. Providing the development teams with model-based tools and methods can support decisions regarding trade-offs between platform changes and platform flexibility. The methods available in the literature are not all well-known in the industry. Additionally, there is little reported in the literature on the assessment of trade-offs between compliance to an existing product and process platform and the user utility/value offered by introducing new technologies.

4.1.3 CONTRIBUTION TO THE THESIS

This paper contributes to the present design study by providing clarification upon the object of the study, defining and bounding the research, and introducing the first empirical efforts. The results suggest that the gap in the current state-of-the-art exists, and the state-of-practice lags even further. This highlights the need to develop not only new methods but also, critically, additional support for implementing tools that reduce the friction of adapting to new ways of working and collaborating in the industry.

4.2 PAPER B: TRADE-OFF ANALYSIS OF FLEXIBLE PRODUCT PLATFORM ARCHITECTURES SUBJECT TO RAPID TECHNOLOGY INTRODUCTIONS

4.2.1 ARTICLE SUMMARY

This study proposes a novel model-based method to analyse the impact of new technology integration efforts on product platforms by quantifying the flexibility of the architecture. The concept was applied and tested in a case study of the early design of a new automotive platform.

The case study analyses three platforms, their constraints, and three competing technologies that can be used to implement a head-up display. By comparing the value provided by a simulated set of alternative designs and the flexibility of the platforms that enable them, a balanced platform can be identified where the "design excesses" that enable the flexibility to adapt the designs to future scenarios can be limited to avoid waste. This analysis allows decision-makers to weigh the priorities of all stakeholders of the platform over its lifecycle, particularly when early-stage decisions about its structure and bandwidth are being made.

4.2.2 CONCLUSIONS

This study proposes a novel model-based method to analyse the impact of new technology integration efforts on product platforms by quantifying the flexibility of the architecture. The associated case study was designed to determine which areas in current practice could benefit the most from the proposed approach. The fractional impact and dynamic uncertainty of the parameters considered in the decision-making process were synthesised to provide a relevant figure of merit.

This method was applied, tested, and updated in a case study for the early design of a new automotive platform. The results of this study suggest that the method can support product platform architects in managing multidisciplinary deliberations around the introduction of new technologies to existing platforms. This study examined the factors thought to contribute to the support of sound decision-making in such a context.

The proposed method offers a novel perspective on managing the lifecycle of product platforms. Overall, this study supports the idea that the industrial state-of-practice lags behind current literature on the analysis of platform metrics. The insights gained from this study may be of assistance to researchers in the fields of modularity, product platforms, and flexibility as well as practitioners in need of support for their decision-making processes.

4.2.3 CONTRIBUTION TO THE THESIS

This first journal paper combines the results of the first empirical design study with insights from other activities carried out in parallel. In doing so, it proposes a first approximation of a prescriptive method to address the assessment of flexibility and value impact on product platforms' architecture when introducing new technologies. The application of the method to a case study invites reflection on which steps are straightforward or difficult to perform, as well as how effective the results are versus the expectations and final decisions of the practitioners involved.

4.3 PAPER C: DESIGNING MULTI-TECHNOLOGICAL RESILIENT OBJECTS IN PRODUCT PLATFORMS

4.3.1 ARTICLE SUMMARY

This conference paper focuses on how an uncertainty-protected product platform can be designed at an early stage with minimal impact on the overall platform structure.

There exist several design approaches to protect against uncertainty, which depend on the sources of uncertainty and the mechanisms used to combat them. These include reliability, robustness, adaptability, versatility, resilience, and flexibility.

The design of product platforms using flexibility provides protection against uncertainty through restructuring the architecture in case of need (i.e., active protection). However, modularity of platforms is seldom complete, and multi-domain designs have complex change propagation paths.

The use of resilience, in contrast with flexibility, aims at protecting against uncertainty without restructuring the platform architecture (i.e., passive protection). This is a significant motivation for applying resilient design principles to next-generation product platforms instead of only flexibility principles.

Furthermore, a means of increasing the resilience of platforms is to introduce "resilient design objects".

4.3.2 CONCLUSIONS

This paper proposes the introduction of stand-alone components ("resilient design objects") in the regions of the product platform that are likely to be most affected by change. These components embody resilience and can absorb different types of changes to deal with uncertain situations without the need to alter the structure or configuration of the product platform. The paper also hints at how future work might focus on extending the matrix of multi-technological resilient objects and define a systematic design method that selects and evaluates which of those objects are more valuable to be inserted in specific regions of the product platform.

4.3.3 CONTRIBUTION TO THE THESIS

Utilising a value model capable of evaluating the lifecycle value of different resilient objects could be helpful and effective in deciding which object to choose, beyond punctual performances and costs.

4.4 PAPER D: INTERACTIVE MODEL-BASED DECISION-MAKING TOOLS IN EARLY PRODUCT PLATFORM DESIGN

4.4.1 ARTICLE SUMMARY

An interactive model-based decision-making support system is proposed as a tool to solve the challenges identified. This paper includes the description and results from an experimentation with the main technological foundations of such a tool. These include a web-based front end and a real-time NoSQL database in the back end. The client web application (webapp) enables user inputs, runs quantitative models, and visualizes results. The database records results and allows the use of common inputs and common visualization of the results. The models that run directly in the client are developed offline and can be continuously deployed with no downtime for concurrent users. The technology stack used demonstrates that rapid prototyping of tools using state-of-the-art web technologies provides quick results and enables researchers to create quick iterations that are easily deployed in industrial use cases. The presented method is a new approach to providing digital support to the design process by enabling better informed decisions during early phases of the product development process.

