Products Design Organizations: How Industrial-Aged Companies Accomplish Digital Product Innovation

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Submitting this Ph.D. thesis is typically considered an individual achievement. However, in this particular instance, it is essential to acknowledge the tremendous support I have received, without which this thesis would not have been possible.

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ABSTRACT

The automotive industry is a prime example of digital technologies reshaping mobility. Connected, autonomous, shared, and electric (CASE) trends lead to new emerging players that threaten existing industrial-aged companies. To respond, incumbents need to bridge the gap between contrasting product architecture and organizational principles in the physical and digital realms. Over-the-air (OTA) technology, that enables seamless software updates and on-demand feature additions for customers, is an example of CASE-driven digital product innovation. Through an extensive longitudinal case study of an OTA initiative by an industrial-aged automaker, this dissertation explores how incumbents accomplish digital product innovation. Building on modularity, liminality, and the mirroring hypothesis, it presents a process model that explains the triggers, mechanisms, and outcomes of this process. In contrast to the literature, the findings emphasize the primacy of addressing product architecture challenges over organizational ones and highlight the managerial implications for success.

ZUSAMMENFASSUNG

Digitale Technologien bieten neue Möglichkeiten zur Wertschöpfung und führen zur Entstehung neuer Marktteilnehmer. Dies stellt etablierte Industrieunternehmen vor existenzbedrohende Herausforderungen. Diese müssen neue digitale Produkte entwickeln, die neben physischen Komponenten auch digitale Komponenten enthalten. Um digitale Produktinnovation zu erreichen, müssen Unternehmen des industriellen Zeitalters die Kluft zwischen unterschiedlichen Produktarchitektur- und Organisationsprinzipien in der physischen und digitalen Welt überbrücken. Diese Herausforderung ist insbesondere in der Automobilbranche relevant, wo CASE-Technologien (Connected, Autonomous, Shared und Electric) die Mobilitätslandschaft neugestalten. Ein Beispiel für durch CASE getriebene digitale Produktinnovation ist die Over-the-Air (OTA)-Technologie, die nahtlose Software-Updates und bedarfsgesteuerte Funktionserweiterungen für Kunden ermöglicht. In einer umfassenden Fallstudie zu einer OTA-Initiative eines etablierten Automobilherstellers aus dem industriellen Zeitalter erforscht diese Dissertation, wie diese Organisationen digitale Produktinnovationen umsetzen. Aufbauend auf Theorien der Modularität, Liminalität und der Spiegelungshypothese wird ein theoretisches Prozessmodell vorgestellt, das die Auslöser, Mechanismen und Ergebnisse eines solchen Prozesses erklärt. Im Gegensatz zur Literatur betonen die Ergebnisse, dass die Bewältigung der Herausforderungen der Produktarchitektur Vorrang vor den organisatorischen Herausforderungen hat, und heben die Auswirkungen auf das Management für den Erfolg hervor.

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LIST OF ABBREVIATIONS

API	Application Programming Interface
ART	Agile Release Train
CASE	Connected, Autonomous, Shared and Electric
ECU	Electronic Control Unit
e.g.	exempli gratia (Latin) – for the sake of example
et al.	et alia (Latin) – and others
EV	Electric Vehicle
EU	European Union
FoD	Function on Demand
FOTA	Firmware Over-the-Air
GDP	Gross Domestic Product
HPC	High-Performance Computer
ICAS	In Car Application Server
IS	Information Systems
IT	Information Technology
KEFAG	Karosserie, Elektrik, Fahrwerk, Antrieb, Gesamtfahrzeug (German)
IBM	Infotainment Backend Module
IIM	Infotainment In-Car Module
ODX	Open Diagnostic Data Exchange Standard
OEM	Original Equipment Manufacturer
OTA	Over-the-Air
OTA FC	Over-the-Air Functional Controller
PEP	Produktentwicklungsprozess (German)
RQ	Research Question
SAFe	Scaled Agile Framework
SOP	Start of Production (Date)
SOTA	Software Over-the-Air
Tbd.	To be detailed
UNECE	United Nations Economic Commission for Europe
VR	Verbundrelease (German)

1 INTRODUCTION

The automotive industry is a vital sector, contributing nearly 7% to the Gross Domestic Product (GDP) of the European Union (EU), employing approximately 6% of the EU workforce, and accounting for roughly 30% of the EU's research and development expenditure (Cornet et al., 2023). In the aftermath of World War II, European original equipment manufacturers (OEMs) like BMW, Audi, Volkswagen (VW), Volvo, Mercedes Benz, and Renault, along with more than 17,300 associated companies, formed an automotive value creation ecosystem that played a pivotal role in shaping the prosperity of an entire continent (Cornet et al., 2023).

However, the landscape is undergoing a profound transformation with the emergence of CASE technologies - representing **c**onnected, **a**utonomous, **s**hared, and **e**lectric vehicle innovations - that are redefining mobility (Ketter et al., 2022; The Economist, 2023a; Tominaga et al., 2023).

Vehicles are evolving into software-defined entities (Koster et al., 2021), and new market entrants, both from within the traditional automotive sector (Tesla, Nio, Geely, BYD) and outside (Waymo, Apple), are challenging established OEMs (Tominaga et al., 2023). These changes are also reshaping the economic power dynamics between nations, exemplified by China's 2022 exports of 3 million light vehicles surpassing Germany's 2.6 million for the first time in history (Cornet et al., 2023).

This shift has not gone unnoticed and has been widely labeled the “race to reinvent the car” (The Economist, 2022). Newspapers even compared VW to the famous Nokia story, raising the question, “What if Germany stopped making cars?” (The Economist, 2023b).

In response, established OEMs recognize the imperative of digital product innovation - integrating digital and physical elements to create novel products (Yoo et al., 2010). Former Volkswagen Group CEO Herbert Diess emphasized this in an internal town hall meeting, stating, “The car will be the most complex tech product in the world! If we don't build it, others will” (Appendix 8.2. - External Source 15).

Thus, the Volkswagen Group has embarked on a journey toward digital product innovation, introducing a new car architecture across its various brands. Through its subsidiary, CARIAD (CAR - I AM DIGITAL), which boasts over 5,000 employees, the company seeks to bolster its software capabilities and maintain competitiveness (Volkswagen, 2022). Nonetheless, as illustrated by CARIAD's experiences, realizing such initiatives is fraught with challenges with software delivery delays causing ripple effects in car deliveries worldwide (Menzel et al., 2022). These difficulties are not unique to Volkswagen, as a study by the Boston Consulting Group suggests that up to 70% of similar initiatives fail to achieve their intended objectives (Forth et al., 2020).

The challenges faced by traditional industrial-aged companies are fundamentally rooted in their existing product architectures, product development practices, and organizational structures, which were once pivotal to their past success but have now become impediments to harnessing the potential of digital technology (Besson & Rowe, 2012; Kaganer et al., 2023; Sebastian et al., 2023; Vial, 2019).

In contrast to digital-native companies like Google or Apple, which exemplify potential “best practices” in and for digital product innovation, established industrial-aged companies and their executives face a distinct hurdle. While they may comprehend the requisites for success, execution often proves challenging (Forth et al., 2020). With existing customer bases, established products and practices, and brands symbolizing product quality, they often resist abandoning their current approaches in favor of uncertain future innovation endeavors (Besson & Rowe, 2012; Christensen, 2016).

Given the profound economic significance of the automotive industry and the formidable challenges confronting industrial-aged OEMs, understanding *how industrial-aged organizations accomplish digital product innovation* becomes a matter of utmost relevance.

1.1 Motivation and Research Problem

In the past decade, a stream of literature at the intersection of management and information systems has begun to investigate the question of what it takes for industrial-aged organizations to pursue digital product innovation (Appio et al., 2021; Chanias et al., 2019; Hanelt et al., 2020; Hinings et al., 2018; Kaganer et al., 2023; Menz et al., 2021; Oberländer et al., 2021; Piccoli et al., 2022; Ross et al., 2019; Sebastian et al., 2017; Svahn et al., 2017; Vial, 2019; Woerner et al., 2022; Yoo et al., 2010, 2012).

For example, the MIT Center for Information Systems, working with more than 80 incumbents, has identified four different pathways 1) Industrialize, 2) Delight customers first, 3) Alternate focus, like stair steps, and 4) Create a new unit that firms pursue to create value from digital (Woerner et al., 2022). Each of these pathways comes with its own challenges (van der Meulen et al., 2020; Woerner et al., 2022). Regarding the automotive industry, Svahn et al. (2017) describe how the Swedish carmaker Volvo is experiencing four competing concerns around innovation capabilities, innovation focus, innovation collaboration, and innovation governance in an initiative to pursue digital product innovation in the form of a connected car.

The examples illustrate that numerous case studies have been conducted to investigate how industrial-aged companies can pursue digital products and the tensions and challenges that seem to accompany that process (Berente & Yoo, 2012; Danneels & Viaene, 2022; Hylving & Schultze, 2020; Kaganer et al., 2023; Svahn et al., 2017; Wimelius et al., 2021; Woerner et al., 2022).

Different research streams have investigated those tensions, both on the product architecture and organizational levels, trying to explain how established organizations can succeed with digital product innovation.

Digital product innovation relies on combinations of physical and digital components (Yoo et al., 2010). Consequently, literature has investigated the different product architectures required to integrate physical and digital architectures (Hylving & Schultze, 2020; Piccoli et al., 2022; Yoo et al., 2010, 2012). In principle, it is argued here that the layered modular architecture of digital technology stands in sharp contrast to the top-down often highly integrated, and hierarchical product architecture of physical products (Hylving & Schultze, 2020; Yoo et al., 2012, 2010). The layered configuration of digital technology assumes a bottom-up logic in which stable components form the core of the technology stack, whereas components on the application layer are more flexible. Thus, product knowledge can be incomplete as the final product emerges through the generative platform layer that has high generativity and affords different products and services on the application layer (Fürstenau et al., 2023; Hylving & Schultze, 2020). This stands in contrast to the integrated hierarchical product architecture pursued in physical design, as here components with high interdependence become clusters connected through interfaces (Baldwin & Clark, 2000). However, to do this, the product must be fully known before this modularization step (Hylving & Schultze, 2020).

The “layered modular architecture”, a type of hybrid architecture (Yoo et al., 2010) is supposed to resolve this conflict. While the literature has started to investigate how that is pursued in practice and has proposed three transformations necessary to achieve layered modular architecture (Hylving & Schultze, 2020), more evidence and validation are needed to advance the understanding of accomplishing digital product innovation in practice.

Digital product innovation also requires substantial changes in the organizing logic of the firm (Yoo et al., 2012, 2010). In principle, the organizing logic is tied to the product architecture and its characteristics (Baldwin & Clark, 2000). Here a stream of literature advocates to mirror the product architecture within the organizational structures and practices (Burton & Galvin, 2022; Colfer & Baldwin, 2016; MacCormack et al., 2012; Sorkun & Furlan, 2017). Since industrial-aged companies aim to accomplish digital product innovation with different product architectures, they are challenged to combine different product architectures and their organizational implications (Hylving & Schultze, 2020; Lee & Berente, 2012). On the one hand, digital technology affords new ways of organizing and orchestrating resources within and across organizational boundaries to generate value (Hanelt et al., 2020; Vial, 2019; Woerner et al., 2022; Yoo et al., 2012, 2010). On the other hand, organizations consist of well-established inertial routines and institutionalized practices that are hard to change since they result from past path dependencies and have served as vital for past success (Besson & Rowe, 2012; Drechsler et al., 2020; Kaganer et al., 2023; Vial, 2019). To accomplish digital product innovation firms must overcome those tensions and transform their business strategy (Chanias et al., 2019; Menz et al., 2021; Vial, 2019), their organizational structure (Appio et al., 2021; Dremel et al., 2017; Vial, 2019), their product development practices, their budgeting practices (Drechsler et al., 2020; Vial, 2019) and their identity (Wessel et al., 2021).

Thus, it seems that the generativity, editability, and recombinatorial nature of digital technology acts as an impetus for changes fundamentally different in the scope and outcomes of the transformation than in prior IT-enabled contexts (Kaganer et al., 2023; Vial, 2019; Wessel et al., 2021). As a consequence, digital technologies seem to challenge existing assumptions on innovation which requires “reinventing” digital innovation management (Nambisan et al., 2017).

Thus, accomplishing digital product innovation and generating value from recombining digital and physical components requires integrating both different product architecture paradigms as well as completely different organizing logics. This results in the following problem statement as a departure point for the thesis:

The thesis addresses the problem that industrial-aged organizations need to integrate conflicting product architecture logic and their required organizing logic to accomplish digital product innovation.

1.2 Research Questions and Research Goals

To address the given problem statement presented in the previous section, three types of managerial questions, research, and investigative questions were formulated (Emory & Cooper, 1991; Recker, 2021). Whereas the managerial question focused on the audience and the practice impact, the research question focused on the general purpose of the study. The investigative question identifies sub-questions that must be answered to respond to the research question. Since the dissertation pursued a problem-based approach, the managerial question was first introduced, then a research question was derived, and investigative questions were developed to answer the overall research question.

The managerial question was developed based on the researcher's intrinsic motivation based on previous experience in practice, existing literature in the field of information systems (Besson & Rowe, 2012; Vial, 2019; Yoo et al., 2012, 2010), and validated through informal conversations with practitioners:

1. *Managerial Question: How can practitioners deal with organizational inertia and accomplish digital product innovation?*

From this managerial question, an overarching research question was formulated:

2. *Main Research Question: How do industrial-aged organizations accomplish digital product innovation?*

Three investigative research questions were formulated to answer this overarching research question:

3. *Investigate Research Question 1. What is the current body of knowledge regarding organizational inertia in industrial-aged companies?*[1]

4. *Investigative Research Question 2. What are the practices industrial-age organizations pursuing for digital product innovation?*

5. *Investigative Research Question 3. What is the process of how digital product innovation is accomplished in an industrial-age organization?*

The overall research intention is explanatory. The first and the second investigative research questions are descriptive, whereas the third research question is explanatory.

Following Gregor's (2006) taxonomy of theories, research goals were formulated and classified, and a complementary research approach was pursued (Table 1: Research Goals).

The first research goal is to summarize relevant research on the challenges industrial-aged organizations face in pursuing digital product innovation. A

[1] The answer to this research question is not explicitly addressed in this dissertation but is part of a conference paper in which the literature review findings are presented.

literature review was conducted with information systems and management studies to reach that goal.

The second research goal is to analyze organizations' practices to achieve digital product innovation and layered modular architecture. To meet that research goal, an in-depth case study of a digital product innovation initiative of an industrial-aged organization was conducted.

The third research goal is explanatory and attempts to explain the process of accomplishing digital product innovation in an industrial-aged organization. An in-depth single case study was conducted as in the case of the second research goal.

Table 1: Research Goals

Research Goal (Research Question; Type of Research)	**Research Approach**
Summarize current research on organizational inertia in digital innovation activities of incumbent companies. (RQ 1; Analysis)	Literature review on existing studies of information systems and management literature around digital transformation activities
Analyze the practices organizations pursue to accomplish digital product innovation. (RQ 2; Analysis)	In-depth-case study of a digital product innovation initiative pursued in an industrial-aged organization
Explain the process of accomplishing digital product innovation in an industrial-aged. organization (RQ 3; Explanation)	In-depth-case study of a digital product innovation initiative pursued in an industrial-aged organization

1.3 OVERVIEW OF PUBLICATIONS

The dissertation's content is built on publications in the information systems community (Figure 1), particularly tracks around the special interest group on digital transformation, innovation, and digital entrepreneurship.

Figure 1: Articles relevant to the Dissertation

Phase 1: Conceptual Foundations

Investigate Research Question 1. What is the current body of knowledge regarding organizational inertia in industrial-aged companies

Article 1

Title	Understanding Inertia in Digital Transformation
Authors	Thomas Haskamp, Christian Dremel, Carolin Marx, Falk Uebernickel
Method	Literature Review
Results	Presentation of a Research Framework
Outlet	Proceedings of the 42nd International Conference on Information Systems
Status	Published

Phase 2: Empirical Theory-oriented Research

Investigative Research Question 2. What are the practices industrial-age organizations pursuing for digital product innovation?

Investigative Research Question 3. What is the process of how digital product innovation is accomplished in an industrial-age organization?

Article 2

Title	Punctuated Multi-Layered Liminality in Digital Transformation
Authors	Thomas Haskamp, Christian Dremel, Youngjin Yoo, Nicholas Berente, Falk Uebernickel
Method	Single Case Study
Results	Presentation of a Three Tensions and Liminal Mechanisms
Outlet	Proceedings of the 43rd International Conference on Information Systems
Status	Published

Article 3

Title	The Unfolding of Digital Transformation in Pre-Digital Companies
Authors	Thomas Haskamp, Axel Hund, Jun-Patrick Raabe, Falk Uebernickel
Method	Meta-Analysis of Case Studies
Results	Presentation of Two Dominant Narratives
Outlet	Proceedings of the 44th International Conference on Information Systems
Status	Published

Phase 3: Empirical Practice-oriented Research

Managerial Question: How can practitioners deal with organizational inertia and accomplish digital product innovation?

Article 4

Title	The New in the Old: Managing Inertia and Resulting Tensions
Authors	Thomas Haskamp, Christian Dremel, Carolin Marx, Ulla Rinkes, Falk Uebernickel
Method	Multiple Case Study
Results	Framework for the Management of Inertia
Outlet	Book Chapter in Book Series "Digitalization and Sustainability: Advancing Digital Value"
Status	Published

Namely, three peer-reviewed conference papers were published as part of the International Conference on Information Systems, and one article was published for a practice audience as part of a peer-reviewed book chapter.

The first paper, "Understanding Inertia in Digital Transformation: A Literature Review and Multilevel Research Framework," authored by Thomas Haskamp, Christian Dremel, Carolin Marx, and Falk Uebernickel, presented at the International Conference on Information Systems in Austin, Texas, United States, 2021, where it also received the CIO-Best Paper Award is a literature review of the management and information systems literature. It seeks to investigate the current body of literature on organizational inertia in digital transformation studies, and based on a review of 32 studies, it presents a framework including antecedents, attributes, dimensions, theoretical assumptions, moderators, and consequences around the construct of organizational inertia. From this framework, it derives four research avenues to advance the understanding of organizational inertia in digital transformation.

The second paper, "Punctuated Multi-Layered Liminality in Digital Transformation: The Case of an Automotive Platform," authored by Thomas Haskamp, Christian Dremel, Nicholas Berente, Youngjin Yoo, and Falk Uebernickel, was presented at the International Conference on Information Systems in Copenhagen, Denmark in 2022. This paper is a single case study of PremiumCar, and leveraging the concept of liminality, it investigates how PremiumCar implements an OTA platform. It finds three liminal mechanisms on the three layers and develops the concept of punctuated multi-layered liminality to conceptualize the process of how PremiumCar integrates the OTA platform. It contributes a third view of liminality to the literature and presents the central paper for the dissertation.

The third paper, "The Unfolding of Digital Transformation in Pre-digital Companies: A Meta-case Analysis," authored by Thomas Haskamp, Axel Hund, Jun-Patrick Raabe, and Falk Uebernickel for the International Conference on Information Systems in Hyderabad, India, in 2023. Based on a meta-case analysis of 32 digital transformation initiatives published in management and information systems literature, it presents two main narratives and corresponding research avenues. Thus, it seeks to advance the research on digital transformation from a descriptive to a more explanatory stage.