4.4.2 CONCLUSIONS

The method presented in this paper is a new approach to providing digital support tools for the design process. Tools that can enable better-informed decisions during the product development process, as the inputs of different stakeholders, can be collected and unified in a coherent view. Thus far, the experiments have demonstrated that rapid iteration of the user interface and data models is possible with modern tools, and this results in highly engaged stakeholders. Such an approach could help managers empower designers to act without seeking approval for every decision. Further development of more sophisticated models and interfaces is needed to validate the method in actual industrial cases.

4.4.3 CONTRIBUTION TO THE THESIS

This paper provides an investigation of the means to implement upcoming design studies and is aimed at validating the implementation of the method in a computer platform. The exploration of web-based technologies has led to valuable insights regarding development time, learning curves, and potential technology stacks. Therefore, this effort serves as a useful pathfinder for research.

5 FINDINGS

This chapter 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 first findings from the studies carried out for this thesis identify what drives the need of considering flexibility for future product platforms and what challenges firms encounter. Subsequent insights concern trade-offs between flexibility and constraints and the methodological implications of balancing such trade-offs. Finally, results regarding proposed approaches to operationalization and tool implementation are presented.

Firms and practitioners in the automotive sector encounter some challenges that impede the implementation of product platforms capable of addressing uncertain changes. These challenges were identified in Paper A and can be grouped and categorized in different ways, such as the origin of the threat (i.e., internal or external to the firm), or its prevalence in different industries (i.e., specific to the automotive sector or not). A more interesting categorization might consider common mitigation strategies, as the same approach could alleviate the effects of several challenges at once. For example, improving the interdisciplinary discussion of flexibility via coordinative artifacts (i.e., sketches, assembly drawings, prototypes, or computer simulations used for design communication [Schmidt and Wagner, 2002]) for flexibility could address "interface management", "production integration", "lack of models to assess early decisions", "change propagation", and other challenges simultaneously.

The following sections explore some of these mitigation strategies that can address several challenges effectively.

5.1 THE NEED AND VALUE OF FLEXIBILITY FOR EFFECTIVE TECHNOLOGY INTRODUCTION

In Papers A and C, the need for flexibility for effective technology introduction was explored, and evidence was gathered empirically. Having a flexible platform is the most promising way to overcome most of the challenges discussed in the previous section.

Customers in the automotive sector are placing increased demands on product functionality, performance, and environmental efficiency, and regulatory requirements are expected to continue to raise the standards for energy consumption and safety in the coming years (Bielaczyc and Woodburn, 2019). At the same time, ground-breaking technologies (e.g., digitalization [Llopis-Albert *et al.*, 2021], electrification [Lequesne, 2015] and automation [Siroki *et al.*, 2019]) are maturing and are expected to be integrated into products to meet such increased demands from customers and society. These changes in markets, regulations, and technology introduce uncertainties that demand automotive product platforms be designed with flexibility in mind.

These insights lead to the development of the working definition of the flexibility of a platform presented in this thesis: *a platform is considered more flexible (or to have more "valuable flexibility") when it allows for more alternative designs (including using new technologies) of higher value*.

This definition is crucial to this work because it provides a path to the quantification of flexibility (the number and value of the designs allowed by the platform constraints), which can be achieved using existing information within the firm.

5.2 PRODUCT PLATFORM CONSTRAINTS: LIMITATIONS TO FLEXIBILITY IN PRODUCT PLATFORM DESIGN

Constraints determine the bandwidth of the product platform parameters (De Weck *et al.*, 2003). In other words, there are limits to what can be achieved with the platform. This is important to consider when designing and developing a product platform, as it will help to focus on what is possible and what is not. Paper A and Paper B highlighted how the development of product platforms and derived product variants are constrained by a specific set of aspects.

The research conducted thus far has highlighted two major types of platform constraints:

1. Technology/technically driven constraints: constrains that must be defined due a limitation of the technology or its implementation in the platform (e.g., "performance", "technology maturity").
2. Legislation driven constraints: constraints that limit possibilities of the design due to the requirement of following legal rules of the market where the products are intended to be sold or any other laws that apply on the location of the production system (e.g., "meet environment regulations", "meet labour laws").

The next section will provide two industrial examples highlighting the implications of the constraints of the design for a flexible product platform.

5.2.1 TECHNOLOGY-DRIVEN CONSTRAINTS

A real industrial example of a technology-driven constraint for a platform is highlighted in paper B, where the geometrical constraints imposed by the need of assembling (also known as "packaging" in the automotive sector) all systems within a certain volume limits the performance of some of the systems.

The industrial problem investigated in Paper B was related to the integration of a Head-Up Display (HUD) unit in different automotive platforms. The main challenge for this integration was the packaging of the unit and the components around it, including the Cross Car Beam (CCB), the dashboard with the instrument panel, the braking system including the pedal frame, and the steering column (Figure 5). The geometry of, and the interaction with, the location of the windshield and dashboard opening was also critical to optical path design and performance.

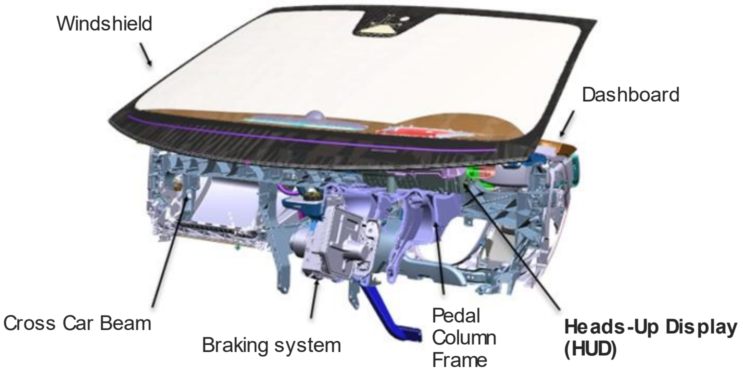


FIGURE 5 HEAD-UP DISPLAY AND ITS SURROUNDING

This case study highlights how the architecture of a product platform introduces constraints on the design of products that can be built on the platform. These constraints may limit the ability to customize or redesign products and may also limit the ability to update or replace components of the product. In the case of the HUD, the performance of the system is intimately linked to space available for the optic system. In other words, it can deliver a larger and more accurate image to the driver if the image source, mirrors, and other components are bigger.

Implication of the technology-driven constraint of this case study on platform decision-making

The implication of the volumetric constraint is that the performance of the system thus needs to be balanced against the space available as well as the performance and cost of the components around the HUD. For example more space could be made available if a different steering system was used, such as a steer-by-wire (SBW) system. Ultimately, the design decision about the performance of all systems needs to take each of these trade-offs into account. A platform with more flexibility enables more options for decisions that must sacrifice less of some dimensions to achieve more overall value.

The development of this case and the decisions taken around the trade-offs mentioned are further expanded upon in section 5.3, where the modelling approach to compare and value the competing interests is presented.

5.2.2 LEGISLATION-DRIVEN CONSTRAINTS: AN INDUSTRIAL CASE

Legislation-driven constraints are constraints that limit possibilities of the design due to the requirement of following the legal rules of the market where the products are intended to be sold or any other laws that apply on the location of the production system.

A case study on an area of a vehicle impacted by legislation-driven constraints was performed at a trucks manufacturer. The Lower Front (LF) area of the cab (see Figure 6) is where several structural and functional systems are situated, specifically in the bottom of the front face of the truck. In this area, the Front Underrun Protection (FUP), head lights, air grill, sensors, and other systems for the maintenance of the truck are located.

FIGURE 6 LOWER FRONT AREA (HIGHLIGHTED IN RED) OF A TRUCK CAB

The regulations that most constrain the development of product platforms in the automotive sector, and in particular the commercial trucks segment, are those related to environmental issues and safety concerns:

- Environmental regulations: more stringent rules about fuel consumption require manufacturers to optimize the aerodynamic shape of the truck body, and other regulations aimed at the protection of the environment limit the use of certain materials and processes (because of limitations on both the use of raw materials themselves and the carbon footprint of some processes).
- Safety regulations: requirements on the safety of not only the drivers and passengers of vehicles but also that of other road users greatly affect the design of large and heavy trucks, specifically regarding lateral impacts and the possible under-run of smaller vehicles below the truck.

Implication of the legislation-driven constraint of this case study on platform decision-making

The example of the lower front showcases a situation where the regulatory changes (or expected changes) mentioned drive the need for introducing new technologies into an existing platform. This need is presented with accompanying trade-offs regarding cost and the maintenance of a multi-brand strategy. The costs incurred from such a change were mostly attributable to the need for changing production setup and tooling, as well as the additional materials required for new components.

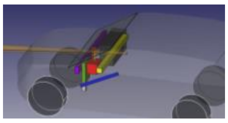
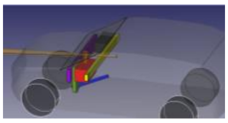
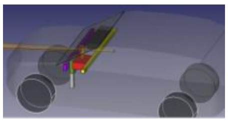
A more insidious issue is the maintenance of a multi-brand strategy based on the same product platform. This strategy aims at delivering a differentiated set of products to different markets and niches by tying the performance level and price of the products to different brands. This sets the bar for greater visual and functional differentiation than when the products are marketed under the same brand.

The design decision central to this case is how much commonality is too much in a global platform, particularly if the goal is to deliver functionally and visually distinct products with varied price points. In other words, how much flexibility needs to be built into the platform? The current approach was found to be heavily driven by the engineering of costs and the concerns of internal stakeholders regarding production issues. Again, a more flexible platform enables a larger number of valuable options to be selected.

5.3 TRADING OFF BETWEEN FLEXIBILITY AND PRODUCT PLATFORM CONSTRAINTS FOR EFFECTIVE TECHNOLOGY INTRODUCTION

The two case studies presented above highlight the importance of platform flexibility when questioning the introduction of changes to the architecture that challenge platform constraints. To quantify and analyse this issue in depth, Paper B considers three product platform alternatives (see Table 3).

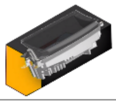
TABLE 3 PLATFORM ALTERNATIVES

Platform	CAD of surrounding components	Relevant geometrical constraints
Platform A: Current High maturity		Length <300mm Width <300mm Height <200mm
Platform B: Under development Medium - High maturity		Length <400mm Width <300mm Height <200mm
Platform C: Conceptual Low maturity		Length <300mm Width <300mm Height <100mm

The first alternative (Platform A) is currently in production and, thus, it is a highly mature alternative with fewer degrees of freedom available. However, its costs are understood well and somewhat optimized, and it provides a modest volume for the HUD. The second alternative (Platform B) is currently under development, and it is an evolution of the first, but more space has been allocated for the HUD to allow for greater performance. Finally, the third option (Platform C) is a conceptual design that might prioritize other systems in the car and rely on the improvements of alternative technologies to fulfil the HUD functions.

Three alternative technologies are also considered in this study (see Table 4). The first technological alternative considered is a second-generation HUD, which is characterised by moderate size and cost and high technology maturity but low performance in the selected figures-of-merit (image size, Field of View [FoV], and distance to image). The second alternative, a more modern but still second-generation option, is the Augmented Reality (AR) HUD. This alternative improves on the weak performance of the first option while using similar underlying components, but it does so by dramatically increasing the size of the unit (as well as the cost). The third alternative is a third-generation HUD, specifically a Holographic Waveguide AR-HUD. This technology is less mature than the previous alternatives, and it promises to combine high performance with low volume, albeit at a high cost.