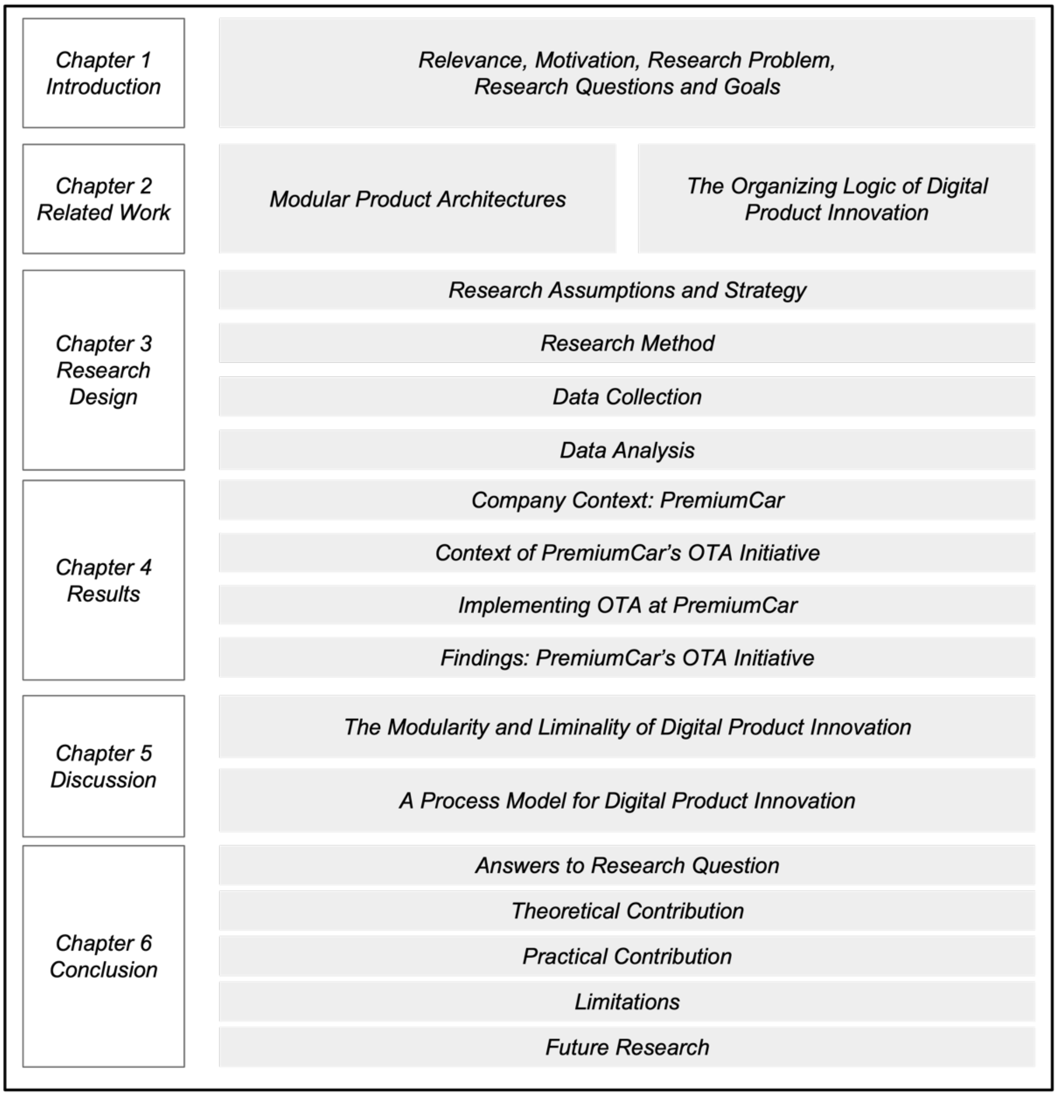
The last book chapter, "The New in the Old: Managing Inertia and Resulting Tensions in Digital Value Creation," authored by Thomas Haskamp, Christian Dremel, Carolin Marx, Ulla Rinkes, and Falk Uebernickel, presents a framework to manage organizational inertia in practice and was published part of book on *Digitalization and Sustainability: Advancing Digital Value* by the Interest Group on Digital Innovation, Transformation and Entrepreneurship.

While the conference papers are part of the overall framing of the dissertation, from a content perspective, this dissertation primarily draws on article 2 and an iterated version of this conference paper. Further, many more papers were published on the scope of digital innovation, transformation, and entrepreneurship as part of the Ph.D. which can be found in Appendix 8.1, Table 38, and Table 39.

1.4 STRUCTURE OF THE DISSERTATION

This dissertation is structured into six chapters (Figure 2). The first chapter introduces the topic by highlighting its relevance and presenting the overall research endeavor.

Figure 2: Structure of the Dissertation



Chapter two then introduces selected related work around modular product architectures and digital product innovation from the information systems and management domain. Chapter three introduces the research design around the single case study, grounded theory, and narratives as data analysis approaches. Chapter four presents the company context, the context of the digital product innovation initiative, its implementation, and the findings from the analysis. In chapter five, the findings are discussed considering previously introduced literature, and a process model is developed to answer the RQs. The dissertation concludes with a few remarks highlighting the contribution made, the implications of this work, its limitations, and outlining future research that can be derived from it.

1.5 Dissertation Core Reasoning

To ease the reading and foreshadow the line of argumentation of the dissertation, a summary of the core arguments is given here:

Industrial-aged organizations need to integrate conflicting product architecture logic and their required organizing logic to accomplish digital product innovation.

Following the mirroring hypothesis, the product architecture and organizational logic should predominantly align.

Based on an in-depth and long-term case study of a car manufacturer's digital product innovation centered around integrating Over-the-Air software updates into vehicles, this dissertation yields four key findings:

First, industrial-aged organizations indeed need to reconcile contrasting modular product architecture principles, which they accomplish through the enablement of product architectures.

Second, industrial-aged organizations need to attune different product development routines to harmonize diverse product development processes across various layers of the product architecture.

Third, expanding the organizational structure based on the mirroring of product layers is crucial.

Fourth, redesigning resource allocation practices and adopting concurrent routines is necessary.

Drawing from these findings and integrating literature from information systems and management, a process model is proposed to elucidate how industrial-aged organizations achieve digital product innovation and integrate divergent logics.

Contextual triggers include external market pressures and existing architectural frames within the industrial-aged organization, serving as starting points for digital product innovation efforts.

Reciprocal mechanisms, such as product architecture enablement, organizational expansion, alignment of product development routines, and resource allocation redesign, explain how industrial-aged companies pursue digital product innovation.

As outcomes, a nested layered modular architecture, an organizational superstructure, and a set of concurrent routines are presented.

In contrast to the preexisting literature, the developed process model enriches the digital product innovation literature by emphasizing changes in the product architecture as drivers of change that are linked to organizational practices.

Practically, it presents four levers for executives and suggests that to accomplish digital product innovation, executives should focus on incorporating modularity into the product architecture and aligning product architecture decisions with the organization.

2 RELATED WORK

“A product is generally defined as 'something that is made to be sold, typically produced through an industrial process, or, less commonly, obtained through farming” (Dictionary, 2023). Consequently, digital product innovation can be understood as “the creation of new combinations of digital and physical components to develop novel products” (Yoo et al., 2010, p. 725). Thus, accomplishing digital product innovation requires understanding how to combine the digital and physical components and is a matter of product architecture. So, product architecture, defined as “the arrangement by which a product's functionality is allocated to physical components” (Ulrich, 1995, p. 419), forms a crucial foundation of the product and is the focal point for the recombination efforts required to achieve digital product innovation (Yoo et al., 2010). With the product architecture comes a decision for an organizing logic (Sambamurthy & Zmud, 2000; Yoo et al., 2010), referring to the “managerial rationale for designing and evolving specific organizational arrangements in response to an enterprise’s environmental and strategic imperatives” (Sambamurthy & Zmud, 2000, p. 107). This can involve the organizational structure, its product development processes, but also its budgeting and resource allocation practices (Lee & Berente, 2012; Nambisan et al., 2017; Vial, 2019).

Addressing how industrial-aged organizations transition toward digital product innovation and blend existing approaches with new digital ones has been explored in the information systems and strategic management literature. From the product architecture perspective, the concept of modularity (Baldwin & Clark, 2000; Brusoni & Prencipe, 2001; Yoo et al., 2012, 2010) and the layered modular architecture (Hylving & Schultze, 2020; Yoo et al., 2010, 2012) have been employed to examine how industrial-aged organizations achieve digital product innovation. Similarly, from the organizational perspective, the strategic management literature has employed the mirroring hypothesis (Colfer & Baldwin, 2016; Hylving & Schultze, 2020; MacCormack et al., 2012) to study how companies can succeed with digital product innovation. The mirroring hypothesis posits a fundamental correspondence between the organizing approach and the technical product architecture (Colfer & Baldwin, 2016).

The information systems community has explored these organizational aspects in the context of digital product innovation using various terms such as digital innovation (Lee & Berente, 2012; Svahn et al., 2017; Yoo et al., 2012), digital product innovation (Wang et al., 2022), digital innovation management (Nambisan et al., 2017), digital transformation (Hinings et al., 2018; Nambisan et al., 2019; Sebastian et al., 2017; Vial, 2019), and recently also under the term digital x (Baiyere et al., 2023). For the sake of consistency, the dissertation uses the term digital product innovation, following Yoo et al.'s (2010) definition of digital innovation as "the creation of new combinations of digital and physical components to develop novel products" (p. 725).

The related work section is organized in two subchapters. The first will introduce existing work on modular product architectures, while the second part will present current knowledge on the organizing logic and approaches for digital product innovation.

2.1 Modular Product Architectures

The term modularity serves as a foundational concept in product architecture design (Alexander, 1964; Baldwin, 2023; Simon, 1991; Ulrich, 1995; Yoo et al., 2010). This chapter aims to elucidate the concept of modularity and its significance in the context of digital product innovation, examined from both management and information systems perspectives. To accomplish this, the chapter will begin by introducing foundational concepts, followed by a detailed exploration of the research problem.

2.1.1 Design Rules: Modularity in Product Architectures

One starting point for understanding the concept of product architectures is Ulrich's work (1995). He defines product architecture as "the scheme by which the function of a product is allocated to physical components" (Ulrich, 1995, p. 419). Ulrich further distinguishes between two ideal types of product architectures: modular and integral. He explains:

> *"A modular architecture includes a one-to-one mapping from functional elements in the function structure to the physical components of the product and specifies decoupled interfaces between components, an integral architecture includes a complex (non one-to-one) mapping from functional elements to physical components and/or coupled interfaces between components"* (Ulrich, 1995, p. 5).

Crucially, the choice between these ideal types of product architectures is a strategic decision, with integral product architectures prioritizing product performance over product flexibility (Ulrich, 1995).

Building on Ulrich's work, Baldwin and Clark (2000) conducted a case study of IBM's product design strategy for its System/360 and developed the concept of modularity in their pivotal book on the Design Rules – The Power of Modularity. They define modularity as "building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole" (Baldwin & Clark, 1997, p. 1). To address the challenges posed by Moore's Law and the increasing pace of changes in product architectures, designers needed a new approach to product design, and modularity emerged as the answer in the IBM case.

Achieving modularity in practice involves adhering to several important principles. One key principle is the concept of *fundamental isomorphism*, which refers to the idea that the organizing approach of teams responsible for product architectures (task structure) should closely align with the actual product architecture (design structure).

This marks the inception[2] of the mirroring hypothesis in the technology and management domain, emphasizing this fundamental isomorphism (Baldwin & Clark, 2000).

Another important concept in modular design is the notion of *information hiding*. Information hiding is closely related to the concept of abstraction in software engineering and is defined as follows:

> *When the complexity of one of the elements crosses a certain threshold, that complexity can be isolated by defining a separate "abstraction" with a simple interface. The abstraction "hides" the complexity of the element.* (Baldwin & Clark, 2000, p. 73).

To facilitate information hiding, the use of interfaces, which provide detailed descriptions of how different modules interact with each other, becomes crucial. Additionally, integration protocols and testing standards, which outline procedures for assembling the system and testing its functionality, become of central importance (Baldwin, 2023, p. 77).

Lastly, Baldwin and Clark (2000) introduce a set of six actions that can be applied to modular design. These actions include 1) splitting a system into two or more modules, 2) substituting one module design for another, 3) augmenting means by adding a new module to a system, 4) excluding a module from the system, 5) inverting to create new design rules and 6) porting a module to another system.

Achieving modularity offers several practical benefits. Firstly, it reduces complexity by limiting interdependencies in the product design process. Second, it enables concurrent design by resolving interdependencies. Third, it provides a structured approach to accommodate uncertainty in the design process (Baldwin & Clark, 2000; Baldwin & Clark, 1997).

A fundamental concept of modularity is the idea that systems can be divided into modules with well-defined boundaries, minimizing technical or organizational dependencies (Sanchez & Mahoney, 1996). Thus, one of the key advantages of modularity is that transaction costs and coordination needs are high within modules but can be relatively low across modules (Baldwin & Clark, 2000; Baldwin, 2007).

Moreover, this literature suggests that modularity can manifest at various levels, including the "system level (e.g., control systems), sub-systems level (e.g., fuel metering unit), component level (e.g., valve), and sub-component level (e.g., spring)" (Brusoni & Prencipe, 2001, p. 183). Consequently, organizations must engage in decoupling product architectures and can concentrate on coordinating different actors at these different levels. High modularity within the product

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[2] In the 1960ties Melvin Conway in computer science also talked about the idea "that organizations which design systems (in the broad sense used here) are constrained to produce designs which are copies of the communication structures of these organizations (Conway, 1968, p. 31)" . This relates to the basic idea of "mirroring" and is known since then as Conway's Law in computer science. Also central concepts of modularity such as information hiding are known in computer science and software development under terms of "Law of Demeter" (Lieberherr et al., 1988), or "Single Responsibility Principle" (Martin, 2002)

architecture allows for a high degree of specialization within and across companies, as modular product design minimizes coordination among actors by relying on well-defined interfaces (Brusoni & Prencipe, 2001).

However, some literature challenges the notion that clear interfaces and modular product design alone can decrease coordination costs. For instance, Brusoni and Prencipe (2001) argue that while modularity can serve as an effective product design strategy, there are cases where modular product design necessitates the role of system integrators. These integrators act as

> *"knowledge and organizational coordinators to ensure the overall consistency of the product and to orchestrate the network of companies involved in various stages of design and manufacturing"* (Brusoni & Prencipe, 2001, p. 185).

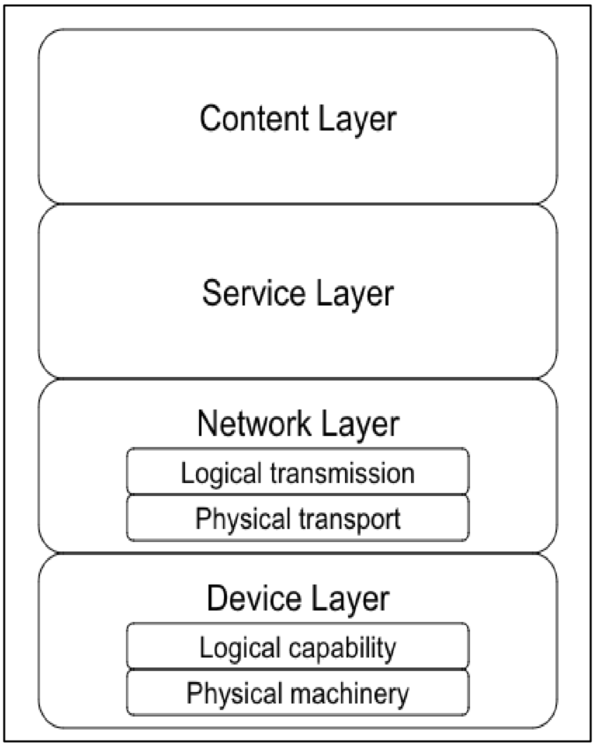
Much of the research has been conducted in the automotive industry, where modularity has emerged as a primary product design strategy. Baldwin and Clark (1997) provide the example of Mercedes-Benz and the development of the driver's cockpit (system) and its components, such as airbags, heating, air-conditioning, and the instrument cluster for a vehicle model. The entire cockpit system was developed by Delphi Automotive Systems, which, in the 1990s, was a subsidiary of General Motors. This subsidiary managed an independent network of suppliers to manufacture the driver's cockpit components. Mercedes-Benz only provided specifications and requirements, based on which the cockpit was later integrated. As this example illustrates, the product (the driver's cockpit) is designed following modularity principles in which the design structure and task structure are exact mirrors of each other to coordinate work with different entities (suppliers, sub-suppliers). Thus, largely independent teams for each subsystem and component collaborate based on pre-defined interfaces. This implies high component knowledge at each coordinating unit, such as a supplier, without requiring extensive architectural knowledge since they can rely on established design rules (interfaces and standards). The automotive industry and its OEMs have become prime examples of reaping the benefits of modularity and assuming the role of orchestrators in the entire supply chain (MacDuffie, 2013).

The literature also highlights that OEMs have a rather idiosyncratic understanding of modules (MacDuffie, 2013). In the industry, a module is defined as "a large chunk of physically adjacent components produced as a subassembly by a supplier and then installed in a single step in an automaker's assembly plant" (MacDuffie, 2013, p. 14). MacDuffie outlines how OEMs outsource key components to suppliers and how the power relationship between OEMs and those suppliers is changing based on product architecture decisions, implying that product architecture decisions affect the industry structure.

2.1.2 Layered Modular Architecture

Within the information systems community, research has investigated the impact of digital technology on product architectures, specifically focusing on product architectures categorized as digital (product) innovation. These innovations, characterized by the presence of both physical and digital components, have been conceptualized as *layered modular architecture* (Yoo et al., 2010). In Yoo's seminal work (2010), this new type of product architecture is introduced. With technological progress around increasing capabilities of microprocessors, cheaper hardware, and memory, companies have started to digitize former hardware products such as cars, phones, and televisions (Yoo, 2010). These developments give rise to the layered modular architecture as a "hybrid of the modular architecture of a physical product and the layered architecture of digital technology" (Yoo et al., 2010, p. 725). As a starting point, Yoo et al. (2010) introduce the layered architecture of digital technology (Figure 3).

Figure 3: Layered Architecture (Yoo et al., 2010, p. 727)



The layered architecture of digital technology comprises four layers: a first device layer around physical machinery and logical capabilities, a second network layer around physical transport and logical transmission, a third service layer, and a fourth content layer (Yoo et al., 2010). This layered architecture of digital technology represents a departure from the previously dominant product design approaches, either integral or modular architectures (Yoo et al., 2010).

The layered architecture of digital technology possesses three unique characteristics: 1) re-programmability, 2) homogenization of data, and 3) the self-referential nature of digital technology. These characteristics distinguish it from non-digital product architectures. The attributes mentioned above highlight the separation between the actual device and service and the content layer. The service and content layers can be changed more flexibly due to their re-programmability (Yoo et al., 2010).

While this understanding of digital product innovation has received much attention in the information systems literature (Yoo et al., 2012, 2010) others have gradually built or departed from the layered modular architecture idea of digital innovation (Hinings et al., 2018; Hund et al., 2021; Kohli & Melville, 2019; Nambisan et al., 2017). Due to its initial focus on the modularity and re-combinability of physical and digital components, this dissertation follows Yoo et al's (2012, 2010) pivotal work on digital innovation and the idea of a layered modular architecture[3].

With the ability to integrate digital technology into physical products, a novel form of digital product innovation has emerged (Yoo et al., 2010). This layered modular architecture represents a hybrid approach that bridges the gap between traditional modular architecture and boundaryless layered architecture. Consequently, the layered modular architecture combines elements from both ends of the spectrum, blending characteristics of these two architectural types (see Table 2).

Table 2: Modular vs. Layered Architecture (Yoo et al., 2010, p.729)

Modular Architecture	**Layered Architecture**
Fixed relationship between the product and its components that are nested in a single design hierarchy	*Loose coupling* of layers whereby innovation can happen on all layers with fluid product boundaries
Product-specific design of a component is driven by functional requirements	*Product agnostic* design of components as products are enacted by the orchestration of an ensemble of components and share high generativity
External production of components through specialized firms	*Layers are coupled* through standards and protocols shared by firms

Emerging digital product innovations frequently leverage the layered modular architecture (Nambisan et al., 2020; Yoo et al., 2012, 2010), and this choice has profound implications for the characteristics of such architectures.

One critical attribute is the concept of "generativity", which can be defined as "a technology's overall capacity to produce unprompted change driven by large, varied, and uncoordinated audiences" (Zittrain, 2006, p. 1980). Within the layered architecture of digital technology, functionality is compartmentalized in a modular

[3] It needs to be acknowledged that different understandings of digital product innovation are used in different disciplines such as management, IS and computer science. For example only the IS discipline holds a vivid discourse on product-architecture related questions and the role of digital technology (Hund et al., 2021; Kallinikos et al., 2013; Mutch, 2010; Nambisan et al., 2017) that is partially compatible but also in conflict with Yoo's understanding of digital innovation. Given the lens of modularity taken for the dissertation, this work is situated on Yoo et al. pivotal work (2010, 2012) who builds on Ulrich's work on product architecture (1995) and Baldwin and Clark's work (Baldwin & Clark, 2000; Henderson & Clark, 1990) on modular product architectures as a starting point to investigate and conceptualize digital product innovation.

fashion, typically situated at the base of the stack (Henfridsson et al., 2014). This arrangement creates a platform that fosters high levels of generativity.

The high generativity of digital technology has been instrumental in explaining the boundaryless nature of digital product innovations (Fielt & Gregor, 2016; Yoo, 2012; Yoo et al., 2012). Innovations that leverage the layered modular architecture often transcend the traditional boundaries of products, roles, organizations, and even industries (Hund et al., 2021; Yoo et al., 2010).