TABLE 4 ALTERNATIVE TECHNOLOGIES

Technology	Typical Volume (litres)	Image size	FoV (degrees)	Distance to image (m)	Current Maturity (TRL)	Cost
(2G) HUD 	*~7 litre*	*Small*	*H: [5, 10]* *V: [2, 4]*	*[1, 5]*	*TRL 9*	*Moderate*
(2G) AR-HUD 	*~15 litre*	*Medium*	*H: [7, 15]* *V: [3, 7]*	*[5, 20]*	*TRL 9*	*High*
(3G) Holographic Waveguide AR-HUD 	*~4 litre*	*Medium*	*H: [10, 20]* *V: [4, 10]*	*[1, 30]*	*TRL 7-8*	*High*

With the alternative platforms and technologies specified, the next step is to measure the flexibility of those platforms ion the context of several potential scenarios.

5.3.1 Measuring Flexibility: Adapting Value-Weighted Filtered Outdegree to the Context of Flexibility-Constrained Product Platforms

The VWFO metric was deemed a suitable starting point for quantifying flexibility in the context of product platforms. Reasons for this assessment were that it is firmly based around Systems Engineering (SE) principles and includes a temporal dimension with changes in requirements over time.

Some modifications were added to better represent a more holistic business perspective of product platforms. Epochs ("a time period of fixed context and expectations") and eras ("a time-ordered series of epochs") were replaced for the concept of scenarios. In this case, the continuous changing of boundary conditions is the input parameter that in turn might alter, for example, the customers' preferences. Last, the original "utility" concept as an expression of the preference of experts and managers was replaced by the Surplus Value (SV) metric proposed in VDD (Collopy, 1996). SV is a simplified equation for a Net

Present Value analysis (NPV), which is a concept typically used by economists as a basis for businesses investment decisions (Vanhoucke *et al.*, 2003).

The detailed definition of the modified VWFO metric is as follows:

$$VWFO_i^k = \frac{1}{N-1}\sum_{j=1}^{N-1}\left[sign\left(SV_j^{k+1} - SV_i^{k+1}\right) * Arc_{i,j}^k\right]$$

where

N is the number of designs considered
k is the current scenario
$k+1$ is the following scenario
i is the design under consideration
j is the destination design
SV_i^{k+1} is the Surplus Value of design i in the $k+1$ scenario
SV_j^{k+1} is the Surplus Value of design j in the $k+1$ scenario
$Arc_{i,j}^k$ is the transition matrix with local value indicating an arc from design i to design j in scenario k

Therefore, this metric proposes that the benefit of a more flexible platform is the ability to transition to a set of designs with higher value over a set of uncertain scenarios given the platform constraints.

5.3.2 UNDER-CONSTRAINED, OVER-CONSTRAINED, AND BALANCED PRODUCT PLATFORMS

The method described in Paper B used the inputs listed in the previous section to model the product platforms in a series of future scenarios. Using the metric mentioned above (modified VWFO), the flexibility of a simulated number of designs for each of the platforms was calculated and plotted in Figure 7, specifically for the designs that were compliant with the platforms' constraints. The simulated designs were generated by a Design of Experiments (DOE) algorithm, which traversed each of the design parameters to generate unique combinations.

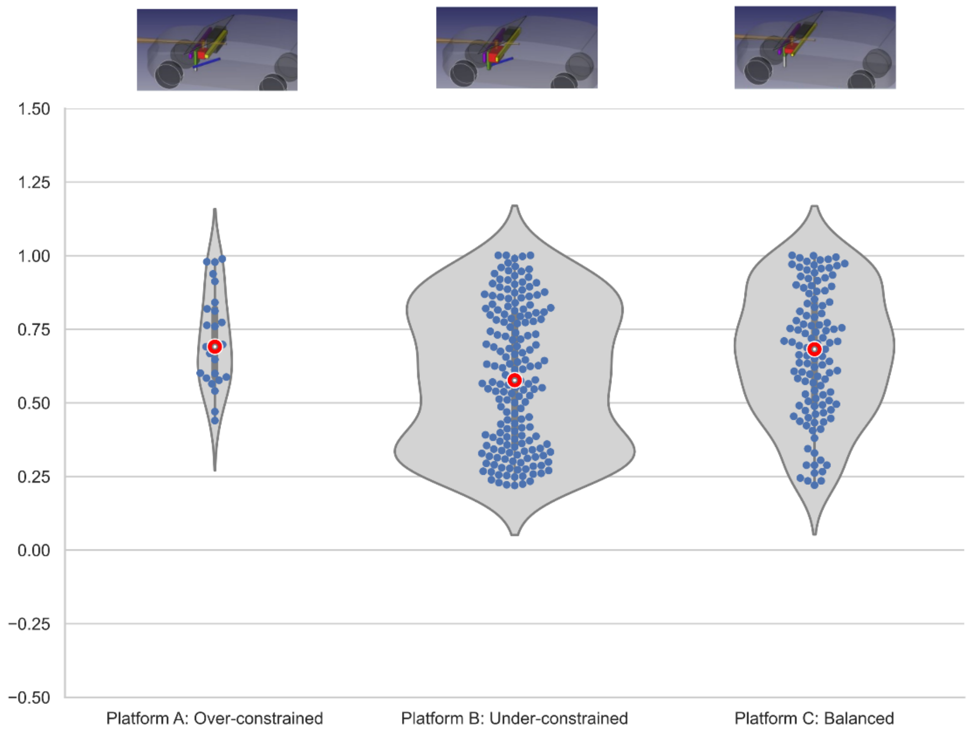


FIGURE 7 FLEXIBILITY FOR ALL PLATFORM-COMPATIBLE DESIGNS

The study (see Figure 7) highlighted how Platform A had a relatively high overall flexibility value (see Table 5), but it enabled a very small number of design alternatives (each represented by a dot in the figure) due to its overly constraining limitations. Conversely, Platform B enabled a relatively large number of alternative designs, but their overall flexibility value was smaller. Under-constraining the platform caused, in this case, a waste of the reserved space, which impacted the options of neighbouring components to utilize that space. Last, Platform C illustrated that with a balanced delimitation of the constraints, a high flexibility value could be achieved without restricting the freedom of defining a wide variety of alternative designs.

TABLE 5 MEDIAN FLEXIBILITY VALUES FOR EACH PLATFORM

Platform	Median flexibility (modified VWFO)
Platform A (Over-constrained)	0,6826
Platform B (Under-constrained)	0,5593
Platform C (Balanced)	0,7030

Thus, the platform with the **most valuable flexibility** was Platform C, as it balanced its flexibility with the associated cost by limiting waste related to reserving space for options that are not realized while delivering the same functionality and performance levels.

These results suggest that working with a metric like the value weighted filtered outdegree, combined with a constraint-based modelling approach, can support decision-making regarding the most valuable flexible platform. This way of working responds to the needs of platform architects in early design stages to make trade-offs between flexibility and product platform constraints. Flexibility for the sake of flexibility wastes value if the constraints the platform imposes on derived variants have not been carefully chosen.

5.4 TOWARDS A METHODOLOGY FOR TRADING OFF BETWEEN FLEXIBILITY AND PLATFORM CONSTRAINTS

The steps of the proposed method used to arrive at the results presented in section 5.4 are developed in detail in Paper B, but a summary is presented in Table 6. Inputs to the method include the stakeholders' expectations, existing technology roadmaps, and market and cost data. The intended outputs are decisions on the design bandwidth of the platform based on a balanced level of flexibility versus constraints.

TABLE 6 SUMMARY OF THE STEPS OF THE METHODOLOGY

Step	Description
1) Strategy and technological definition	
1.1) Identify key product properties	**Inputs**: Stakeholder expectations The expectations and needs of customers, users, and other stakeholders can be generally divided into two main categories: functional properties (i.e., what functions the product performs), and non-functional properties (e.g., the reliability, efficiency, manufacturability, or recyclability of the products). These are dependent on the design parameters or characteristics of the product. **Outputs**: Key product properties
1.2) Define future scenarios	**Inputs**: Stakeholder expectations and key product properties Each scenario is characterized by the values over time of a set of variables regarding the status of the environment around the product platform and a set of design decisions made on the product platform that determine a set of design parameters over time. **Outputs**: Scenarios
1.3) Identify platform alternatives and constraints	Each platform alternative is characterized by its structure (i.e., its constituents and their relationships) and its

Step	Description
	bandwidth for a set of parameters, both of individual components and the whole system. **Outputs**: Platform alternatives
1.4) Identify technology alternatives	**Inputs**: Technology roadmaps Technology roadmaps identify potential technologies for a given function and characterize them by a set of attributes (e.g., cost, maturity, etc.) and performance levels. **Outputs**: Technology alternatives
2) Modelling	
2.1) Create performance models	**Inputs**: Technology alternatives Each of the design solutions considered above might be the result of the application of a different technology to provide a potential solution to the technical need. In this step, the relationship of the performance in terms of the key product properties (or intermediate properties) of the alternative technologies need to be expressed in terms of their design parameters. **Outputs**: Technology performance models
2.2) Create parametric platform architecture models	**Inputs**: Platform alternatives Low-resolution three-dimensional models of the space allocations for each of the design solutions positioned within the constraints of the platform can then be generated as coordinative artifacts to aid in multidisciplinary discussions. **Outputs**: Platform architecture models
2.3) Create value and cost models	**Inputs**: Technology performance and platform architecture models The models of the platforms and technologies are combined to link their performance and extensive attributes to the fulfilment of the stakeholder expectations and production platform costs. **Outputs**: Value and cost models
3) Evaluation	
3.1) Evaluate flexibility metric on scenarios and value model	**Inputs**: Scenarios and value and cost models The Value Weighted Filtered Outdegree (VWFO) metric assumes that the value of a more flexible platform is the ability to transition to a technology with the highest value over a set of uncertain scenarios given its geometrical constraints. **Outputs**: Platforms flexibility
3.2) Decision support regarding platform bandwidth	**Inputs**: Platform's flexibility The results of a Monte Carlo simulation of several designs for each considered platform are presented. Optionally,

Step	Description
	the possibility of interacting with the models, parameters, and input values would support decision makers in allocating the platform bandwidth. **Outputs**: Decisions on the desired bandwidth of the selected platform

The summary presented here is expanded and linked to the industrial case study in Paper B, which includes a flowchart of the method steps and their inputs and outputs.

5.5 TOWARDS DEFINING DESIGN PRINCIPLES FOR MORE FLEXIBLE PLATFORMS

In Paper C, the concept of resilient flexibility objects was explored.

A resilient object can be defined as the part of a product that can absorb change while in use. They should be placed in regions of the product architecture that are most affected by change and where they can effectively interrupt the chain of change propagation among interconnected components.

The design of these objects was proposed to implement flexibility into product platforms. It was found that, by decoupling the flexibility aspect from the platform as a whole and embodying it in predetermined objects within the regions where most value could be derived, different types of changes from uncertain situations could be dealt with without the need to change the structure or configuration of the product platform. An example is provided in Figure 8, where two platforms are depicted, both with and without a resilient object. As the requirements on the system change over time (from scenario a to b, where a new axial force is introduced, and to scenario c, where the torque requirement is updated and a new motor is needed to fulfil the requirement), the platform with the resilient object can maintain its structure and minimize re-engineering costs and scrap wastes.