For instance, the integration of software capabilities into physical products blurs the boundaries of those products. Take, for example, how Tesla has transformed its cars into gaming devices, allowing customers to order online games via OTA as an on-demand feature (Statt, 2019). In this scenario, the steering wheel and brakes serve not only for driving but also as part of a gaming device. This example highlights how, due to the homogenization of data and products, applications like online games can function as standalone products while also being seamlessly integrated into other products, such as a car (Hund et al., 2021).

As introduced by Yoo et al. (2010), the layered architecture of digital technology and the hierarchical architecture of established products often appear to be in conflict (Hylving & Schultze, 2020; Lee & Berente, 2012; Svahn et al., 2017; Yoo et al., 2010). This conflict has been conceptualized in the literature using various terms, such as “hybrid architecture” (Yoo et al., 2010), conflicting “architectural frames” (Henfridsson et al., 2014), and conflicting “configurations of modularity” (Hylving & Schultze, 2020). For example, Hylving and Schultze (2020) discuss the different logics of hierarchal and layered configurations and find different inherent top-down vs bottom-up logics in place which have important implications for the product design process (Table 3).

Table 3: Hierarchical vs. Layered Configuration (Hylving & Schultze, 2020)

Dimension	**Hierarchical Configuration**	**Layered Configuration**
Logic of module configuration	Top-down decomposition, aggregation logic	Bottom-up- core-periphery logic
Implication for product innovation	The product has to be fully known prior to modularization	The product can be incomplete as it serves as a platform with generative capabilities

On one hand, the layered architecture of digital technology follows a bottom-up core-periphery logic, where products are constructed layer by layer from the bottom up. Digital products can be incompletely launched and then further developed thanks to their generative capabilities (Lehmann & Recker, 2022). Consequently, they can be developed iteratively, relying on continuous development and integration of digital components into the physical product.

On the other hand, the hierarchical product architecture of physical products follows a top-down logic, where the product is initially designed and then decomposed into its various components that together create a cohesive system (Baldwin & Clark, 2000). To manage the interfaces among these different components, the entire product must be thoroughly understood before it's broken down into distinct modules. These modules are then manufactured through a supply chain that is orchestrated based on established standards and clearly defined interfaces.

Yoo et al. (2010) have proposed a new hybrid form of product architecture - the layered modular architecture - and others (Henfridsson et al., 2014; Hylving & Schultze, 2020; Lee & Berente, 2012; Svahn & Kristensson, 2022) have begun to study how companies navigate that tension and how they refine assumptions on the notions of modularity in digital product innovation (Table 4).

Table 4: Product Architecture Findings in the Automotive Domain

Study	Product Architecture Findings
Lee & Berente (2012)	Based on the evolution of emission control systems in the automotive industry, they propose two distinct product hierarchies – dual product hierarchy - of the inclusionary and the digital control hierarchy that need to be decoupled to work.
Hylving & Schultze (2020)	Based on the study of the increasing digitalization of the driver's information module they find that different hierarchical and layered modular configurations of physical and digital products are at odds. The case company requires three transformations to accomplish layered modular architecture: 1) uncoupling of the digital control system from the physical product hierarchy, 2) the layering of the digital control system and 3) the reconnecting of the two architectures.
Henfridsson et al. (2014)	Based on the case study of the infotainment system of a carmaker they identify two architectural frames that are at odds, namely the network of patterns frame vs the hierarchy of parts frame which are resolved through mixtures of different approaches.
Svahn et al. (2017)	Based on the implementation of a connected car initiative at Volvo, they find different organizational tensions and also that Volvo developed a Cloud-Centric Product Architecture and that product architectures were frozen before production time.
MacDuffie (2013)	Based on three case studies (Common, Ford, and Hyundai) of automotive modules the author finds different understandings of modularity within OEMs and derives understandings of modularity as a property, as a process, and as a frame from it.

Lee and Berente (2012) introduce a dual-product hierarchy framework, building on the work of Mesarovic et al. (1970), to characterize products as consisting of two primary systems: an inclusionary hierarchy system and a control hierarchy system. The inclusionary hierarchy system comprises various subsystems that are interconnected. In contrast, the control hierarchy system encompasses local decision control units and higher-level coordinator units. Historically, local decision control systems were tightly coupled, but the advent of increased digitalization efforts has led to their decoupling from the subassemblies they govern. This shift has given rise to new digital control systems, which entail the "control of physical systems with a digital computer or microcontroller". They function as local decision units, requiring minimal human intervention, and are responsible for monitoring and controlling various components, which are indirectly interconnected. They often serve as the core integrative systems for complex products (Franklin et al., 1998; Lee & Berente, 2012). As they point out, “these digital systems monitor and control components with respect to other indirectly connected components, often acting as the core integrative systems of those complex products” (2012, p. 1428).

These transformations in product architecture have significant implications for original equipment manufacturers (OEMs). OEMs must now take on the role of system integrators, necessitating a broader knowledge base in product design that extends beyond component and architectural integration levels. This requires gaining a deeper understanding of the inner workings of new sub-architectures and components, along with organizational knowledge on how to integrate specialists into the supply chain (Lee & Berente, 2012). This also implies that firms must “know more than they make” (Brusoni & Prencipe, 2001, p. 597).

Hylving and Schultze (2020) delve into the conflicts within product architecture in the context of the increasing digitalization of the driver's information module. They corroborate the notion that hierarchical and layered modular configurations conflict. To address these conflicts, Hylving and Schultze (2020) introduce practices and structures related to partial mirroring and mirror-breaking. These practices encompass non-hierarchical organizational arrangements like matrixed reporting structures, as well as collaborative and iterative development practices, including agile development methods (Hylving & Schultze, 2020; Lee & Berente, 2012) and joint decision-making processes and communication channels (Hylving & Schultze, 2020).

Drawing from a case study of a car manufacturer's digitalization journey focused on the Driver Information Module, Hylving and Schultze (2020) identify three key transformations that the organization undergoes to implement the layered modular architecture successfully, namely 1) Decoupling the digital control system from the physical product hierarchy, 2) Layering the digital control system, 3) Reconnecting the two architectures, effectively reconciling the hierarchical and layered modular approaches.

In a similar vein, Henfridsson et al. (2014) conducted a case study on a carmaker's infotainment system and identified two conflicting architectural frames: the network of patterns frame and the hierarchy of parts frame. They discovered that this conflict was resolved by implementing a mixture of approaches that incorporated elements from both frames.

Svahn et al. (2017), in their case study of Volvo's connected car initiative, identified four types of tensions related to product architecture. These tensions revolved around the need for a cloud-centric product architecture (aligned with the layered architecture of technology) and the procedural challenge of freezing product architecture before production, limiting flexibility for software teams.

Furthermore, MacDuffie (2013) conducted case studies on automotive modules within Common, Ford, and Hyundai. His research highlighted varying interpretations of modularity within OEMs, including modularity as a property, as a process, and as a frame.

In summary, the literature on modularity has started to explore the conflicts that companies face when pursuing digital product innovation. While some practices have been identified, such as decoupling and integrating digital control systems, the literature has not identified a process of how firms successfully implement layered modular architecture. Additionally, the relationship between product architecture decisions and organizing principles remains unexplored (Henfridsson et al., 2014; Hylving & Schultze, 2020).

2.2 The Organizing Logic of Digital Product Innovation

Along with changing the product architecture, accomplishing digital product innovation also requires embracing an organizing logic that is different from "traditional" innovation, which has sparked the need for reinventing innovation management (Hund et al., 2021; Kohli & Melville, 2019; Nambisan et al., 2017; Yoo, 2012; Yoo et al., 2010).

When using the term organizing logic (Sambamurthy & Zmud, 2000; Yoo et al., 2010), for the dissertation three main concepts are at the center of attention. Given that this dissertation explores digital product innovation, it is essential to consider not only the product development process and practices but also the organizational structure within which these development processes occur. Additionally, the allocation of resources within the organization plays a significant role in shaping the structural elements that contribute to the achievement of digital product innovation.

As a fundamental theoretical departure point to investigate how industrial-age organizations accomplish digital product innovation on the organizational level, the mirroring hypothesis is introduced. Then, in the second part, we review relevant work that needs to be considered on product development, organizational structure, and resource allocation for digital product innovation. Lastly, as a departure point to conceptualize the procedural characteristics of how industrial-age organizations move to digital product innovation, the notion of liminality is introduced.

2.2.1 The Mirroring Hypothesis

Connected to modularity research (Baldwin & Clark, 2000), a sub-stream has developed the mirroring hypothesis as a guiding principle for organizing product development (Baldwin, 2023; Brusoni et al., 2023; Brusoni & Prencipe, 2001, 2006; Cabigiosu & Camuffo, 2012; Colfer & Baldwin, 2016; Furlan et al., 2014; Hylving & Schultze, 2020; Jacobides et al., 2016; MacDuffie, 2013; Sanchez & Mahoney, 1996; Sorkun & Furlan, 2017).

In essence,[4] the mirroring hypothesis states that:

> *"Organizational ties within a project, firm, or group of firms (e.g., communication, collocation, employment) will correspond to the technical dependencies in the work being performed."* (Colfer & Baldwin, 2016, p. 1)

[4] There is a multiplicity of definitions of mirroring available. Henderson and Clark for example define mirroring with the following words "Organizations are boundedly rational, [hence] their knowledge and information-processing structure come to mirror the internal structure of the product they are designing."(1990, p. 27). For the dissertation, the definition of Colfer and Baldwin (2016) is used since it's the dominating one in current discussions.

Originating from modularity, the mirroring hypothesis attempts to help manage complex systems through information hiding to conserve scarce cognitive resources (Colfer & Baldwin, 2016). Information hiding, which means isolating dedicated modules and teams that work on these modules becomes a key underlying premise for the mirroring hypothesis, as this isolation allows the correspondence between the technical and organizational structure (Baldwin & Clark, 2000; Colfer & Baldwin, 2016).

Research on mirroring as a product design strategy reports mixed results and different interpretations (Colfer & Baldwin, 2016). The literature distinguishes between mirroring used as a *descriptive* (predicting a correlation between technical and organizational ties) or a *normative* (recommending a correlation between technical and organizational ties) idea (Colfer & Baldwin, 2016).

One literature review reports that in descriptive studies, mirroring finds support in 70% of empirical studies, whereas in normative studies only 42% of empirical studies mirroring was considered a success (Colfer & Baldwin, 2016). In another review (Sorkun & Furlan, 2017) with 83 empirical studies, 31% of papers found supporting evidence for mirroring, whereas 69% challenged mirroring.

One risk in pursuing mirroring is the mirroring trap. This occurs when companies focus on the current architecture too much and become a victim of other architectural innovations outside the organization. One way of dealing with this threat is partial mirroring, "in which firms define their knowledge boundaries more broadly than their task boundaries" (Colfer & Baldwin, 2016, p. 724) which allows them to integrate new developments into their practices.

Other studies also vividly discuss the pros and cons of the mirroring hypothesis highlighting the boundaries of mirroring, but also its benefits (Cabigiosu & Camuffo, 2012; Furlan et al., 2014; MacCormack et al., 2012).

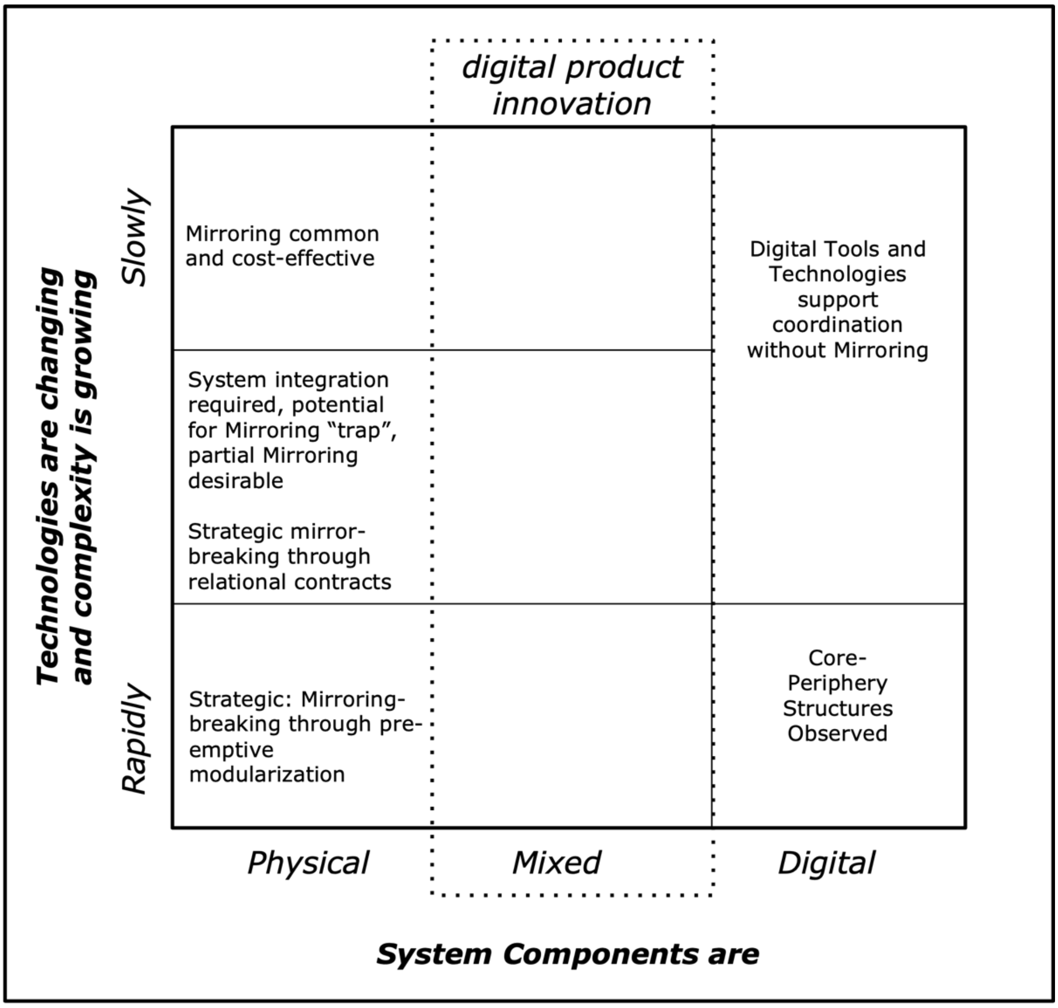
The literature highlights that the effectiveness of mirroring as a strategy seems to depend greatly on the specific context. Context here refers to the speed of technological changes and the type of system components (Colfer & Baldwin, 2016).

Research suggests that in situations where products consist of fully physical components and the technological changes are slow, mirroring seems to work efficiently and cost-effectively (Colfer & Baldwin, 2016). It seems to be that with the increasing speed of technological changes, companies need to depart from mirroring as a strategy for two reasons. Firstly, increasing technological changes require closer collaboration and system integration. And second, digital technologies seem to afford coordination without mirroring.

Research in strategic management so far has provided a thorough understanding of physical components in both slowly and rapidly evolving industries.

Whereas the systems largely composed of digital components have been investigated on the digital tool level, systems that are composed of mixed physical or digital components such as digital product innovations have received less attention in the strategic management domain which culminates into the call for investigating the boundary conditions of mirroring (Colfer & Baldwin, 2016). A current overview of findings for mirroring as product design strategy and its effectiveness is provided in Figure 4.

Figure 4: Findings - Mirroring Hypothesis (Colfer & Baldwin, 2016, p. 729)



Some research in the information systems domain has started to investigate mirroring for digital product innovation contexts (Colfer & Baldwin, 2016; Hylving & Schultze, 2020; Lee & Berente, 2012). That stream initiates a departure from Baldwin's and Clark's (2000) fundamental isomorphism. They argue that digital innovation might require engaging in an approach of "partial mirroring" (Hylving & Schultze, 2020) or "mirror breaking" (Colfer & Baldwin, 2016).

They have identified a set of practices to accommodate the architectural changes triggered by the integration of digital product innovation (Table 5).

There seems to be a shift in the roles of OEMs as systems integrators (Jacobides et al., 2016; Lee & Berente, 2012). Based on studies of nine OEMs research has argued how OEMs dominate the value chain and how their efforts as systems integrators shift power and affect the entire task distribution in the supply chain (Jacobides et al., 2016). Further, it has been argued that OEMs need to possess broader product design knowledge beyond the component and architectural integration level (Lee & Berente, 2012). With technological shifts (through digital control systems) they need to gain a better understanding of the inner workings of the new sub-architecture and components, including the organizational knowledge on how to integrate specialists into the supply chain (Lee & Berente, 2012).

Table 5: Overview of Mirror-Breaking Practices

Dimension	**Findings**
Roles	*OEMs as System Integrators:* OEMs need to possess broader product design knowledge beyond the component and architectural integration level. With technological shifts (through digital control systems) they need to gain a better understanding of the inner workings of the new sub-architecture and components, including the organizational knowledge on how to integrate specialists into the supply chain (Lee & Berente, 2012).
Practices	*Non-hierarchical organizational arrangements:* Organizations need to engage in setting up non-hierarchical organizational arrangements such as matrixed reporting structures (Hylving & Schultze, 2020). *Collaborative development practices:* Organizations need to engage in setting up collaborative and iterative development practices, for example, agile development practices (Hylving & Schultze, 2020; Lee & Berente, 2012). *Joint decision-making and communication:* Organizations need to engage in setting up joint decision-making practices and practices that allow for communication between different actors (Hylving & Schultze, 2020).

In terms of practices, organizations need to engage in setting up non-hierarchical organizational arrangements such as matrixed reporting structures, engaging in collaborative and iterative development practices such as agile development practices (Hylving & Schultze, 2020; Lee & Berente, 2012) and need to set up joint decision-making and communication channels (Hylving & Schultze, 2020).

2.2.2 Organizing for Digital Product Innovation

In addition to the mirroring hypothesis which presents the underlying theoretical assumption, research in the digital innovation and transformation domain has investigated the changes required in the organizing logic, specifically in the product development process, and regarding structural issues such as organizational structure and resource allocation practices of organizations (Drechsler et al., 2020; Grover et al., 2022; Lehmann & Recker, 2022; Svahn et al., 2017; Vial, 2019).

Both the literature in practice and theory highlights the differences in product development routines for physical as well as digital products (Lehmann & Recker, 2022; Svahn et al., 2017; Wang et al., 2022). In general, product development highlights different aspects of how firms develop and design new products which involve planning, coordination, and decision-making routines (Brown & Eisenhardt, 1995). Thus product development can be considered a design process consisting of a set of organizational routines - collective capacity to perform recognizable patterns of action (Feldman & Pentland, 2003) - pursued that lead to the final product.

With regard to digital product innovation, the malleable nature of digital technology and its unique characteristics lead to high levels of generativity and convergence (Yoo et al., 2010, 2012). This triggers "wakes of innovation" (Boland et al., 2007) that lead to a new type of "combinatorial innovations" (Yoo et al., 2012), in which combinations between physical products and limitless arrangements of digital objects act as a source for new products and services (Yoo et al., 2012). Realizing these combinatorial innovations requires a strong shift in organizing, as in contrast to traditional physical products, combinatorial innovations based on digital technology need to be designed without knowing the "entire product" as digital innovations are "ever-in-the making" (Lehmann & Recker, 2019). Thus, the boundaries of such products and services remain incomplete since users can continue to explore and derive new functions from the product (Yoo et al., 2012). As a consequence, many organizational theories and existing assumptions, for example, determined product lifecycles (Yoo et al., 2012) or architectural innovations (Henderson & Clark, 1990), do not necessarily hold true anymore (Nambisan et al., 2019; Yoo et al., 2012).

In response to the dynamic nature of digital innovation, many firms have started to experiment with the concept of agility (Antons et al., 2019; Gerster et al., 2021; Grover, 2022; Warner & Wäger, 2019) understood as the "capability [of a unit] to capitalize on emergent opportunities or avoid emergent threats under constrained or unfolding time frames" (Grover, 2022, p. 1083). Past literature has differentiated between this capability (being agile) and the specific practices of agility (doing agile) (Eilers et al., 2020). For the latter, a set of different frameworks (e.g. Scrum, SAFe[5]) have emerged to scale product development for digital product innovation in a fast and iterative manner (Dikert et al., 2016). However, this literature has

[5] SAFe presents a Scaled Agile Framework and includes a set of organizational principles and workflow patterns for organizing and scaling agile practices (Knaster, 2018)

questioned whether Agile frameworks should also applied in the development of physical products (Antons et al., 2019).