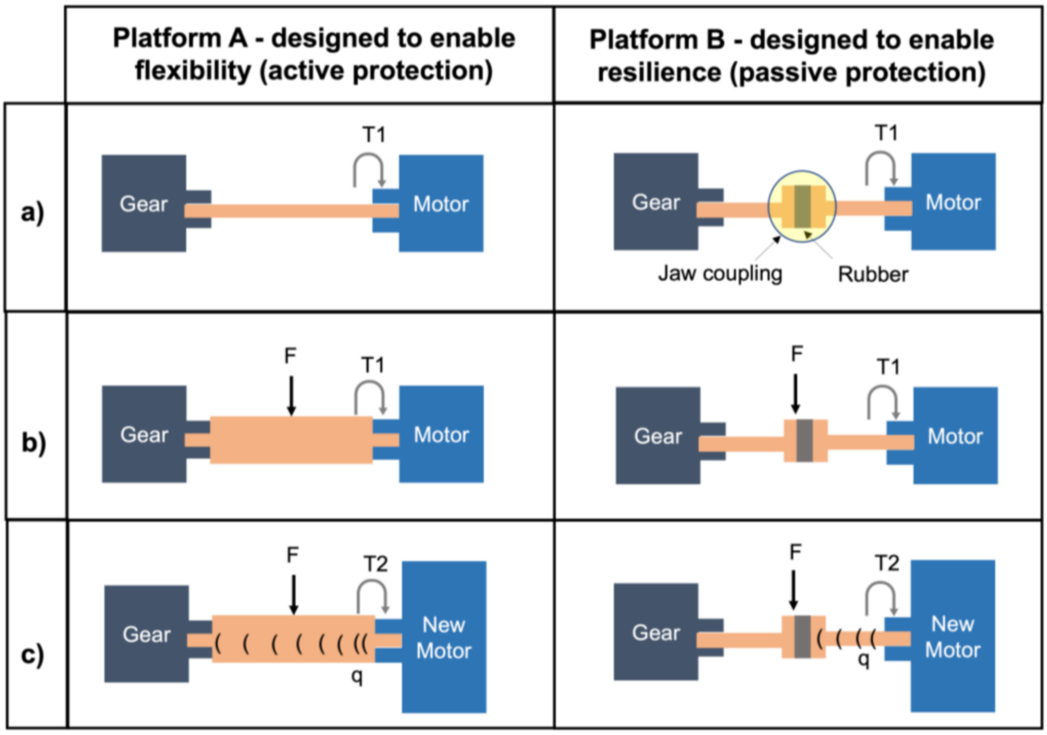


FIGURE 8 COMPARISON BETWEEN A PRODUCT PLATFORM DESIGNED TO ENABLE FLEXIBILITY (ACTIVE PROTECTION AGAINST UNCERTAINTY) AND A PRODUCT PLATFORM DESIGNED TO ENABLE RESILIENCE (PASSIVE PROTECTION AGAINST UNCERTAINTY) USING A JAW COUPLING AS 'RESILIENT OBJECT'.

These stand-alone components ("resilient design objects") that embody resilience are introduced in the regions of the product platform that are likely to be most affected by changes, as determined, for example, by Change Propagation Algorithms (CPA, Clarkson *et al.*, 2004). Utilising a value model capable of evaluating the lifecycle value of different resilient object options could be helpful and effective in deciding which resilient object to choose, beyond specific performances and costs.

Future work in this area will focus on extending and classifying a catalogue of multi-technological resilient objects. It will also be concerned with defining a systematic method to design, select, and evaluate which resilient objects are more valuable to be inserted in specific regions of the product platform.

5.6 USING CONSTRAINT OBJECTS AND FLEXIBILITY METRICS AS COORDINATIVE ARTEFACTS FOR EFFECTIVE PRODUCT PLATFORM DECISIONS

Value models have been described to foster cross-boundary discussions in design when used as coordinative artefacts (Panarotto and Johansson, 2019). They increase the ability to systematically represent intangible objectives in the description for a system and support design decision making.

Proposing a new theoretical method on its own does not result in the industry adopting it directly from the literature. A strategy for implementing of a tool embodying the method and presenting a usable DSS is required for the adequate validation, dissemination, and exploitation of the proposed method.

In Paper D, a study was conducted regarding the implementation of such a tool. Tool development was used to investigate both technological and social aspects of the prospective methodology. Subsequently, an experiment was conducted with many concurrent users to validate the development decisions and social aspects of the system.

The tool was model based, with the models themselves defined offline (before the tool was used) and then running as a web app on the user client. The quantitative models included in the tool were related to product architecture (e.g., different geometries and features), engineering performance of the product (e.g., weight, handling in different conditions), product value (e.g., different functionality levels depending on customer experience), manufacturing cost (including both fixed and variable costs), and sustainability of the product (i.e., a lifecycle CO_2 emissions model).

The data used by the application were stored in an online real-time database; therefore, all clients had instant access to the latest data committed to the database. This synchronisation enabled interactivity between users through the tool. The modelling of the data was kept constraint-free by using a NoSQL database. In particular, a document database without a predefined schema was used. This decision enabled a very rapid iteration cycle during the development of the tool. However, the downside of this approach is the potentially more difficult path to real-world implementation due to lack of API stability, and more difficult testing and documentation production.

The tool client itself was implemented as a Single Page Application (SPA), a modern means of building web applications that provide effective interaction options via reactive components. This architecture was found to enable a pleasant development experience and a level of interactivity for users that they expect from modern web applications.

Early design decisions for a platform can have a large impact on the parameters of the final product. For example, if it is decided to make a platform that is easy to use and accessible to everyone, it may be necessary to compromise features or functionality.

Alternatively, if it is decided to focus on developing powerful features and neglecting ease of use, the product platform may be difficult for some users to navigate. It is important to make these decisions thoughtfully to meet the goals of both internal and external stakeholders, such as the users of the products. To support these decisions for a given platform, each scenario has parameters (costs, regulations, etc.) that are inputs to the models and can be modified by the users. The costs, regulations, and other factors vary by scenario. Therefore, it is important to understand how each scenario can evolve differently based on these input variables.