In terms of other structural issues around organizational structure and resource allocation, the literature vividly discusses new forms of organizing being adopted to accomplish digital product innovation (Drechsler et al., 2020; Vial, 2019). This includes shifts away from vertically integrated hierarchies to distributed networked organizations for new product development (Drechsler et al., 2020), but also the emergence of new organizational forms dedicated to digital product innovation such as competence centers (Dremel et al., 2017) or dedicated organizational units called digital innovation units to decouple digital product development from traditional product development (Haskamp et al., 2023; Lorson et al., 2022; Svahn et al., 2017). This also comes along with changes in the understanding of the IT department (Gregory et al., 2018; Urbach et al., 2019) and the executive role of the CIO (Haffke et al., 2016; Hess et al., 2016), moving away from an order-taker role towards becoming part of the actual product that is sold. Thus, digital technology makes established role boundaries blurry, whether internally or externally, as the roles of users and producers become challenged (Hund et al., 2021). This also includes changes in the organizational practices of budgeting (Lee & Berente, 2012). Thus digital technologies result in connected products that transcend established industrial boundaries (Porter & Heppelmann, 2014) leading to new customer-oriented domains (Weill et al., 2021). Whereas companies were considered to provide specific solutions to customer problems, like a carmaker building cars for its customers, companies now need to understand which user needs they aim to serve. By understanding their user needs, they can design a product that can meet these needs most efficiently and satisfyingly.

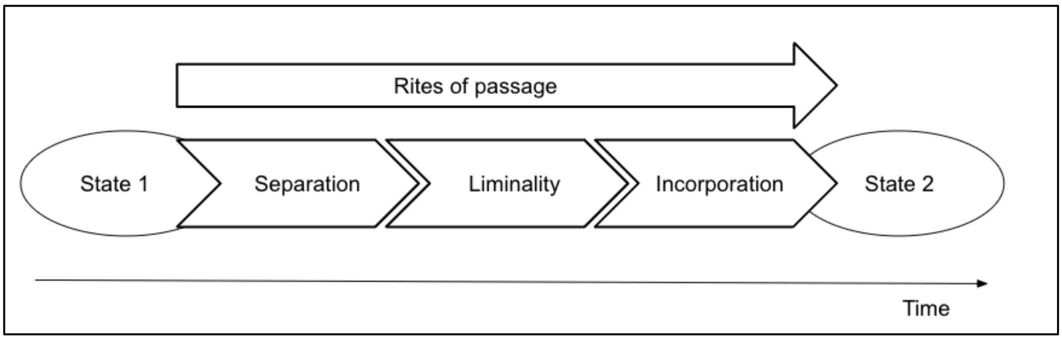
2.2.3 The Liminality of Digital Product Innovation

To explain the process of how industrial-aged organizations accomplish digital product innovation, research has turned to the concept of liminality (Henfridsson & Yoo, 2014; Orlikowski & Scott, 2021)

The notion of liminality and the term liminal comes from the Latin "limen" (i.e., "threshold"). Turner (1969) and Van Gennep (1961) are the intellectual fathers of the concept used in sociology and anthropology.

Van Gennep defines liminality in his book Rites de Passage as "rites which accompany every change of place, state, social position, and age" (van Gennep, 1961). Van Gennep studies how different communities deal with transitionary stages in life (birth, adolescence, marriage, death) and how they have developed different rituals for managing these transitions. From this work, he derives a three-stage process model that includes a pre-liminal phase, a liminal phase, and a post-liminal phase to explain the separation from something, the threshold, and the incorporation into something new (van Gennep, 1961).

Figure 5: Liminality (Van Gennep, 1961)



Turner's work builds on this and introduces the notion of a "liminal state," which arises between the separation and detachment of someone from a structure toward the individual being reincorporated into something new (Turner 1969). The respective period of time is shaped by ambiguity as liminal entities are also referred to as "passengers", and are "neither here nor there, they are betwixt and between the positions assigned and arrayed by law, custom, convention, and ceremonial." (Turner 1969, p. 359). Turner considers these phases of liminality as "a dialectic process dialectical process that involves successive experience of high and low, communitas and structure, homogeneity and differentiation, equality and inequality. Thus, a liminal "period" has attributes of both the previous and the new state and is temporarily undefined (Tagliaventi 2019; Turner 1969). While liminality initially presents a transitionary concept, it can also become permanent when the transitioning entity cannot transition successfully into the post-liminal phase (Szakolczai, 2016).

The concept of liminality has gained traction in different disciplines. Terms such as liminal spaces (Putra et al., 2023; Shortt, 2015), liminal innovation practices (Beech, 2011; Mertens, 2018), liminal hotspots (Greco & Stenner, 2017) and liminal processes (Howard-Grenville et al., 2011) have been used in psychology and management research. Also, the organizational change literature highlights the notion of in-betweenness. For example, Weick & Quinn (1999) explain that two important features of both episodic and continuous change processes are: (a) "semi-structures poised between order and disorder with only some features being prescribed and (b) intentional links in time between present projects and future probes to reduce discontinuity and preserve direction" (Weick & Quinn, 1999, p. 371).

In the study of digital product innovation, research has used liminality as a concept to unpack the process (Henfridsson & Yoo, 2014; Orlikowski & Scott, 2021; Scott & Orlikowski, 2022). Here, liminality refers to transitionary periods in which liminal tensions between the status quo and the described socio-technical future are addressed through liminal innovation practices. Orlikowski and Scott (2021) use the term liminal innovation practices to explain how digital innovation leads to ongoing and continuous transitions between experimentation and implementation. They further introduce three types of tensions: namely pragmatic, tactical, and existential tension, which generate pressure for change. With these tensions, the existing way of doing becomes no longer possible due to feasibility aspects. Thus, such tensions generate liminal innovation practices. Those liminal innovation practices "create the conditions of possibility for experimenting with new activities, products, and services that take advantage of the socio-material enactments that continue to be feasible and available, thus repurposing existing capacity in new ways (Orlikowski & Scott, 2021, p. 4).

Consequently, for them, liminality is an ongoing and continuous modality of organizing. This view of liminal shifts is contrasted by Henfridsson and Yoo's understanding of liminality as a singular, discrete transitionary period (Henfridsson & Yoo, 2014). Henfridsson and Yoo (2014) refer to the "liminality of institutional entrepreneurship as a state of ambiguity faced by institutional entrepreneurs when their new possible innovation trajectory is not fully formed but coexists side-by-side with established trajectories" (Henfridsson and Yoo 2014, p. 946). Here, three generative mechanisms shape the liminal period: reflective dissension, imaginative projection, and proactive elimination. Through these three mechanisms, innovators take mindful actions by willfully suspending the commitment to the existing social and material conditions that underpin organizing practices to envision a different, albeit fragile, future. Thus, they argue, a liminal period concludes with a shift in innovation trajectory and constituting organizing practices.

3 RESEARCH DESIGN

The overall research design aimed to address the research question regarding how industrial-aged companies achieve digital product innovation by employing a process research approach (Berends & Deken, 2021; Cloutier & Langley, 2020; Garud et al., 2017; Langley, 1999, 2007). This process-oriented approach was implemented through a longitudinal, in-depth, embedded single-case study method (Yin, 2011). Data analysis adhered to grounded theory principles (Corbin & Strauss, 2015) and was centered on narrative data (Pentland, 1999). This chapter will introduce the foundational research assumptions, the research strategy, the research method encompassing the embedded single-case study, the data collection procedures, and the data analysis approach.

3.1 RESEARCH ASSUMPTIONS AND STRATEGY

In terms of fundamental research assumptions (Orlikowski & Baroudi, 1991), the dissertation adopts a process philosophy approach (Rescher, 2000). This ontology has its origins in the works of various philosophers. For instance, Heraclitus is often credited with coining the phrase “Panta rhei”, which translates to “everything flows” in Greek. According to Rescher (2000), this idea was embraced by several later philosophers, including American pragmatist John Dewey, French philosopher Henri Bergson, and English mathematician Alfred North Whitehead. Whitehead emphasized that nature unfolds as a continuous process and is constantly changing (Whitehead, 2010).

Rescher (2000) extrapolated from this philosophy a scientific research approach in which the central focus of investigation would be actual occurrences and events. These events and occurrences are situated within specific temporal and spatial contexts. Furthermore, they exhibit a relational nature, suggesting that the unfolding of an event or occurrence, the process of becoming, is inherently linked to or influenced by other events (Rescher, 2000). Therefore, Rescher defines a process by three key characteristics: It consists of “1) a complex of occurrences that 2) exhibits a certain temporal coherence, and a process has 3) a structure, representing a formal generic pattern of occurrences” (Rescher, 2000, p. 24)

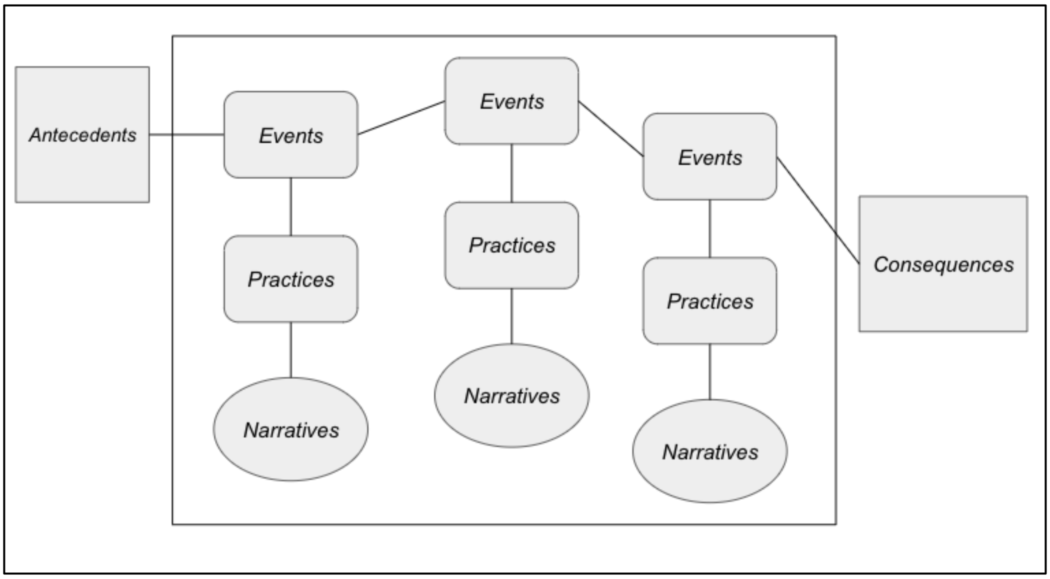
In contrast to variance research, which seeks to examine the relationships between antecedents and consequences, process research delves into how phenomena emerge, develop, evolve, or conclude over time (Langley, 1999). Its objective is to “consider phenomena dynamically – in terms of movement, activity, events, change, and temporal evolution” (Langley, 2007, p. 271).

Process research is deemed a suitable approach when fundamental concepts and subjects of investigation undergo processes, and when the sequence and timing of activities are of significance (Langley, 1999, 2007). As a result, while variance research generates “know-that” knowledge, process research generates “know-how” expertise (Langley, 2007). Specifically, the outcome of process research can manifest as a process theory, defined as “an explanation of how and why an organizational entity changes and develops. This explanation should identify the generative mechanisms that cause observed events to happen and the particular circumstances or contingencies behind these causal mechanisms” (Van De Ven & Poole, 1995, p. 512).

Generative mechanism, often used with the lens of critical realism (Mingers & Standing, 2017), are defined as “causal forces that would have to exist in order to explain a given phenomenon” (Williams & Wynn, 2018, p. 318). Generative mechanisms can appear as situational mechanisms (macro-micro), action formation mechanisms (micro-micro), or as transformational mechanisms (micro-macro) (Hedström & Ylikoski, 2010).

In the study of digital phenomena, which are characterized by fluidity and boundarylessness (Yoo et al., 2010), recent research has embraced process and practice approaches to capture the dynamics of digital innovation (Chanias et al., 2019; Kouamé & Langley, 2018) (Figure 6).

Figure 6: Practice and Process Perspective (Kouamé & Langley, 2018)



This approach combines practices and processes to connect macro-level events and activities with micro-level events and activities (Kouamé & Langley, 2018). As illustrated in Figure 6, a practice and process perspective aims to delve into the procedural nature of events, examining the antecedents, practices, and consequences involved in how events unfold (Kouamé & Langley, 2018). For this study, narratives are utilized to trace events and the associated practices (Pentland, 1999).

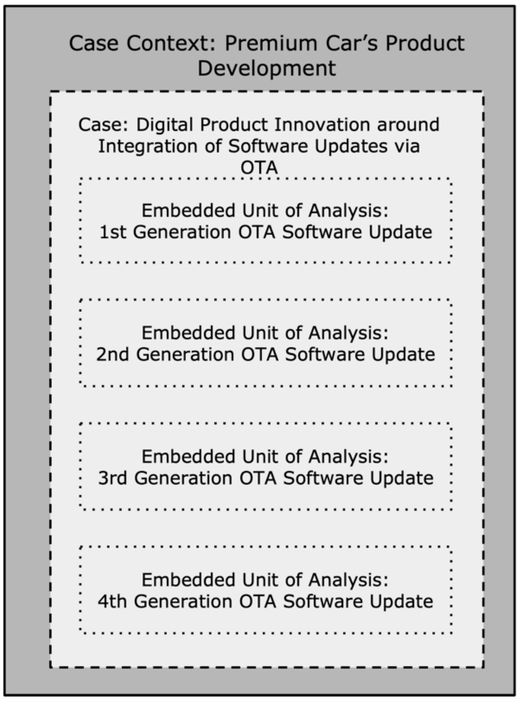
A practice is defined as “routinized types of behavior which consist of several elements, interconnected to one another: forms of bodily activities, forms of mental activities, 'things' and their use, a background knowledge in the form of understanding, know-how, states of emotion, and motivational knowledge” (Reckwitz, 2002, p. 249). While practice-based approaches were historically considered distinct from process approaches, Burgelman et al. (2018) have proposed an integrative view that sees processes and practices as interconnected, aiding in the comprehension of events unfolding in organizational contexts. This integration enables the establishment of a connection between micro-level events and activities and macro-level strategic outcomes at the organizational level (Kouamé & Langley, 2018).

3.2 RESEARCH METHOD

The research method chosen, as part of the process research approach, is an embedded single-case study design (Yin, 2011). This design is valid when the case represents a typical, revelatory, or longitudinal case with “two or more different points in time” (Yin, 2011, p. 42). Single-case studies are appropriate when the study aims to address “how” research questions (Yin, 2011). Despite some limitations such as limited generalizability, a single-case study is a valid approach for investigating how digital product innovation can be achieved. To study such processes, single in-depth cases are suitable, as they align with a process-oriented approach (Garud et al., 2017). Such an approach necessitates longitudinal, rich, and diverse data (Langley et al., 2013), and it may involve multiple units of analysis for cross-case replication (Langley et al., 2013).

The embedded single-case design of this study focuses on the carmaker PremiumCar's (pseudonym) product development activities which provide the case context. The case itself is the digital product innovation initiative concerning software updates via OTA. The single case on the OTA digital product innovation initiative can be regarded as typical because adding OTA capabilities to an existing hardware product (cars) is a typical example of digital product innovation in the automotive industry (Koster et al., 2021; Svahn et al., 2017). This initiative encompasses both social and technical changes that require a deep understanding of details, making a single case study an appropriate choice (Yin, 2011). The embedded units of analysis encompass various generations of software updates via OTA.

Figure 7: Embedded Single Case Study Design based on Yin (2011)



3.2.1 Embedded Unit of Analysis – OTA Generations

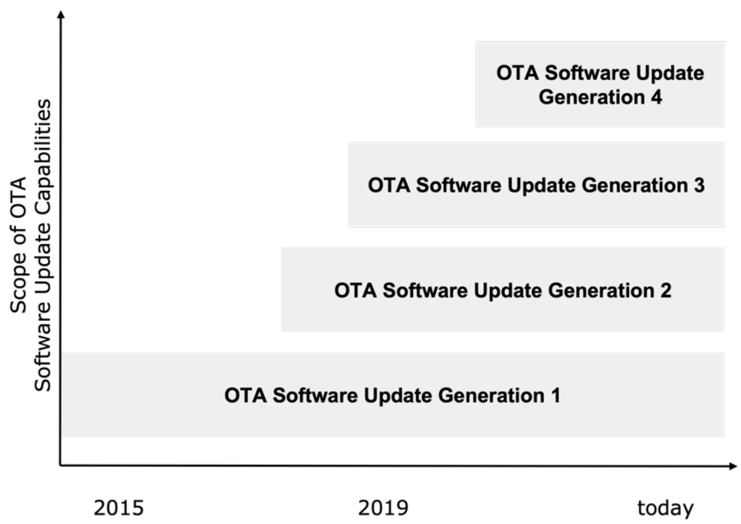
Building on the process approach previously introduced, temporal coherence and temporal bracketing (Langley, 1999) were applied. This resulted in the identification of four generations of software updates via OTA (OTA SU) (Table 6), which also serve as the embedded units of analysis (Yin, 2011).

Table 6: Overview of OTA Generations at PremiumCar

Generation	1. OTA SU	2. OTA SU	3. OTA SU	4. OTA SU
Update Capabilities	Updates of maps on IIM	Updates infotainment system	Infotainment updates and codification of 26 control units	Updates for all vehicle components
Relevant Vehicles	Models Alpha, Gamma	Models Alpha, Beta, Gamma	Model Delta	Model Epsilon
Go-Life	2015	2019	2019	Tbd.
First Use	2016	2021	2021	Tbd.

It's worth noting that, although the OTA team uses the term "releases" to denote various maturity levels of the offboard architecture landscape, the term "generation" is used in this study to encompass the socio-technical nature of the phenomenon. This includes all aspects related to product architecture changes as well as organizational changes. Additionally, while the OTA team's "releases" pertain to specific vehicle series, the term "generation" encompasses different vehicle series. Throughout the progression of generations, the OTA update capabilities expand from initially providing updates to single components or modules of the vehicle to the final attempt in the 4th generation, where the goal is to access the entire vehicle. Importantly, it's noteworthy that instead of one new generation entirely replacing the previous one, each generation partially builds on the foundations of its predecessor (Figure 8).

Figure 8: OTA Generations at PremiumCar



This means that once a car series has been equipped with a generation of OTA components, it remains active. Consequently, as PremiumCar's software update capabilities expand in scope, different approaches to software updates via OTA are managed simultaneously for various car series at PremiumCar.

It's important to note that, for the purpose of this study, only new changes within each generation are considered. Additionally, it's worth considering that this study is centered on the OTA initiative and does not encompass all other changes (e.g., the transition to electric vehicles, which had a significant impact on vehicle architecture) that occurred in the industry and at PremiumCar at the same time. Therefore, for the study and the architectural sketches presented from one generation to another, it is assumed that the vehicle architecture remains relatively stable[6] until the radical shift in the 4th generation.

[6] This assumption is made since all vehicle generations until generation 4 use the same vehicle platform architecture.

3.3 DATA COLLECTION

Process data is expected to be longitudinal, rich, and varied (Langley et al., 2013). To achieve this, a triangulation approach incorporating multiple sources of data was employed (Yin, 2011). This approach encompassed interviews, observations of meetings, participation in workshops, and analysis of both internal and external materials. The data collection process was structured into different phases, each serving a specific purpose (Table 7).

Table 7: Data Collection Phases

No	Phase and Time	Activities
1	Acquisition and preparation phase (03/2021 – 05/2021)	- Acquisition of case study partner - Definition of potential interesting digital product innovations - Agreement on scope of study and signing of non-disclosure agreement (NDA) - Onboarding of researcher on overall digital transformation and product innovation approach and activities
2	1st Round initial explorative data gathering: (06/2021 – 08/2021)	- Getting to know the context and exploration of three different digital initiatives through 14 interviews - Creating 1st event timelines exploration of first topics - Expansion of research team
3	2nd round deep-dive ART OTA Data: (09/2021 – 12/2021)	- Second round of 17 Interviews including deep dive into OTA initiative through attendance of product increment plannings of the OTA initiative (Agile Release Train OTA Data) - Decision to focus on OTA
4	3rd round deep-dive ART OTA Data: (01/2022 – 04/2022)	- Deep dive OTA initiative through interviews (29) and participation in product increment plannings (Online) - Write Up of 1st findings as conference paper for the ICIS 2021
5	4th round of deep-dive ART OTA Data: (06/2022 – 11/2022)	- More follow-up interviews to validate first artifacts for comparative analysis of vehicle generations. - Workshop for discussion of artifacts in Cleveland
6	5th round of validation and refinement phase (12/2022 – 06/2023)	- Validation workshop at PremiumCar - Validation interviews of different artifacts with OTA initiative team members depicting the evolvement of product architectures and organizational changes

During the first phase, which aimed to address the research question concerning how practitioners deal with organizational inertia as part of digital product innovation initiatives in industrial-aged companies (see Chapter 1.2), the author and the primary supervisor reached out to potential companies in their LinkedIn network to gauge their interest in participating in the study. Three companies, including members of PremiumCar's digital transformation office, agreed to participate. Following this, a non-disclosure agreement was signed, and the scope of the study was defined. PremiumCar representatives suggested studying three Agile Release Trains (ARTs) from their virtual product organization initiative as the initial scope. To provide context, a two-hour onboarding session was arranged during which the digital transformation office's leadership team provided an overview of their digital transformation strategy and activities.