The tool embodies a simple product configurator as an effective proxy for decision support systems. Utilizing the inputs of the users and predefined models, a simulation of the product attributes was calculated and visualised for the users. With this information, users were able to tweak the design inputs and obtain instant feedback on the impact of these changes on the attributes of the product. The users could then make the decision to proceed and commit it to the database, or not.

It was found that constrained objects within a product architecture coupled with a flexibility metric can be an effective coordinative artefact used by concurrent users to explore the product platform design space. Furthermore, the trade-offs made to define a balanced level of constraints maximize the valuable flexibility of the platform architecture.

6 DISCUSSION

This chapter uses the results and findings from previous chapters to discuss the research problem and answer the research questions. Further discussion is provided regarding the novelty of the findings compared to the current state of the art, research quality, validation of the results, and the scientific and industrial contributions made by this licentiate thesis.

The research problem was expressed in chapter 1 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, this thesis endeavoured to answer the questions posed in section 1.4.

6.1 ANSWERING RESEARCH QUESTION 1

RQ1 *What are the challenges of designing flexible product platforms that can efficiently integrate new technologies?*

Designing a product platform entails defining sensible constraints that lead to valuable future product variants. Over-constraining the platform would lead to the impossibility of efficient derivation of new products using certain new technologies. Under-constraining it would lead to waste of materials, underperformance, and reduced benefits from platforming. Knowing what design decisions lead to more **valuable flexibility** of the product platform is the key challenge. The ability to quantify and objectively visualise the impact on both value and cost of the introduction of new technologies in decision situations is vital. Paper A also demonstrated that several of these decisions rely on "in context" arguments and support evidence of mixed quality. Introducing a modelling assisted methodology can equalize the different perspectives and focus the effort on developing the sources of the data needed for modelling. This is a major step forward for prompting a change process.

6.2 ANSWERING RESEARCH QUESTION 2

RQ2 *How can decisions about the integration of new technologies and flexibility trade-offs in the early phases of platform development be supported by tools and methods for product platform architects?*

Platform designers can be supported by parametric models of the platform architecture and by using those models in conjunction with market, cost, performance, and other models. They can also be aided by a method to evaluate and compare scenarios and strategies that incorporate future uncertainty. Further assistance can be provided by tracking the evolution of those parameters over time so decisions can be adjusted based on the available data. A promising approach to address these decisions in platform development has been proposed that incorporates Set-based Concurrent Engineering (SBCE), functional platform modelling, and change propagation (Raudberget *et al.*, 2015).

6.3 ANSWERING RESEARCH QUESTION 3

RQ3 *How should the value of flexibility in product platforms concerning customer needs and the production system be defined, modelled, and assessed?*

The value of flexibility can be effectively considered by using the VDD approach for the definition of what makes a product platform valuable, modelling the architecture and performance of the alternative technologies considered, and creating a metric (such as the VWFO metric) that provides each alternative product platform a score on how much value it delivers to its stakeholders over its lifecycle.

6.4 SCIENTIFIC CONTRIBUTION

The research approach used for this study allowed for the contribution of realistic case studies as well as novel theoretical approaches to the scientific literature. The results described in Chapter 0 can be interpreted in the context of the academic frame of reference in Chapter 2.

The challenge of managing uncertainty in the HUD case study is analogous to the use of "management by uncertainty" for propagating uncertainties in and between the product and organizational domains and the evolution of their architectures in an automotive project (Harmel *et al.*, 2006). In this methodology, a traditional DSM tool was used, and, despite considering the product, process, and evolution of the organisation, the methodology does not provide coverage of all stakeholders as comprehensively as the VDD approach.

The importance of a sophisticated and well-understood architecture for the product platform leads to the importance of well-defined interfaces, and, moreover, a shared interpretation of the definition of an interface (Parslov and Mortensen, 2015). This was shown to be especially critical due to its impact on development lead time in multidisciplinary teams, where functions required varied expertise for the selection and development of appropriate technologies.

The development of environmental technologies to fulfil the mandates of new environmental regulations was shown to pose challenges in the identification and commercialization of potential innovations (Clark and Paolucci, 2001). This was corroborated in the LF case study, as regulation-driven constraints led to the redesign of the vehicle architecture. The role of suppliers in solving these challenges is sizeable but requires further investigation.

The management of both product and process variety, and the trade-off between them, has been explored from the perspective of mass customization (Daaboul *et al.*, 2011). The aforementioned study even considered the value derived to be an effective measure and provided a case study in the shoe industry. However, the method used lacks any validation in more complex products: as is the case in most model-based methods in the literature, the focus is on single products and not larger product platforms.

A recent study combined VDD and "traditional" multidisciplinary design optimization (MDO) to examine an industrial case (Jung *et al.*, 2021). It solved the problem of maximizing the net present value (NPV) for a firm producing a family of washing machines. The limitation of this approach, which this thesis attempts to overcome, is the lack of consideration for future potential members of the product family that will incorporate new technologies. If the product platform is not flexible enough to derive those efficiently, the lifetime value obtained from the product platform will not be maximized. The proposed concept of valuable flexibility is the key to the future-proof design of product families.

6.5 INDUSTRIAL CONTRIBUTION

The problem of how to best use product platform to integrate new technologies is considered by the industry, and it is reflected in the importance given to the discussion and collaboration around the architecture of products at companies. However, this top-down concern has been shown to cause friction and conflict when inherited by domain experts and component designers. Factors that contribute to this status are descriptions of architectures not being widely shared, lack of quantification of uncertainty, and difficulty in bringing a balanced and comprehensive picture for decision makers to base their choices on.