With the contextual background established, the second phase involved the initiation of the first exploratory data collection round. Interviews were conducted with key participants from each pilot ART, resulting in a total of 14 interviews. Preliminary data analysis was carried out, and a timeline of events was created (Appendix 8.2, Chapter 1.5). Early on in these interviews, challenges related to integrating the agile approaches introduced through SAFe with the predominantly vehicle-focused product development process were consistently mentioned. The lead researcher met with a senior researcher[7] with expertise in the automotive domain and held regular weekly sessions to discuss interview findings. The first author also started to write up narratives of events (see 3.4.1.2. and Table 13) and also started to inductively code the interviews conducted (Corbin & Strauss, 2015). In this phase, it was also decided that interviews centered around a specific team, namely the team managing OTA updates (called OTA Data [pseudonym]). This was the case as the project sat at the intersection of hardware and software, aligning with the team's research objectives around digital product innovation.

Consequently, a third round of interviews was conducted, and the first author participated in two PI planning sessions of the OTA Data team held during this phase. In the third phase, two senior researchers[8] with extensive experience in digital innovation in the automotive industry joined the team. Bi-weekly sessions were introduced to present ongoing findings and define next steps. During this phase, the team explored various theoretical lenses, progressing from the initial framing of organizational inertia to socio-technical perspectives, and eventually delving into liminality and modularity as constructs to interpret the data. The empirical data often revealed transitionary situations in which participants described themselves as “caught in two worlds” or “in-between”, leading to the adoption of liminality as a potential lens. Additionally, the team recognized different levels of action and the central role of the product architecture. In this context, modularity emerged as a foundational theoretical framework to unpack product architecture changes and relate them to organizational changes. Utilizing these three concepts and the empirical data, the team developed a conference submission for the International Conference on Information Systems, which underwent the peer review process and was presented at the conference in December 2022.

Subsequently, feedback from the conference was used to initiate another round of follow-up interviews, marking the fourth phase. While the researcher was on a research stay at the MIT Center for Information Systems in Boston, findings were discussed, and an in-person data analysis workshop took place during a conference in Cleveland. This facilitated the development of initial artifacts and tables for the comparative analysis. These artifacts and tables were then validated and refined in the fifth phase of data collection, which concluded with a workshop involving key

[7] Dr. Christian Dremel
[8] Prof. Dr. Youngjin Yoo and Prof. Dr. Nicholas Berente

stakeholders to validate the comparative analysis. This was then followed by an inductive analysis adhering to grounded theory principles that are presented in the later section (Corbin & Strauss, 2015).

As mentioned, the data collection process encompassed various instruments, including interviews, analysis of internal and external documents, observations, and a dedicated data-gathering workshop.

3.3.1.1 Interviews

Interviews are a valid tool for data gathering in case studies (Langley, 1999; Myers & Newman, 2007; Yin, 2011). They can be categorized into more structured and less structured types (Myers & Newman, 2007). In this study, the type of interviews evolved as the research progressed. Initially, the interviews followed a guideline that focused on the projects and digital innovation activities (Appendix 8.2, Chapter 1.1 and 1.2.) with different focus areas depending on the interviewee's expertise. However, as the study matured, the interview approach shifted more towards a narrative approach, where interviewees were encouraged to share specific stories around the emerging themes and the interviewer followed up on these narratives (Pentland, 1999). The interview procedure followed the guidelines outlined by Myers and Newman (2007) (Table 8).

Table 8: Interview Guidelines (Myers and Newman, 2007)

Step	Guideline (Myers and Newman (2007)	Application for Case Study
1	Situating the researcher as an actor in the domain	The researcher introduced the research endeavor and himself at the beginning of each interview and explained the research setup and the academic intentions.
2	Minimize social distance with actors	To minimize social distance, PremiumCar internal terms and concepts were used, and if the researcher was unsure, asked about them. Further, interviews with some interviewees were conducted multiple times, which minimized social distance, and an in-presence workshop was conducted.
3	Represent various voices	To represent different voices, different internal stakeholders from different departments were approached and asked to participate in the study.
4	Everyone is an interpreter	The interviewer adjusted the interview style to the interviewee, first asking for stories to which the interviewees responded and then digging into accounts for specific events.
5	Use mirroring in questions and answers	Mirroring was used to validate stories and avoid misunderstandings. Further, very soon, excel sheets with a list of events and sketches or figures were sent over to participants as a foundation for discussion and to ensure shared understanding.
6	Flexibility	Interview questions and stories were adjusted based on the interviewee's expertise.
7	Confidentiality of disclosure	Anonymity was promised at the beginning of each interview for each interviewee.

Furthermore, a diverse range of voices from different departments was included in the study. Overall, the interviewees can be categorized into two groups (Table 9).

Table 9: List of all Interviewees

#	Interviewee (Department)[9]	# Interviews	Lengths (in min)
Virtual Product Organization (VPO) Team		**35**	**1.622**
1	Director of Digital Transformation (IT)	3	143
2	Director of Digital & Innovation (CEO)	4	113
3	Director of IT Research and Development (IT)	4	232
4	VPO - Steering Team Member Production (P)	2	99
5	VPO - Steering Team Member Production 2 (IT)	3	143
6	VPO - Steering Team Member Finance (IT)	3	121
7	VPO - Steering Team Member Finance 2 (IT)	2	90
8	Senior Product Owner MyCar App (IT)	2	83
9	VPO - Steering Team Member Logistics (IT)	3	131
10	VPO - Steering Team Member Sales (IT)	3	148
11	Managing Director Digital Lab (DL)	1	44
12	Project Lead Digital Strategy (CEO)	1	39
13	Project Lead Innovation Strategy (VD)	1	97
14	Project Lead Digitalization (CEO)	1	43
15	Project Lead Innovation Management (CEO)	1	52
16	Senior Manager SAFe (EX)	1	44
OTA Software Update Team		**48**	**2.708**
1	Head of Department IT & Electronics (IT)	4	183
2	Principal Product Manager (IT)	7	462
3	Senior Product Owner OTA (S)	1	35
4	Junior Testing Engineer (S)	1	51
5	Senior Solution Architect (IT)	5	416
6	Release Train Engineer (IT)	3	183
7	Scrum Master (EX)	2	98
8	OTA Architecture & Infrastructure - Flashing (VD)	1	83
9	OTA Connect & Functions (EX)	1	53
10	OTA Infotainment & Development (VD)	1	54
11	OTA Architect - Data-Driven Services Delta (IT)	2	171
12	Head of OTA – Delta (IT)	1	110
13	Senior Product Owner OTA (V)	1	51
14	Head of Connected Car (VD)	2	86
15	Product Strategy Manager OTA (CEO)	1	54
16	Vice President – Delta (CEO)	1	55
17	Senior Developer (SUB)	1	41
18	Head of Department Data & AI Strategy (IT)	1	43
19	Project Manager Vehicle Delta (CEO)	1	50
20	Director R&D Charging (VD)	1	72
21	Head of Electromobility (VD)	1	59
22	Director Innovation Chassis (VD)	1	50
23	Project Manager Charging (CEO)	1	46
24	Project Lead Chassis Delta (CEO)	1	43
25	Project Lead Chassis Gamma (CEO)	1	57
26	PremiumCar Sales Center (S)	1	25
27	OTA - Software Development Lead (IT)	1	54
28	Software Engineer Electrics & Electronics (IT)	1	23
Total | 44 Interviewees		**83**	**4.330**

The first group consisted of interviewees from the virtual product organization team, who could provide insights into the broader digital transformation activities and structural changes related to the virtual product organization that directly

[9] List of Departments: IT = Information Technology Department, CEO = CEO Department, P = Production, DL = Digital Lab, VD = Vehicle Development, EX = External Consulting Company, S = Sales, SUB = SoftwareCorp

affected the OTA team. The second group was the OTA team, responsible for integrating software updates via OTA. This resulted in a total of 83 interviews with 44 individual interviewees. A detailed list of all interviews including the IDs used in the thesis is given in Appendix 8.2 – Chapter 1.3.

The main researcher positioned himself as an active participant in the topic domain by introducing himself and the research endeavor, explaining its purpose, and securing permission to conduct the study through the CIO. To minimize social distance, multiple interviews were conducted with interviewees, and the software used by PremiumCar employees - Microsoft Teams - was adopted. To distinguish between actual events and people's experiences, interviews focused on storytelling, with follow-up questions used to ensure a comprehensive understanding of the situations and events described by interviewees. The interview guide was adjusted based on the interviewee's knowledge domain. Anonymity was guaranteed for all interviewees.

3.3.1.2 Analysis of Documents, Observations and Workshops

To ensure triangulation of data sources (Yin, 2011), interview participants were requested to share relevant documents and slides related to the topics discussed during interviews. These documents, listed in Appendix 8.2 – Chapter 1.3., amounted to 444 pages of internal data, which were utilized in the analysis. Additionally, external information from press releases and online materials relevant to the OTA story or PremiumCar's activities was actively researched and incorporated if confirmed by interviewees (Appendix 8.2 – Chapter 1.3.). This external data contributed 81 pages to the analysis. These documents were used to corroborate interviewee statements, create figures and diagrams depicting important artifacts, and develop event timelines.

Furthermore, the researcher conducted two observations of two-day Product Increment planning sessions for the entire ART OTA Data team, which took place online. During these observations, the researcher took detailed notes, which can be found in the appendix (Appendix 8.2 – Chapter 1.6.). These observations not only provided valuable data but also helped the researchers immerse themselves in the company's domain and generated additional questions that were subsequently integrated into the interview guidelines. The data gathered during these observations was also utilized in the data analysis. Additionally, in the 3rd and 5th phases of the research project, workshops were conducted. The first workshop in the 3rd phase involved presenting intermediate results to the leadership team of the digital transformation office. The second workshop, conducted in the 5th phase at the OTA team's office, was used to validate initial findings from the comparative analysis. All data from these various sources was uploaded to Atlas.Ti Cloud, where it was accessible to the research team and used in the analysis.

3.4 DATA ANALYSIS

To answer the research question and explain how industrial-aged companies accomplish digital product innovation, grounded theory was chosen as a qualitative methodology with the purpose of *"constructing theory grounded in data"* (Corbin & Strauss, 2015, p. 3). Choosing grounded theory as a methodology for qualitative research presents a good choice in case one aims to explain something by developing a theoretical contribution (Corbin & Strauss, 2015). This matches the intention of the study. While grounded theory often draws on memo writing (Corbin & Strauss, 2015), this study used narratives as a cornerstone of analysis (Pentland, 1999). Such narratives served as the basis for constructing the theoretical accounts.

3.4.1.1 Grounded Theory

Grounded theory is a qualitative methodology that encompasses a variety of theory development approaches with different objectives (Urquhart et al., 2010; Wiesche et al., 2017). For this study, the grounded theory approach developed by Corbin and Strauss (2015) was chosen due to its alignment with a process-oriented perspective and its suitability for developing a process theory. Several key concepts are essential to grounded theory, including coding, concepts, dimensions, memos, and properties (Table 10).

Table 10: Key Terms in Grounded Theory (Corbin & Strauss, 2015, p. 57)

Key Terms	**Explanation**	**Evident in the Case Analysis**
Coding	Denoting concepts to stand for meaning	Coding of interviews in multiple rounds and attempts
Concept	Words used by analysts to stand for interpreted meaning	Concepts involve terms for mechanisms
Dimension	The range over which a property can vary	Terms used to construct mechanisms
Memos	Written records of analysis	Instead of memos, narratives were written (Pentland, 1999)
Properties	Characteristics of qualities of a concept that define, give specificity, and differentiate one concept from another	Properties are ranges of dimensions of mechanisms, such as vertical integration is a property of the dimension "Compound Structure of Product Architecture" which is again part of the concept "Product Architecture Enablement"

Coding for example involves the practice of assigning concepts to represent meaning in qualitative data (Corbin & Strauss, 2015). In this study, open coding of interviews was conducted in multiple rounds to identify and categorize key concepts. Concepts are the words or terms used by analysts to symbolize interpreted meaning in the data (Corbin & Strauss, 2015). In this study, concepts were used to name and represent the identified mechanisms. Dimensions describe the range or variation of a property (Corbin & Strauss, 2015). In this study, dimensions were employed to characterize and define the mechanisms identified. For example, the terms used in this study to construct the mechanisms were dimensions. Memos are written records of the analysis process. However, instead of traditional memos, narratives (Pentland, 1999) were utilized in this study to document and make sense of the analysis. Properties refer to the characteristics or qualities of a concept that differentiate it from others and provide specificity (Corbin & Strauss, 2015).

Grounded theory in the information systems domain involves some key guidelines (Table 11) to ensure rigor (Corbin & Strauss, 2015; Urquhart et al., 2010).

Table 11: Guidelines for Grounded Theory (Urquhart et al., 2010)

Guideline	Explanation	Evident in the Case Analysis
Constant Comparison	Constant comparison is the process of constantly comparing instances of data labeled as a particular category with other instances of data in the same category	- Coding of interviews in Atlas.TI and in mechanism development process following (Corbin & Strauss, 2015)
Iterative conceptualization	Researchers should increase the level of abstraction and relate categories to each other through a process of iterative conceptualization. In grounded theory, this is done using theoretical coding.	- Coding of interviews in Atlas.TI - Development and constant comparison in mechanism development process (Corbin & Strauss, 2015) based on inductive open coding
Theoretical sampling	Importance of deciding on analytic grounds where to sample from next in the study. Theoretical sampling helps to ensure the comprehensive nature of the theory and ensures that the developing theory is truly grounded in the data.	- Different research phases with mixes of data gathering, analysis, and discussion within the research team in which the research focus was constantly iterated and narrowed down
Scaling up	Scaling up is the process of grouping higher-level categories into broader themes. Scaling up contributes to the generalizability of the theory.	- During the stages of the mechanism development, more and more codes were assigned and the plausibility of dimensions, properties, and concepts was validated
Theoretical integration	Theoretical integration means relating the theory to other theories in the same or similar field. It is the process of comparing the substantive theory generated with other, previously developed, theories.	- During data analysis and mechanism development, theories in the digital innovation literature were constantly compared and discussed by the research team

The first guideline involves constant comparison which describes "the process of constantly comparing instances of data labeled as a particular category with other instances of data in the same category" (Urquhart et al., 2010, p. 369). This was conducted during the open coding of interviews and in the mechanism development process. The second guideline involves iterative conceptualization which describes that "researchers should increase the level of abstraction and relate categories to each other through a process of iterative conceptualization. In grounded theory, this is done using theoretical coding" (Urquhart et al., 2010, p. 369). The iterative conceptualization was accomplished in the case setup through multiple interview rounds and data analysis rounds where interviews were coded and the emerging themes were discussed in bi-weekly calls. Also in the development and constant comparison of codes and concepts in the mechanism development process (Corbin & Strauss, 2015) this was applied based on inductive open coding. Thirdly theoretical sampling which describes the "importance of deciding on analytic grounds where to sample from next in the study. Theoretical sampling helps to ensure the comprehensive nature of the theory, and ensures that the developing theory is truly grounded in the data" (Urquhart et al., 2010, p. 369). The study adheres to that principle by following different phases (Table 7) in which in every phase the research focus was adjusted. From the beginning with a quite broad focus on digital transformation and innovation initiatives which was followed by an introduction session where afterwards the research focus was narrowed down. Then, a first understanding of the OTA initiative was acquired after which the decision was made to focus on specific aspects of the OTA initiative after the coding of the emerging four themes. The next guideline of scaling up "is the process of grouping higher-level categories into broader themes. Scaling up contributes to the generalizability of the theory (Urquhart et al., 2010, p. 369). This was applied during the stages of the mechanism development where more and more codes were assigned and the plausibility of dimensions, properties, and concepts were validated following grounded theory procedures (Corbin & Strauss, 2015). Also the principle of theoretical integration was incorporated. Theoretical integration means "relating the theory to other theories in the same or similar field. It is the process of comparing the substantive theory generated with other, previously developed, theories" (Urquhart et al., 2010, p. 369). This was accomplished during data analysis and mechanism development theories in the digital innovation literature were constantly compared and discussed within the research team. Along with grounded theory concepts and guidelines, narratives played a central role in data analysis.

3.4.1.2 Narratives

A narrative approach is recommended for process approaches (Langley, 1999) and writing up narratives of events helps the researcher create a chronology of the events. For this case, narratives were considered the main product of data analysis, which is recommended for single case studies (Langley, 1999). This is the case, as it allows one to "achieve an understanding of organizational phenomena not through formal propositions but by providing "vicarious experience" (Lincoln & Guba, 1985, p. 359) of a real setting in all its richness and complexity" (Langley, 1999, p. 659). A narrative strategy here relies on "thick descriptions" of ongoing events. Often narratives are combined with embedded themes that are then the foundation for theoretical explanations. From the narrative perspective, theory is considered to be "an account of social process, with emphasis on empirical tests of the plausibility as well as careful conditions to the scope conditions of the account

(DiMaggio, 1995, p. 391). Thus, a narrative " is a story that describes the process, or a sequence of events, that connects cause and effect" (Pentland, 1999). Thus, patterns of events are theoretical constructs that can be derived from stories. Following Pentland (1999), a narrative has five core properties (Table 12).

Table 12: Properties of Narratives (Pentland, 1999)

Core Concept	Indicator for	Evident in the Case Study through
Sequence	Patterns of events	Events within each OTA Generation
Focal actors	Role, social network, and demographics	1) OTA Team was initially part of the IT department, 2) Product line representatives and teams
Voice	Point of view, social relationships, and power	Point of view and power come with the organizational embeddedness of actors, the product line principle, and the emergence of a product OTA with the Virtual Product Organization
Moral context	Cultural values and assumptions	Since PremiumCar is a luxury carmaker, PremiumCar's value and assumptions are in contrast to digital elements (size)
Other indicators	Other aspects of context	Other aspects included contextual changes such as competitive moves, the takeover, the IPO by PremiumCar, the implementation of EV's

Firstly a sequence that reflects the notion of temporal coherence (Langley, 2007) represented through a pattern of events (within each OTA generation as my embedded units of analysis). Secondly, each narrative has focal actors that take over a certain role, have demographics, and are embedded into a social network. Thirdly, these different actors have a voice representing their point of view, relationships, and power structures which informs their perspective (e.g., the relationship between IT and vehicle development teams). Fourthly, all these elements are embedded into an evaluative context that builds their frame of reference and carries a cultural context (e.g., PremiumCar as a luxury carmaker). Thus, for the data analysis, firstly profiles of each software update generation were created, and core information was gathered around these generations.

Then, in a second step seeking temporal coherence (Langley, 1999), a list of events for each narrative based on the empirical data was created (Appendix 8.2. – Chapter 1.5). This timeline was then validated and refined in an iterative fashion with different interviewees (Principal Product Owner (IT), and Release Train Engineer (IT)). To cross-validate stories and increase temporal coherence, different stories around the same event were compared and validated for coherence with the interviewees. Such narratives were complemented by the available internal and external sources, as well as data from workshops. This procedure led to a total of 14 narratives relevant to the research questions (see Table 13).

Table 13: Narratives at PremiumCar

No	Narrative

N.1.	FastCar's IBM and IIM for OTA
N.2.	The Software Update Process at Premium Car and the Business Connector
N.3.	The Control Unit Legacy of the Integrated Vehicle Architecture
N.4.	A Radical Departure: Mission E and Technology Carrier Model Delta
N.5.	The OTA Functional Controller
N.6.	The OTA Backend Start-Up Solution
N.7.	Becoming a Product – OTA Data
N.8.	Developing PCC OTA 1.0 – The Technical Cut
N.9.	Developing PCC OTA 2.0 – The Modulithic Cut
N.10.	The Virtual Product Organization
N.11.	OTA Data becomes an Agile Release Train part of the Virtual Product Organization
N.12.	The Software-Corp. Domain Architecture and Software Corporation
N.13.	Developing the Online Remote Update Next
N.14.	From KEFAG to Systems Engineering: Changes in the Product Development Structures

The grounded theory literature differentiates between different types of codes that are used in the data analysis process (Corbin & Strauss, 2015; Saldana, 2012) (Table 14).

Table 14: Types of Codes (Saldana, 2012)

Type of Code	Explanation
Open coding	Initial coding of the empirical data
Axial coding	Categorizing of open codes is also often used to reorganize data
Selective coding	Theory or concept-informed coding of the dimensions

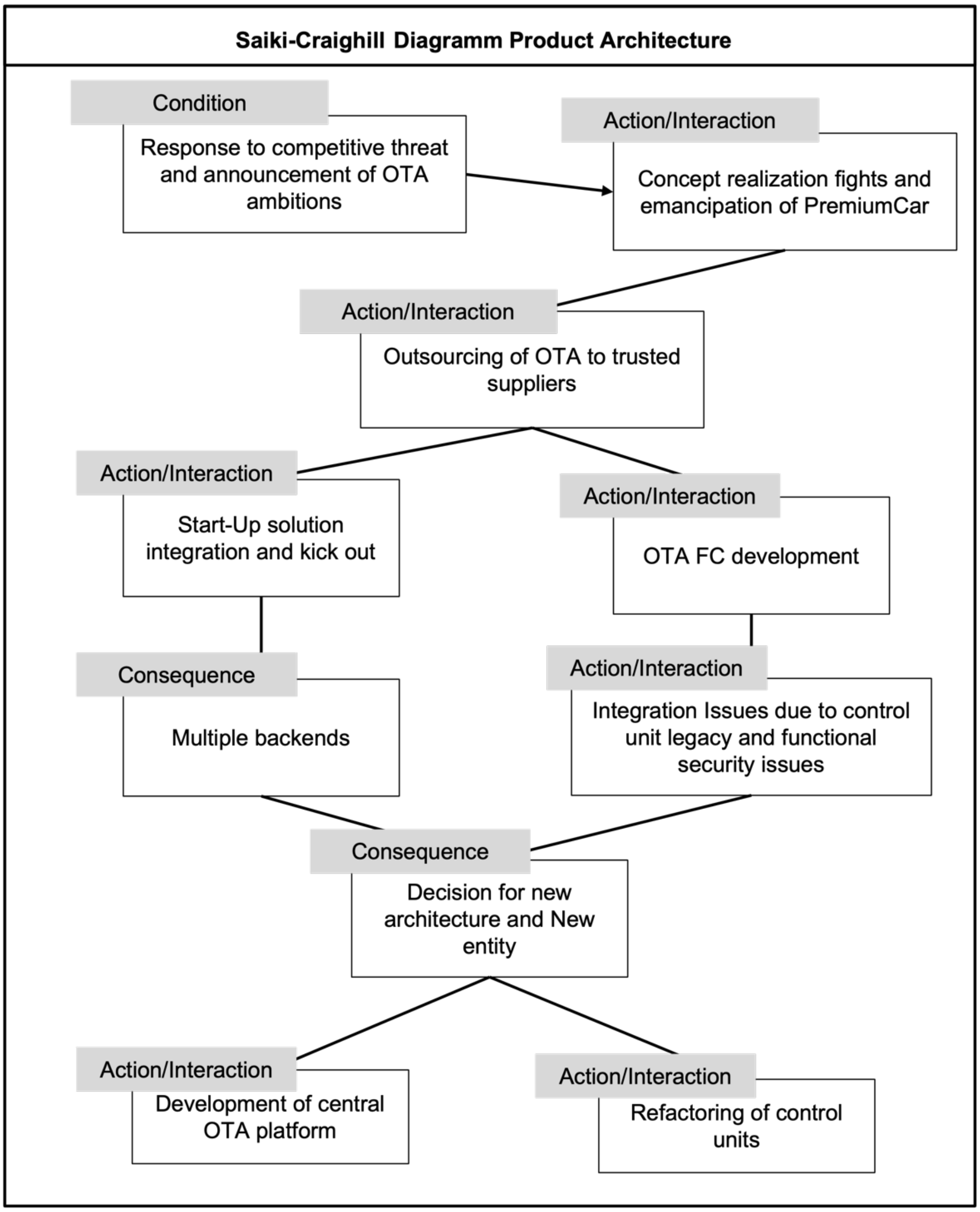
Open Coding is often applied as the first initial step of analysis where quotes from the empirical data are labeled often very close to the actual words used by the interviewees (Saldana, 2012). Then in the second stage often axial coding is performed to find overarching categories for the open codes (Saldana, 2012). Lastly, selective coding is applied to group the axial codes into higher-order dimensions. Such selective coding can be informed by the theoretical lens (Saldana, 2012).

For the actual analysis, a first open coding of interviews with key informants (Principal Product Manager, Senior Product Owner OTA, Senior Solution Architect, and Head of Department IT & Electronics) of the case events around OTA was performed where the inductive analysis led to 103 open codes, 63 axial codes that were organized around four selective codes around product architecture, product development, organizational structure and resource allocation.

After this first round of coding and in line with the overall process of the research strategy taken (Berends & Deken, 2021), Corbin and Strauss (2015) suggest selecting specific stories or narratives as the starting point of the analysis. Here, conditions that serve as triggers of the overall event are investigated, as well as actions and interactions of actors that lead to certain outcomes or consequences.

For example, for the dimension product architecture that emerged from the data, the narrative of the OTA Functional Controller served as the foundation to develop an initial understanding of the events which was visualized through a corresponding Saiki-Craighill diagram as suggested by Corbin and Strauss (2015) and depicted in Figure 9.

Figure 9: Saiki Craighill Diagram Product Architecture (1st Version)



From this Figure as a starting point, all axial codes that were related to product architecture questions were gathered and specified whether they referred to the condition, actions, or consequences of a product architectural change in the given context (Table 15).

Table 15: Coding Process Analysis Step 1 - Example Product Architecture

Condition/Action/ Consequence	Axial Codes - Product Architecture
Condition	Competitive pressure and inspiration; regulatory demands; changing customer expectations; control unit architecture; product architecture as a monolithic system; risk sensitivity for potential OTA failures

Actions	Pre-condition requirements, integration into vehicle communication architecture, integration of standardized interfaces within the product architecture, standardization of the hardware/device layer across vehicles, modularization of control units into areas, introduction of layered architecture, refactoring of functions
Consequences	Mix of old and new components on the service layer, multiplicity of backends, workshop updates instead of OTA updates, partial updateability of ECUs

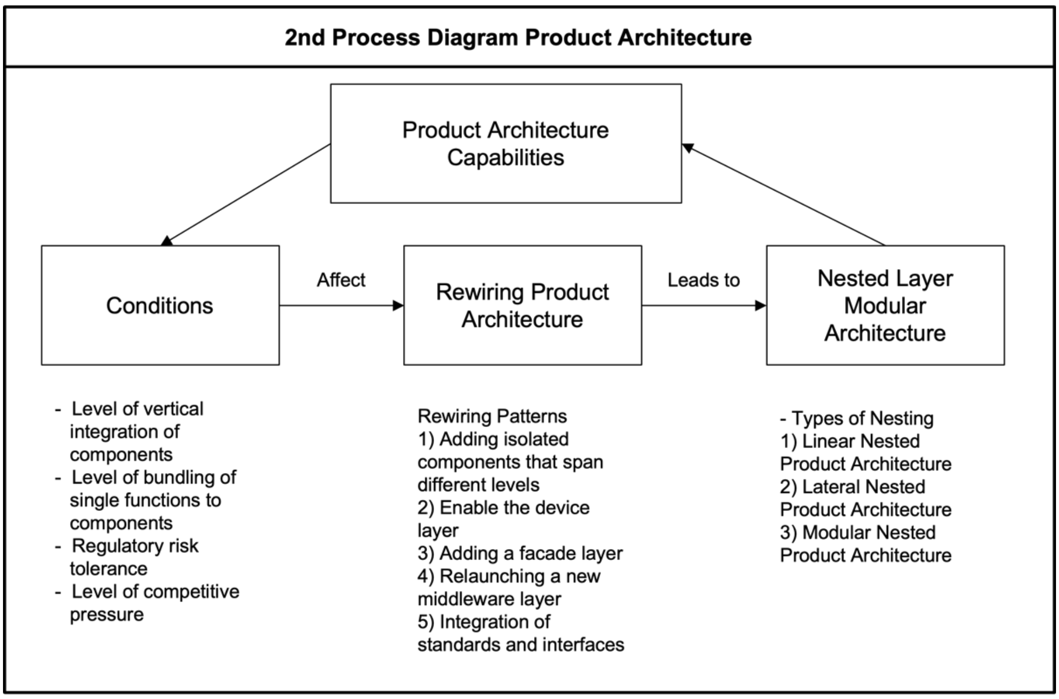
From this step, a set of concepts was developed to refine the specific conditions, actions, and consequences of the product architecture changes (Table 16).

Table 16: Coding Process Analysis Step 2 - Example Product Architecture

Condition/Action/ Consequence	Refined Concepts
Conditions	Vertical Integration
	Bundling of functions to components
	Competitive pressure
	Regulatory risk tolerance
Actions	Rewiring level
	Rewiring patterns
Consequences	Linear nested layered modular architecture,
	Lateral nested layered modular architecture
	Modular nested layered modular architecture

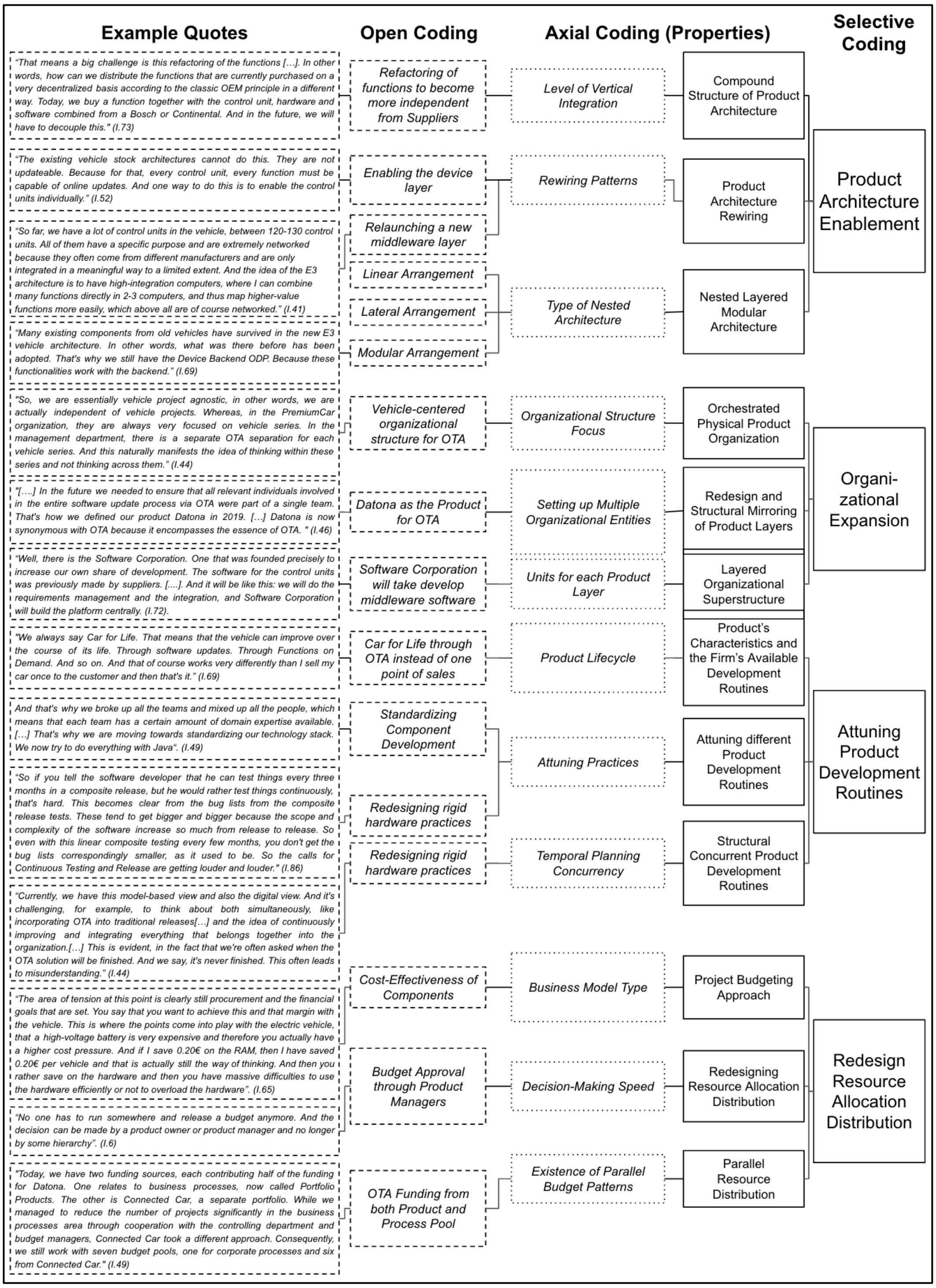
To sharpen the emerging concepts and their properties, subsequent process diagrams (Corbin & Strauss, 2015) were developed that represent the procedural nature of events around product architecture. The emerging codes and the diagrams then served as the basis upon which to construct a theoretical explanation of the events represented by a mechanism diagram depicted in Figure 10.

Figure 10: Coding Process Analysis Step 3 - Example Product Architecture



Such diagrams were then validated if they could explain other product architecture narratives (e.g., Software-Corp. Domain architecture narrative) and refined further until it led to a final diagram that received the label of mechanism since it was supposed to explain the changes observed. Based on those coding steps data structure emerged (Figure 11) as well as the mechanisms and the underlying dimensions.

Figure 11: Representative Data Structure



The final diagrams and all dimensions including an example quote are displayed in the results inductive analysis sections.

4 RESULTS

The results chapter is divided into two sections. The initial section provides an introduction to the chosen case company, PremiumCar, including its organizational structure, culture, and position within the automotive ecosystem. It also delves into the OTA initiative and the various OTA integration endeavors encompassing four OTA generations and their respective vehicle series.

The latter part of the results section delves into the findings derived from the case study. Drawing upon a comparative and inductive analysis of the case data, it presents four emerging themes. Additionally, a theoretical process model is crafted to elucidate how organizations entrenched in the industrial age achieve innovation in digital products.

4.1 Company Context: PremiumCar

PremiumCar is a boutique automobile manufacturer that specializes in crafting high-performance luxury sports cars. Further, PremiumCar is closely affiliated with the mobility conglomerate, MobilityGroup.

At present, PremiumCar boasts a product portfolio comprising four distinct lines, encompassing six unique vehicle series. These vehicles from sports cars, such as the Alpha and Zeta models, to SUVs, including the Beta and Epsilon variants, as well as sedans represented by the Gamma and Delta models. The Delta line is particularly notable as it marks PremiumCar's foray into fully electric vehicles, while all other models are available in various configurations, encompassing combustion engines, hybrids, and electric powertrains.

While PremiumCar is recognized as a successful small-scale niche player within the broader automotive ecosystem, it faces significant competitive challenges from emerging car manufacturers in various domains.

The case trends are anticipated to have a profound impact on the entire automotive industry and its value chain (Ketter et al., 2022; Tominaga et al., 2023). For instance, these developments have attracted new competitors from diverse sectors to enter the automotive market, including electric vehicle pioneers like Tesla and Nio, Chinese-based automakers such as BYD, technology firms like Google's autonomous driving subsidiary Waymo, as well as ride-sharing providers like Uber. These emerging competitors pose formidable challenges to established players like PremiumCar in the market (The Economist, 2022).

From an investor's perspective, PremiumCar represents a highly profitable opportunity. With an operating return on sales of approximately 16%, PremiumCar ranks among the most lucrative choices for shareholders seeking investment in the automotive industry.

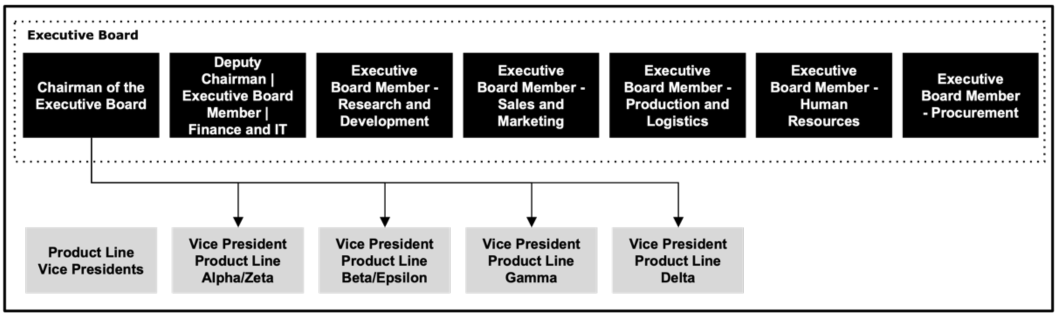
Much of PremiumCar's success can be attributed to its unique corporate culture—a mix of frugality and a proud tradition of race engineering. This unique culture has fueled numerous innovations in engine and chassis design. Over the past several decades, PremiumCar has not only honed its vehicles' distinct aesthetics but has also cultivated an organization that relies on a set of unparalleled engineering capabilities. These encompass a detailed product development process and an organizational structure optimized for the design and manufacturing of luxury sedans, sports cars, and SUVs at the highest standard.

At the heart of PremiumCar's organizational structure lies the product line principle, originally referred to as “Baureihenorganisation” in German. This principle underscores that the development of a new vehicle necessitates a substantial degree of autonomy and a predominantly independent organizational arrangement. PremiumCar's documentation offers detailed insights into the product line principle:

> *"The product line coordinates a vehicle family over its entire life cycle – from concept, through development, production, sales, and production support, to the end of production. [...] Each product line operates like a company within a company, and each reports directly to the Chairman of the Executive Board. […] The product line organization takes responsibility for the outcome of a vehicle project, while the standard line organization of the [research and] development department has the technical expertise and is responsible for the scope of its respective area [...]. The product line specifies the "what" and "when", which is to say that it defines the requirements and scheduling of the vehicle project; the line, in turn, defines the "who" and "how", that is the responsibilities and procedure" (External Source 8).*

PremiumCar's organizational structure is heavily influenced by the product line principle. In this structure, alongside the six board members, the Vice Presidents of the product lines directly report to the Chairman of the Board. This arrangement is illustrated in Figure 12, showcasing PremiumCar's organizational hierarchy.

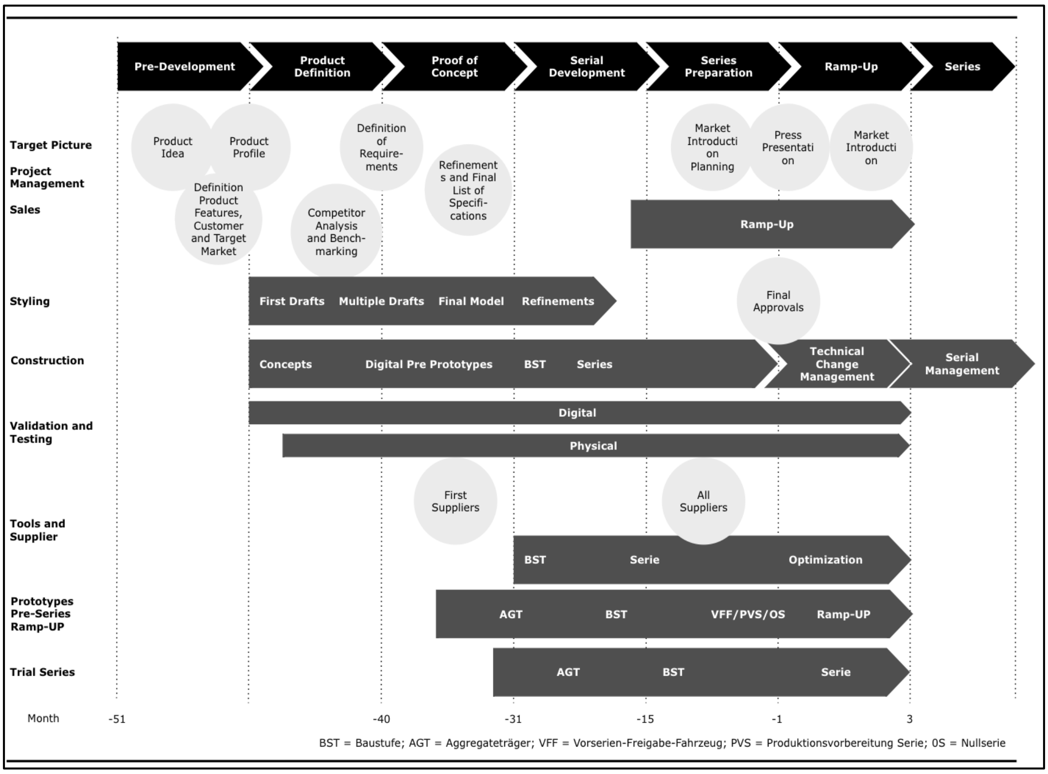
Figure 12: Board Areas and Product Lines at PremiumCar in 2022



The Research and Development (R&D) department of the board provides support to the product lines. R&D follows the KEFAG structure, which encompasses the car body (German: **K**arosserie), electrics (German: **E**lektrik), chassis (German: **F**ahrwerk), drivetrain (German: **A**ntrieb), and complete vehicle (German: **G**esamtfahrzeug) (Albers et al., 2019). Consequently, R&D teams collaborate temporarily with the product line organization to assist with various tasks. These tasks include tasks like sourcing and overseeing potential suppliers for each vehicle sub-system or addressing intricate technical matters related to component realization.