A significant source of constraints is the firm itself and how it is organized. The culture and values of the firm will dictate how the prioritization of different stakeholders' needs is conducted and how various trade-offs are then resolved. The competencies of the individuals involved with product platform development also play a large role. Those that constrain platform development the most are not related to discipline knowledge, as it was found that all stakeholders were experts in their field, but rather the ones concerned with systems thinking and holistic value considerations. Additionally, the physical location of teams who need to interact across different geographical sites also constrained the development of the product platform (e.g., due to Conway's Law [Conway, 1968]).

One of the additional constraints faced by the implementers is the need to meet certain time-to-market goals. The management of associated assets and costs is another of the main constraints identified, including development costs as well as existing production processes and components already designed and in production (either in-house, subcontracted, or off-the-shelf).

The contribution of this study, beyond recognizing and disseminating existing challenges, is to facilitate the resolution of a trade-off between flexibility benefits and product platform constraints.

6.6 VALIDITY AND TRANSFERABILITY OF RESULTS

As most of the studies summarized in this thesis were qualitative, an assessment of their research quality in terms of transferability, credibility, dependability, and conclusions confirmability is necessary.

Regarding the transferability of the results, the studies were conducted with two large global automotive OEMs. The descriptive findings are considered transferable to similar firms. However, when transferring the proposed methodology to other contexts, product type and the user must be examined, among other factors. The transferability of the VISP approach should be further analysed with other automotive OEMs and in additional industries.

No major threats to credibility were found. The participants were able to review the conclusions from workshops and interviews, which reduced the possibility of misinterpretation or error. However, not all proposed methodologies were discussed with all first-phase participants before publication.

A potential threat to the confirmability of the results is that a single researcher planned, conducted, and analysed most of the studies. However, the researcher was assisted by two more senior researchers in every phase of the study, and abundant opportunities for reflection among other researchers in the same field were available.

Threats to the dependability of these studies includes the analysed companies not being chosen randomly but rather by convenience sampling. However, an open-ended interview method was used in which new participants were recruited after interviewing the previous one to increase variation in the sample.

7 CONCLUSIONS AND FUTURE WORK

This final chapter summarizes the previous chapters of this thesis, providing final remarks on the research questions and outlining possible future work to be pursued.

7.1 CONCLUSIONS

This licentiate thesis has focused on understanding how companies trade value and cost when considering technologies to integrate into their product platforms. It has demonstrated how considering the flexibility of a product platform from its design phase is an important factor in maximizing the overall value that can be obtained from the platform by deriving product variants from it that introduce new technologies.

The first research question concerned the challenges of designing product platforms that are sustainable by being flexible to integrate new technologies. It was found that a gap existed in the state of the art regarding the prescription of methods and tools that could be implemented in an industrial setting. Thus, a state-of-the-practice gap also existed between the latest ideas and proposals in the academic realm and the reality in the industrial sector.

The second research question considered the support available during the early phases of platform design and how that support was embodied. This study highlighted how difficulties communicating between different disciplines and the irregular levels at which each of the disciplines operates concerning the use of models and other coordinative artefacts inhibit rational discussion when presenting options to decision-makers. Furthermore, the management of uncertainty was not found to be standardized or systematically handled. Tracking the outcomes of decisions once better information was made available was also lacking. Therefore, the development of model-based methods and tools that take all these considerations into account was suggested. In particular, the development of a methodology that uses the flexibility of the platform as a key metric to assess the impact of the introduction of new technologies was proposed.

The third research question was primarily concerned, with studying ways of measuring and utilising flexibility in operational terms. After careful consideration, the Value Weighted Filtered Outdegree (VWFO) metric (Viscito and Ross, 2009) was selected as the most appropriate thus far for dealing with both uncertainty and using the concept of value from the VDD methodology. In Paper B, this choice was expanded upon and used in a case study.

The results indicate that the academic state of the art is not only ahead of the industrial state of practice but also diverges as increasing numbers of case studies are presented without a path forward from the theory behind their interventions into generalized tool implementation. Even if such tools would nevertheless need to be customized to certain industries or the specific operations of individual firms, a common (and even "platform-based") approach to the development of these tools would greatly support the work of platform architects as well as the efforts of instructors of both current practitioners and those still in the education system.

The findings of this thesis will help advance the field of product platform design, contribute to the development of more effective product platforms and thus the generation of more valuable products.

7.2 FUTURE WORK

In the remainder phase of the research culminating on a PhD thesis, the following research challenges will be addressed in more depth:

- The study of the production platform (i.e., the collection of production equipment, interfaces, processes, and knowledge from which production systems and their constituent elements can be efficiently derived and developed [Sorensen *et al.*, 2018]) and its characteristics will enhance the relevance of the trade-offs that can be studied by using the proposed methodology as well as cost modelling activities. Concerns such as optimizing the layout of the production facilities (Reisinger *et al.*, 2022), identifying production platform candidates (Sorensen *et al.*, 2020), and integrating product and platform platforms (Siiskonen, 2019) will be further studied for their incorporation into the methodology and validation case studies.
- Incorporation of the impact of sustainability considerations into the methodology, as an important factor to trade-off against value, cost, and flexibility. This is likely to be an area of concern for several more years and cannot be expected to be solved withing the present research study, but a first mechanism for the introduction of, for example, already defined sustainability criteria (Hallstedt, 2017) will be introduced.
- The development of both software tools implementing the methods proposed for the methodology and ways to validate them. A potentially straightforward way to proceed is to use the Solomon four-group design method, which is a robust method for assessing interventions.

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9 APPENDICES

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

Paper B Trade-off Analysis of Flexible Product Platform Architectures subject to Rapid Technology Introductions

Paper C Designing Multi-Technological Resilient Objects in Product Platforms

Paper D Interactive model-based decision-making tools in early product platform design