A third fundamental element within PremiumCar's vehicle development structures is the product development process, encompassing critical activities and milestones for creating a new vehicle (Rudert & Trumpfheller, 2015). This vehicle development process often coordinates a network of suppliers responsible for manufacturing individual components (Schuh et al., 2008). The product development process for the vehicle commences 51 months before the production start date with the formulation of the vehicle's core concept. It culminates with the commencement of production and the car's market introduction. Each phase features significant milestones, including the product mission, concept decision, design freeze, launch approval, pilot series, production start, and market introduction. For instance, during the design freeze phase, which occurs 25 months before production commences, the vehicle and its interfaces are definitively established and locked in (IS 15). The product development process for the car is depicted in Figure 13.

Figure 13: Car Development Process (Rudert & Trumpfheller, 2015)



The product development process necessitates collaboration among various internal departments at PremiumCar, in addition to external suppliers responsible for developing various components. An essential practice for orchestrating these diverse stakeholders and synchronizing them within the demanding vehicle development timeline is the "compound release" practice (German: Verbundrelease). This practice serves as a pivotal juncture for coordinating various stakeholders. As PremiumCar describes this practice:

> *"PremiumCar regularly tests the entire software in a so-called "compound release" during the development of a new model. This involves testing all the individual programs that will later be distributed across several dozen control units. The software is only allowed to be used in a produced car when everything functions faultlessly in the network."* (Winterhagen, 2015)

Compound releases are an integral part of the vehicle development process, occurring at regular intervals of 4-12 weeks, commencing during the serial development phase.

4.2 Context of PremiumCar's OTA Initiative

A pivotal technology in the connected car domain is Over-the-Air (OTA) technology, which, according to industry reports, has the potential to yield savings of up to $7,500 per vehicle. Additionally, it presents new sales opportunities through the sale of Functions on Demand (Koster et al., 2021). McKinsey similarly forecasted substantial growth in the software market of the automotive industry, projecting an increase from $34 billion to $84 billion between 2020 and 2030 (Gerding, 2019).

Gartner defines OTA[10] as "the ability to download applications, services, and configurations over a mobile or cellular network" (Gartner, 2023). This technology, initially popularized in the smartphone industry, is now expanding into other devices and domains, including the automotive and home appliances sectors (Bauwens et al., 2020).

Implementing OTA in cars relies on three technological prerequisites. Firstly, there must be an updateable device within the vehicle, typically a control unit referred to as the "Target Control Unit" at PremiumCar. This unit manages specific vehicle components and can be flashed with new software updates. Secondly, there must be a component onboard the vehicle capable of receiving the software update package, decrypting it, conducting pre-condition tests, and ultimately flashing the target control unit. Thirdly, there must be a backend platform external to the car that serves as the interface for the aforementioned component. This backend platform manages campaign management, coordinates the distribution of software packages to vehicles, calculates the software packages each car should receive, and constructs and encrypts each software package before transmitting it to the onboard vehicle component that receives the software package.

Therefore, OTA technology in the context of cars encompasses a collection of both onboard and offboard elements that perform tasks facilitating the transmission of software packages between a server and a client (the car).

In the well-established automotive industry within which PremiumCar operates, traditional software updates are considered a standard business process. Traditional instances of software updates occur at various stages, starting early in the vehicle development process, continuing on the manufacturing line, during the delivery process (port actions), and finally in the customer workshop. This practice also applies to PremiumCar, which has conducted software updates via cable on five occasions (see Table 17).

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[10] Experts differentiate between Software Updates via OTA (SOTA) and Firmware Updates via OTA (FOTA). In the case of SOTA updates, the actual software of a component is updated, whereas a firmware update (FOTA) serves as a prerequisite and equips the component slated for an update with the essential operating software (Bauwens et al., 2020). For the purposes of this thesis, the term OTA is employed, encompassing both FOTA and SOTA updates.

Table 17: Software Update Occasions at PremiumCar

No	Software Update Occasion
1	Flashing of components during the vehicle development process at compound releases (VR) for testing purposes
2	Flashing tests of single components during the vehicle development process in pre-development
3	Flashing of selected control units at the production line where they receive their first update
4	Flashing during so-called port actions where cars are flashed during the delivery process when cars were waiting in ports
5	Flashing at the customer workshop where flashing a control unit was a standard procedure to deal with bugs in components

The practice of running software updates for customers via OTA was explored by a few automakers quite early on. Updating car software through OTA, directly impacting customers, gained traction with the initial introduction of professional connectivity and infotainment functions in vehicles around the early 2010s (Hylving & Schultze, 2020; Svahn & Kristensson, 2022; Svahn et al., 2017; Weill et al., 2023). During this period, automakers began offering features such as navigation map updates and in-car entertainment system enhancements. However, it garnered significant public attention when Tesla incorporated OTA updates into its Model S sedan in 2012, making it a prominent feature (Lavrinc, 2012). As reported at the time:

> "*Over 100 Model S drivers will receive the auto industry's first-ever over-the-air operating system update for their new sedans within the next two weeks, Tesla says. In addition to a handful of minor code changes, the mandatory upgrade to 1.9.11 will tweak the range calculator to lower the car's estimated driving range by 35 miles.*" (Lavrinc, 2012)

This innovation, coupled with Tesla's continued provision of updates, spurred other manufacturers to embrace OTA as an industry standard. Tesla's noteworthy public relations move during Hurricane Irma in 2017, where they offered a free charging range extension via OTA to customers fleeing the hurricane, further expanded the recognition and adoption of OTA technology (Hsu, 2017).

Since then, OTA technology has evolved into a customer expectation and a profitable business model for automakers (Koster et al., 2021). Under the framework of Software-defined vehicles (Koster et al., 2021) or the term "Car for Life" (used by PremiumCar), OTA has become an integral component of every car manufacturer's digital strategy (Koster et al., 2021; McKinsey, 2021; Svahn et al., 2017; Weatherbed, 2022).

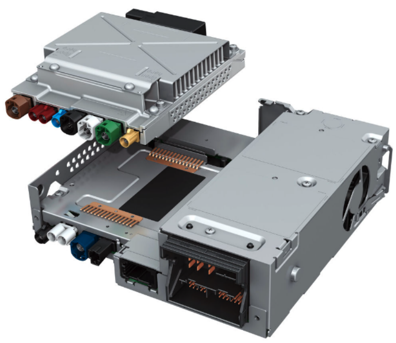
4.3 IMPLEMENTING OTA AT PREMIUMCAR

PremiumCar ventured into early experimentation with OTA for specific components, predominantly relying on an infotainment component developed and maintained by FastCar, an internal sibling company within the MobilityGroup, to facilitate this endeavor.

4.3.1 PremiumCar's Early Beginnings

PremiumCar's first OTA-relevant component was the onboard module of the Infotainment In-Car Module (IIM - Figure 14) along with the corresponding Infotainment Backend Module (IBM). Originally developed by FastCar in 2009, the IIM serves as the foundational multimedia unit in FastCar's vehicles, delivering multimedia and connectivity functions across its various generations. It consists of a core module centered around radio car control, encompassing multiple radio tuners, a sound amplifier, and interfaces to the data buses. Additionally, there is another module based on the Multimedia Extension (MMX) board, which, in conjunction with an Nvidia processor, manages media-related functions including navigation features, voice control, and telephone capabilities (FastCar, 2017).

Figure 14: Version of the Infotainment In-Car Module (IIM) (FastCar, 2017)



The IBM serves as the corresponding backend platform provided by FastCar for managing and transmitting updates to the IIM. Consequently, the IBM functions as the central platform through which various services can be activated, deactivated, or exchanged (Fonstad & Mocker, 2016).

In 2015, PremiumCar integrated the IIM2 and the IBM into their Alpha and Gamma models, marking the first generation of software updates via OTA. These updates primarily focused on improving navigation services, particularly updates to navigation maps.

The introduction of the second generation IIM2+ significantly expanded PremiumCar's OTA capabilities. Recognizing that efficient OTA updates depended on a fast and stable internet connection, PremiumCar introduced the connected gateway as a solution. Within the vehicle, the connected gateway serves as a router, facilitating communication between multiple protocols and connected services (Agashe, 2021). The IIM2+ incorporated support for the LTE standard, enabling PremiumCar to introduce new connectivity services that went beyond map updates.

For instance, leveraging live traffic data, the IIM2+ allows for route optimization based on real-time online data for selected vehicles (MediaCenter, 2017).

4.3.2 Technology Carrier Delta

In 2015, the role of OTA updates in the automotive industry underwent a significant transformation. Tesla pioneered OTA updates in 2012 and continued to provide reliable updates until 2015, consistently adding new features to enhance the user experience. Concurrently, the electric vehicle market began to expand, compelling PremiumCar to take action.

PremiumCar's management recognized these industry shifts, including the growing importance of OTA updates and the increasing popularity of electric vehicles (EVs). In response to these developments, PremiumCar unveiled a groundbreaking vehicle model - the Delta.

The Delta model was designed to serve as a “technology flagship” for PremiumCar. It not only marked PremiumCar's entry into the fully electric vehicle market but also aimed to cater to the digital-savvy demands of younger customers. PremiumCar's internal analysis revealed that in rapidly growing markets like Asia and the Middle East, the average customer age was significantly lower (around 35 years old) compared to their more established European market (with an average customer age of 55). These younger customers expected a user experience akin to their smartphones, including the ability to use applications such as Spotify and Google Maps while driving. This also entailed receiving regular software updates to address bugs and introduce new functionalities.

PremiumCar sought to meet these expectations, and in 2015, PremiumCar's chairman unveiled “Mission E”, the internal codename for the Delta model, at the international motor show in Frankfurt, Germany. In a subsequent press release following the motor show, PremiumCar emphasized the car's digital features, particularly its OTA capabilities:

> *“The concept vehicle can also be configured externally from a tablet via [Premium Car] Connect. Using “Over the Air and Remote Services”, the driver can essentially change the functional content of the vehicle overnight. A simple update via the integrated high-speed data module is all it takes to implement the travel guide or additional functions for the chassis, engine, or infotainment system.”* (Newsroom, 2015)

For PremiumCar, a company whose legacy was built upon combustion engines, the Delta represented not only a radical shift in drivetrain technology but also a transformation in exterior design and interior features. As the current Vice President (CEO) overseeing the Delta product line explains:

> *“It all started with Mission E, our concept for EVs, which we presented at the motor show. It was clear that such a vehicle requires a modern and appealing interior design, including a touchscreen user interface and multiple displays. And it was also clear that this needed a different level of electronics and software. And one learning from the smartphone industry*

was that once a car has a display and entertainment, it needs to be connected, and we need to be able to provide the vehicle with up-to-date software over the air all the time." (I.75)

This decision represented a profound departure from PremiumCar's prior connectivity efforts. Previously, PremiumCar could only provide OTA updates for a specific component (IIM). However, with the Delta model, the ambition was to expand OTA capabilities to encompass software updates for all conceivable vehicle components.

4.3.2.1 Development of the OTA Integration Concept

Internally, PremiumCar's management board initiated the pre-development phase during which a cross-functional team formulated a vehicle concept for the Delta model. This included a sub-team tasked with defining the technical requirements for OTA implementation. The sub-team, a novel project led by the product line, involved members from R&D, after-sales, and the IT/Electronics team. With the market introduction of the Delta model announced for 2019, the team had a clear objective. They needed to devise a concept that aligned with PremiumCar's high-quality standards and simultaneously offered a technically feasible solution within the given deadline. It was evident internally that this was an ambitious undertaking since the OTA project faced internal skepticism. Some managers doubted that OTA would be as relevant to customers as predicted, while others argued that the technical complexities of integrating OTA into PremiumCar's vehicle architecture would prove too formidable.

Furthermore, as part of the MobilityGroup conglomerate, PremiumCar had to coordinate its OTA efforts with the leading OTA brand within MobilityGroup, its sister company, FastCar. PremiumCar had a history of adopting core OTA components from FastCar (such as IIM and IBM). However, PremiumCar's vision for the Delta model was poised to challenge this practice, potentially deviating from the overarching MobilityGroup OTA strategy. The Vice President Delta (CEO) sheds light on the discussions:

"A key challenge was that we [PremiumCar] wanted to have a function that the group - specifically FastCar - was already working on similarly. Still, we wanted to have a different specification for this function. In the first few months of 2015, it was a real fight to set up a joint strategy in the group to realize OTA through common hardware and software components. FastCar wanted a different control unit concept to distribute additional OTA functions within the vehicle architecture elsewhere." (I.75)

As he explains, PremiumCar and FastCar had different integration concepts for OTA. PremiumCar's OTA team wanted to incorporate a dedicated OTA Functional Controller (OTA FC) to perform the flashing of other control units, whereas FastCar wished to avoid this and rely on the central control unit gateway. As the person responsible for the OTA Architecture and infrastructure - Flashing (VD) explains the details of the given status quo around the IIM:

"The aim was to realize software updates for the new model without a visit to the workshop. However, this new model is fundamentally based on the MLB-Evo architecture, which, unfortunately, is not inherently fully update-capable. What can be updated online in this case? Only the navigation data through the IIM. In this module, the navigation device and the radio are included, with a very rudimentary ability for the module to download and update its own software. FastCar had already taken a step further in developing this. Considering the external competition, it was essential to make progress." (I.66)

Keeping in mind that the IIM module was developed by FastCar, PremiumCar searched for a new way to integrate the OTA updateability. This required interfering with the existing control units and their online capabilities as he further explains:

"The vehicle platform and the IIM were supported by FastCar, which adds additional context. In this MLB Evo architecture, there were two control units, both of which had separate online capabilities at the time, meaning they were capable of communicating with backends. The aforementioned IIM and a so-called Connect Gateway. The Connect Gateway is also a central control unit that manages the vehicle's network. Typically, it hosts what are called 'gray' services. These are mobile online services like honking, flashing, displaying vehicle status, remote lock, and remote unlock. We then wanted to integrate something into the Connect Gateway for the new Model Delta, allowing us to delete control units. This was a crucial prerequisite for installing new software. FastCar rejected the Connect Gateway for this functionality." (I.66)

The rejection of FastCar triggered PremiumCar to develop a new control unit, called the OTA FC. This integration led to changes in the surrounding product architecture as he further explains:

"This rejection was the driving force behind PremiumCar's idea to develop a new control unit, essentially soldering in a diagnostic tool similar to what is found in workshops. Naturally, this required an online connection. The original idea was to use the Connect Gateway and incorporate a small software component there, providing the ability to download a software update as a package. This idea progressed to the concept phase, leading to the design of the hardware for the control unit. However, it was then communicated from the FastCar side that our concept to modify the Connect Gateway would not be allowed. Simultaneously, there was a minor architectural change in the MLB-Evo modular system. An enhancement was made. There were originally two control units, IIM and Connect Gateway. Both had their own SIM cards, which were needed to establish a mobile connection. They were entirely independent of each other as if there were two separate mobile phones in the vehicle. Then, a new control unit was planned, called the Connectivity-Box, or C-Box for short. It was introduced so that all connections - WLAN, Bluetooth, and mobile network

> *- were integrated into a single control unit. Various antennas, including the GPS antenna, were connected to it. The IIM module, for example, no longer needed to have its antennas and transmit independently; instead, it communicated with this C-Box. The Connect Gateway operated in the same manner. It became apparent that the OTA FC (Over-The-Air Functional Controller) could communicate directly with the C-Box. This initiated the first step toward incorporating new services into this control unit gateway, functioning as a proxy and passing data through. PremiumCar then had to consider how the OTA FC could communicate with the Connectivity-Box. The utilization of the C-Box was already on paper at that time. However, during the subsequent analysis, a problem was discovered: the OTA FC needed to use the vehicle's diagnostic systems. We wanted to use the same mechanism for software updates as when going to the workshop. In the workshop, you connect to the diagnostic port to read errors. That's what we wanted to leverage, as otherwise, we would have had to touch every control unit to introduce new functions. This required tapping into the vehicle's diagnostics. Additionally, those 'gray' services I mentioned earlier, in the Connect Gateway, also partially used the diagnostic capabilities. Then, there would have been two control units accessing it, necessitating coordination between them, and so on. The decision was ultimately made that PremiumCar needed to incorporate those 'gray' services into the OTA FC. This meant PremiumCar had its own gateway. The software responsible for functions like honking, for example, had to be integrated by the OTA FC. The advantage was that the Connectivity-Box existed, having been introduced. Therefore, the 'gray' services were moved to the OTA FC. The usual communication routes still passed through the gateway. Essentially, a tunnel was built to the gateway. It's not an elegant solution, it complicates things, but it was done to ensure compatibility with all other components within the system."* (I.66)

PremiumCar's leadership resolved this conflict by deciding to depart from the MobilityGroup strategy, aligning themselves with the recommendations of their engineering teams. This decision was primarily influenced by time constraints and feasibility, as articulated by the Vice President Delta (CEO):

> *"Our team was skeptical and believed it was a risky approach regarding implementation and complexity [talking about FastCar's approach]. We were also afraid that we could not implement the [FastCars] approach until the announced Start of Production date of Delta. And I think that was the decisive argument for us to say we do it differently. And in the end, we decided that we were deviating from the group approach because we relied on our requirements, and we didn't see a way for a comprise with FastCar and the group."* (I.75)

Consequently, the decision was made to veer away from the MobilityGroup's strategy and proceed with the OTA concept formulated by the OTA team. This concept encompassed two critical elements: the OTA Functional Controller (OTA FC) as the onboard component responsible for managing the distribution and updating of other control units in the vehicle and secondly, a backend OTA solution that facilitated communication between the in-car client and the server hosted at PremiumCar. While PremiumCar's IT team initially sought to develop the backend internally, the product line representatives opted for an off-the-shelf product called the "OTA Backend Start-Up Solution (Pseudonym)". Notably, OTA Backend Start-Up Solution was initially developed by an Israeli-based startup, here called "OTA Start-Up" (pseudonym), which was subsequently acquired by Tier 1 Supplier (pseudonym)[11], in 2015. With the OTA realization concept in mind, PremiumCar's product line teams chose to outsource the development and production of both OTA components - the OTA FC and the corresponding backend - to Tier 1 Supplier. Tier 1 Supplier had previously demonstrated its competence as a reliable automotive supplier, having successfully manufactured key components for previous automotive projects. Despite objections from the IT teams, the decision was finalized to commission the OTA development to Tier 1 Supplier, with the emerging OTA team being responsible for integrating Tier 1 Supplier 's deliveries for both the OTA FC and the OTA Backend Start-Up Solution.

4.3.2.2 Realizing OTA – The OTA FC

The OTA FC played a crucial role in the realization concept. In contrast to previous OTA generations focused on the IIM, the OTA FC promised access to all control units in the vehicle. It was meant to perform a task that many existing control units couldn't handle independently – specifically, diagnosing the existing software package on the target control unit and flashing it with the new software package, as explained by the Principal Product Manager (IT):

> *"To achieve OTA, we had no alternative but to integrate a new OTA FC. In the workshop, each control unit is flashed through an external tester. There is no mechanism for an existing control unit to flash itself. The OTA FC was essentially like putting this external tester into the vehicle; it had the same functions. The OTA FC can diagnose and flash other control units."* (I.46)

However, the OTA team encountered multiple challenges in turning this idea into reality, both from a budgeting perspective and in terms of technical integration.

From a budgeting standpoint, successfully integrating the OTA FC required justifying the required investment of €150 per car. The business case calculation for the OTA FC could include potential savings of around €50 per workshop event. However, this still fell short of the €150 required for the OTA FC. Calculating potential revenue from OTA was challenging due to the lack of experience PremiumCar's team had with OTA and the unpredictability of Functions on Demand sales. As the Senior Product Owner (S) recalls:

> *"The question was, how do we justify the investment of around €150 for the OTA FC to the product line? [...] Our budget scheme focuses on calculating a business case for vehicle components that need to generate*

[11] Tier 1 Supplier then become part of a large south korean manufacturing conglomerate in 2017

> *positive returns within a maximum of six years after the investment. […] So, we started calculating for the OTA FC […] how many updates are we doing every year? 1-2? And how many people will buy the planned Function on Demand Feature? And for what price? So it's hard to predict, but you need to make it happen; otherwise, the product line won't meet its budget requirements and profitability goals."* (I.52)

The OTA team eventually managed to develop a business case that was approved by the product line. However, having overcome one challenge, another emerged related to the control unit legacy within the vehicle architecture.

The Delta project required significant investments in battery and energy management, as it was PremiumCar's first EV. Therefore, as is typical for new vehicle projects, PremiumCar's engineering teams relied on existing components from previous vehicles, adapting them if necessary. This approach saves development time and boosts productivity by spreading development costs across multiple car models.

However, with the existing vehicle platform used for model Delta, PremiumCar's engineering teams inherited some architectural complexities related to the design and communication infrastructure.

Cars are, to some extent, modular products with a vehicle being composed of various subcomponents (e.g., brakes, engine, drivetrain, wheels). Thus, a new car like Delta is developed by recombining different modules, such as the drivetrain and chassis, with only a few components being newly designed and developed. This allows for economies of scale, as development costs can be shared among multiple car models. The vehicle architecture is modular on the component level, where individual modules like the IIM can be integrated into different vehicles using standardized interfaces (e.g., CAN or BUS protocols). Over the years, the integration of more complex components from various suppliers has increased. While in the past, vehicles had only 5-10 control units exchanging information, modern vehicles now have more than 100 control units. This growth in control units, along with expanded connectivity services, has made vehicle communication architecture more complex. By the time of the Delta project's Start of Production, there were more than 120 control units in the vehicle. What was once celebrated as a unique integration effort has become a structural premise, as the growth in control units has made the communication architecture within and outside the vehicle more complex. For example, the infotainment module includes various elements, such as displays, the instrument cluster, loudspeaker systems, and other infotainment functions like a USB connector. This network of control units poses challenges, as described by the Principal Product Manager (IT):

> *"For example, infotainment. It's not just one control unit; it's a module with different elements—for example, displays and the instrument cluster, which also shows infotainment content. There are loudspeaker systems, such as a combination of Bose and Burmester Sound Systems. And all that in combination with other infotainment functions, like a USB connector. So, it's not just one control unit; it's always a network. This network can be relatively small, as in the case of infotainment, but you can also see the*

entire vehicle as a network of different control units. Because all control units have something to do with each other somewhere and communicate with each other to provide vehicle functions." (I.47)

This tightly integrated communication architecture became a challenge, as interfaces within the communication architecture were not clearly defined. The OTA Architect – Data-Driven Services Delta explained the challenges related to signal communication, using an example:

> *"A vehicle... is very signal-driven. Let's take an example. You buy a sensor of some kind, a temperature sensor. You install it in the car, and it sends its data to the bus in Kelvin. Then, everyone who needs this temperature signal listens to it. Let's say there are 30 clients, i.e., receivers of this signal (other control units). What's difficult now is changing this sensor. Let's say we find a better, cheaper manufacturer for temperature sensors, but they provide data in Celsius. That would be a big problem because there's no standardization like in IT, where you have different layers that abstract functions. In the vehicle, you'd have to access all 30 clients to make the adjustment from Kelvin to Celsius."* (I.69)

Such interdependencies became highly relevant during the integration of OTA, specifically of the OTA FC as a meta-control unit within the car. Firstly, with model Delta being an EV, energy management became an issue. In the past, with combustion engine cars, energy consumption was a key parameter, impacting fuel consumption. Fuel consumption is important for customers, regulatory bodies, and approval processes. The OTA FC presented a challenge because the target control unit needed to be activated for the OTA FC to flash another target control unit. As the Senior Product Owner OTA (S) explained:

> *"The Head of Department E/E wanted to integrate the OTA FC to allow flashing software packages of other control units. This had implications for the other control units and their energy management. When the OTA FC sends a signal to another control unit, that control unit needs to be 'awake' to receive the signal. Model Delta had over 100 control units, so we had to approach 100 individuals responsible for the control units and tell them to ensure their control units could be 'awakened' and updated from an external device. Typically, control units are designed to minimize energy use to affect fuel consumption. But with the OTA FC, this was different because we needed to access each of them at any time."* (I.52)

Furthermore, due to safety requirements, OTA updates can only occur when the car's ignition is off. From a regulatory perspective, OTA updates are prohibited while driving. However, many control units are only activated when the ignition is on. This is a necessary condition because if a control unit is not active, it cannot receive an update, as explained by the OTA Architecture & Infrastructure - Flashing (VD) expert:

> *"The exterior sound control unit only operates when the ignition is on in the Model Delta architecture. This is due to the wiring. The control unit is only powered when the ignition is switched on. If the ignition is switched*

off, the exterior sound control unit lacks power. In such a case, you cannot update the exterior sound control unit with the ignition off. However, this was a requirement to ensure that the vehicle was not in a ready-to-drive state during the update, and it led to the exclusion of the exterior sound control unit from the update process due to wiring constraints." (I.65)

These examples of interdependencies in the vehicle's electrical communication architecture were perceived as significant threats because the team was concerned about functional security issues. For instance, Tesla had to recall 362,000 vehicles after an OTA update related to their driver assistance system. The US regulatory body, the National Highway Traffic Safety Administration (NHTSA), investigated 19 accidents in which the software update resulted in unprecedented and uncontrolled vehicle situations (Reuters, 2023; The Guardian, 2023).

PremiumCar, as a reputable brand, was determined to avoid such issues at all costs. Although PremiumCar had not encountered situations like their US-based competitor, the integration of the OTA FC was viewed as a potential source of such problems. During the Delta development, the team also encountered challenges related to functional security. The new OTA FC was interacting and communicating with other control units and the vehicle's head unit. In this context, issues related to signal communication raised concerns about functional security, as explained by the Principal Product Manager (IT):

"Throughout the project, we faced numerous challenges related to functional security. We had to ensure that the OTA FC, which required extensive permissions on the vehicle's bus system to flash other control units, did not disrupt signal communication among the various control units. The OTA FC collected cyclic data from other control units and transmitted it to the backend. We had to ensure that this data collection did not compromise the vehicle's functional security. We encountered situations that were far from ideal. For example, there were instances where the power-assisted steering failed while the OTA FC was collecting data. To address these issues, we introduced an additional tester to assess functional security before the OTA FC could communicate with other control units." (I.46)

As time progressed and the Start of Production drew nearer, the team put extensive effort into integrating the OTA FC, ultimately achieving success.

4.3.2.3 Realizing OTA – The OTA Backend Start-Up Solution

With the decision to incorporate the OTA FC as a crucial onboard component, PremiumCar's product line team also faced the challenge of finding a suitable OTA backend solution. As previously mentioned, they decided to procure the off-the-shelf product OTA Backend Start-Up Solution. Subsequently, the emerging OTA team was tasked with integrating the OTA Backend Start-Up Solution into PremiumCar's IT infrastructure. The Principal Product Manager [IT] elaborated on the core features of the product:

" OTA Backend Start-Up Solution provides a comprehensive OTA solution, encompassing functions such as update package calculation,

documentation integration into our backend system, and the administration and management of various software packages and versions." (I.46)

The decision to outsource the OTA solution was handled through a typical product line process. The team sought suitable suppliers who could present their concepts, which were evaluated based on predefined criteria. In the case of OTA Start-Up, strategic considerations also played a role in the decision-making process. According to the OTA Architecture & Infrastructure - Flashing (VD) expert:

> *"In 2016, we initiated the conceptual tender for the OTA interface during serial development. OTA Start-Up emerged as a potential candidate from the Proof-of-Concept phase. Subsequently, Tier 1 Supplier's acquisition of OTA Start-Up enhanced its appeal, as Tier 1 Supplier was considered a trustworthy partner. The selection of OTA Start-Up was more strategic in nature. While the technical performance evaluation of OTA Backend Start-Up Solution could have been more rigorous, the focus in the automotive industry is on whether the supplier can scale up if the vehicle becomes popular. Additionally, PremiumCar already had a trusted relationship with Tier 1 Supplier due to their collaboration on the Connectivity Box, making OTA Start-Up a logical choice."* (I.65)

As a result, the product line opted for the OTA Backend Start-Up Solution in February 2016. However, the OTA team encountered significant challenges during the implementation of the OTA backend. During the collaboration, it became apparent that the OTA Backend Start-Up Solution conflicted with PremiumCar's existing cybersecurity and privacy guidelines. The Developer OTA Connect and Functions [EX] provided a detailed explanation of how the OTA Backend Start-Up Solution operated:

> *" OTA Backend Start-Up Solution offers a server landscape through the cloud, allowing servers to connect to devices such as cars or phones and facilitate communication. It provides an overview of all vehicles within the software, as well as an overview of all control units for each vehicle. OTA Backend Start-Up Solution also offers the mechanisms required to update multiple vehicles from software level 1 to level 2. We provide the software version to the OTA Backend Start-Up Solution server, which then handles the rest. The process involves an OTA Backend Start-Up Solution client in each vehicle, which periodically reports information, checks for pending updates, and initiates downloads or uploads. The client also reports its status, which is displayed within the OTA Backend Start-Up Solution software. This system provides OTA Start-Up with comprehensive insights into the ECU software of the entire fleet."* (I.66)

However, granting such detailed access to vehicle status data conflicted with PremiumCar's cybersecurity policy, necessitating adjustments to align the OTA Backend Start-Up Solution with PremiumCar's policies. The Developer OTA Connect and Functions [EX] further clarified:

> *"All data leaving PremiumCar must be encrypted to prevent unauthorized access until it is decrypted within the vehicle. Consequently, the functionality of OTA Backend Start-Up Solution was significantly reduced to essentially serve as a data packet transfer mechanism. We only send information regarding completed downloads, while all other information is handled by the gateway. This shift altered the fundamental mechanism, transforming it into the distribution of encrypted packets to vehicles and expecting encrypted response packets in return."* (I.66)

From a backend perspective, this situation compelled the OTA team to develop many backend components themselves. The Senior Solution Architect (IT) responsible for this area explained:

> *"While attempting to integrate OTA Backend Start-Up Solution, we discovered that we were unable to use it as originally intended due to our internal cybersecurity policies. This limitation meant that we could only utilize about 1% of the product's capabilities. Consequently, we found ourselves in a situation where we needed to develop everything that OTA Backend Start-Up Solution was supposed to handle, including update package calculations, documentation, and the administration and management of different software packages."* (I.55)

At a later stage, during the relaunch of Model Delta in 2020, when the OTA team had made progress in developing their backend solution, they sought approval to assume full responsibility for OTA Backend Start-Up Solution's tasks. This transition was accepted by the product development department, as explained by the Principal Product Manager [IT]:

> *"OTA Backend Start-Up Solution constitutes a backend system with a control unit component in the vehicle. The support for this component falls under the Product Development department. Initially, IT provided support due to our involvement in application management. However, in 2020, we proposed that IT take over all aspects of the backend, which was eventually approved. This shift was driven by the new UNECE requirements for Model Delta updates, which rendered the use of OTA Backend Start-Up Solution obsolete."* (I.45)

The key change was due to legislative alterations at the UN level (UNECE), requiring carmakers to provide individualized update packages for each vehicle, a capability that OTA Backend Start-Up Solution lacked. Moreover, OTA Backend Start-Up Solution had limited functionality for operating Function on Demand features, prompting the OTA team to eliminate OTA Backend Start-Up Solution entirely for the release of a new vehicle. The Principal Product Manager [IT] clarified.

> *"We had to create another backend for Model Delta because OTA Backend Start-Up Solution was not equipped to support certain use cases. OTA Backend Start-Up Solution was designed for sending out software packages to multiple vehicles simultaneously, which is the typical process for a*

software update. However, it couldn't handle individual vehicle packages, which we required for use cases like Function on Demand. Customers could purchase features in the store, which were already integrated into the car but locked. These purchases resulted in individual vehicle packages that needed to be sent to each specific vehicle. As OTA Backend Start-Up Solution couldn't accommodate this, we had to develop a new backend solely for these individual vehicle packages. With the introduction of UNECE, it became impossible to use OTA Backend Start-Up Solution for anything other than individual vehicle packages. This limitation led to our decision to discontinue OTA Backend Start-Up Solution." (I.46)

These environmental changes prompted the OTA team to take over the complete development of the backend, receiving approval from the product development department. The Principal Product Manager [IT] elaborated:

> *"We decided to expand our existing backend to handle this, which we had already begun developing. This change allowed us to manage both Function on Demand and software updates. Initially, we phased out the OTA Backend Start-Up Solution backend. Subsequently, we proposed the development of the client component in the vehicle as well. Many of our challenges stemmed from the fact that the backend, client, and control unit did not originate from a single source. Working with a supplier through contracts and complex compound releases posed difficulties. In August or September of the previous year [2021], we received approval from the product development department to build control unit software as well."* (I.46)

For the IT team, this was a drastic leap forward for the OTA team since now the coordination with Tier 1 Supplier was reduced, and the OTA team could coordinate the development of the OTA backend internally.

4.3.2.4 Realizing OTA – Emergence of the 1st PremiumCar OTA Backend OTA Data

Due to OTA Backend Start-Up Solution's non-compliance, PremiumCar's OTA team found themselves tasked with developing their OTA backend IT system to handle tasks initially intended for OTA Backend Start-Up Solution. Consequently, the team embarked on the development of their own OTA backend, relying on microservices, as explained by the Senior Solution Architect:

> *"Looking back, we had limited knowledge of setting up OTA. Therefore, we began with workshops to collectively brainstorm the various microservices required for OTA execution. We understood that for OTA to function, we needed components for sending updates to vehicles. Thus, we created a microservice for package generation. We also recognized the need to identify the software package associated with each vehicle, leading us to incorporate a package manager. Step by step, we integrated various microservices essential for OTA."* (I.58)

However, as they developed the new backend, they aimed to encompass the entire software update process, including other board areas such as sales, production, and R&D. This had previously been a challenge. Before the OTA project, the IT department supporting OTA updates had an extensive set of tools collectively referred to as the Business Connector, for which the OTA team was responsible. This also included tools for managing control unit software.

However, as OTA updates gained significance, the IT team also considered the IT architectural landscape. Since each board member area was represented by a dedicated team within the IT department, multiple teams were working on similar IT applications as part of the OTA software update process. Thus, such projects involved various internal stakeholders. The Principal Product Owner (IT) described the challenges of collaboration across board member areas, citing an example:

> *"Consider customer service, for instance. There's a requirement to globally distribute software artifacts needed in customer workshops. This is logical because customer workshops worldwide require the most up-to-date data to assist customers promptly. Similarly, OTA updates have similar requirements, where we need to distribute artifacts globally so customer vehicles can retrieve the necessary flash containers for updates. However, coordinating this across departmental boundaries was challenging. Data processed by the customer service department had to be managed by systems overseen by the sales department. This led to the existence of two applications for essentially the same fundamental task."* (I.44)

Given these departmental boundaries, the team contemplated a way forward. The OTA software update process, whether executed via OTA or through another communication channel, necessitated collaboration among internal and external stakeholders. Internally, product development and product line teams played vital roles, working initially with a supplier, along with production, where control units were often flashed, and After-Sales, representing workshops where customers received updates. This introduced dependencies on various internal and external parties. The Principal Product Manager (IT) provided an example from another internal department and how the team sought to manage it:

> *"We certainly have dependencies. For instance, if we want to roll out a router update, we rely on receiving a list of vehicles scheduled for that router update from an aftersales system known as the WWS system. Only once we obtain this list can we proceed with the router update. Alternatively, we can take a different approach and handle vehicle updates independently. Currently, we can already perform router updates within the system demo either through the WWS or our solution. By building our solution to use the same interface as the WWS, we aim to minimize dependencies."* (I.48)

Previously, such cross-departmental collaboration occurred within projects, with each department represented. However, the OTA team recognized that achieving OTA required a more collaborative approach. Consequently, they made two crucial decisions. First, they sought to transition from the old project-based approach to an organized product-based approach. Second, they phased out the old Business Connector platform and explored a new IT backend architecture for OTA.

4.3.2.5 Realizing OTA – From OTA as a Project to the Product/ART OTA Data

As illustrated in the OTA project, a key element for coordinating various actors from different departments was the use of projects. These projects followed a conventional waterfall approach and were typically centered around specific functions or tools, such as a project aimed at creating a new data management feature. The Head of OTA-Delta described the traditional development approach during these initial generations:

> "*In IT, these projects are classic waterfall projects. There was a conception phase in which the overall concept was completely thought through. In the implementation phase, the concept was passed on to the related departments, the IT and the product development departments. And the IT project leads were responsible for implementation. And it was represented and prioritized in the relevant committees."* (I.70)

For the OTA team, managing multiple non-aligned projects posed a challenge. Many of these projects touched upon the same IT components, such as data management. The Principal Product Manager (IT) explained:

> *"When considering Model Delta, functions like Function on Demand or software updates, they all had requirements related to the data management toolchain. These were separate projects. Even data management improvements that started as individual projects. When you have only one team, challenges arise in determining the correct sequence and prioritization of these individual projects, as they were not previously prioritized against each other. Synergies between projects were not considered. So, we had to figure out how to move away from this project-based approach and establish a product-oriented approach where requirements could flow into a product and be prioritized against each other."* (I.50)

This setup revolved around PremiumCar's product line orientation, with a strong focus on individual product lines rather than a holistic approach across the organization. The Principal Product Manager (IT) emphasized the need to shift from a vehicle project-centered perspective to one that is vehicle-independent:

> *"We should be vehicle project-agnostic, meaning we should not be directly concerned with every vehicle project. However, PremiumCar's organization is structured around each product line. For instance, the CEO's office has separate OTA responsibilities for each product line, such as Model Gamma, Model Delta, and Model Epsilon. Unfortunately, our thinking often aligns with this structure. We aim to consolidate the OTA topic into one, considering releases of different OTA versions to continuously develop it. For example, Release 3 for Model Delta and Release 4 for Model Epsilon. However, this is challenging due to both the organizational structure and project budgets."* (I.44)

Both the OTA team and PremiumCar's digital transformation office leadership recognized that their organizational structure and task distribution presented challenges for software update development. In response, they initiated various activities.

While the team already used agile approaches for individual projects, particularly for operating projects related to software updates, the expanded scope of software updates presented the OTA team with an opportunity to move away from project-based structures entirely.

While the team already used agile approaches for single projects for operating projects around software updates, now the with the expanded scope for software updates, the OTA team saw an opportunity to fully break free from the project setup. The team defined a product called "OTA Data [pseudonym]. They envisioned their work as a product that included the former business connector and additional applications, placing them at the center of attention. The Principal Product Owner (IT) clarified:

> *"In the past, we were primarily focused on the business connector, essentially serving as a bridge between two systems. However, it became clear that this approach wouldn't work in the future, as we needed to ensure that all relevant individuals involved in the entire software update process via OTA were part of a single team. That's why we defined our product OTA Data in 2019. OTA Data comprises the business connector, numerous applications around it, and the relevant personnel, encompassing three modules: data management, error management, and test management. OTA Data is now synonymous with OTA because it encompasses the essence of OTA. Unfortunately, organizational boundaries prevented us from incorporating all components of OTA Data into OTA. Nonetheless, we're working on achieving end-to-end integration within OTA Data. We named it 'Continuous Delivery for Onboard Software."* (I.46)

This transition did not alter the organizational structure itself, as the team remained part of the IT function. However, it marked the starting point for gradually adopting more agile roles and practices as part of the OTA Data product. One year later, their efforts received further momentum when a new digital initiative known as the "Virtual Product Organization" introduced plans to implement a scaled agile framework (SAFe). Identifying OTA Data as a suitable pilot project, the Virtual Product Organization's leadership saw it as one of the first Agile Release Trains at PremiumCar. The exact implications of this change were not yet clear, but it offered opportunities to address structural dependencies that had hindered the OTA team's progress. They hoped that through the Virtual Product Organization, they could transition away from multiple projects with individual budgets, steering committees, deliverables, and deadlines. The Principal Product Owner (IT) explained how the project-based approach constrained the OTA team's efforts:

> *"Currently, we receive budgets from 14 different projects, each approved by relevant committees. Each project defines its scope, work packages, and budget per package. For instance, for Release 4 of SOTA, let's say we receive a million*

> *euros to develop a production feature. We must utilize that million euros exclusively for that feature, regardless of its importance. We predetermined what the solution should look like, and this million is based on an estimate for the entire project. We are obliged to spend that entire budget, with no regard for whether the last 20 percent, the most resource-intensive part, is worthwhile. This applies to all the other 13 projects as well. We can only prioritize within each project."* (I.44)

Despite the introduction of the Virtual Product Organization, the OTA team continued to be largely funded by projects, as explained by the Principal Product Owner (IT):

> *"Today, we have two funding sources, each contributing half of the funding for OTA Data. One relates to business processes, now called Portfolio Products. The other is Connected Car, a separate portfolio. While we managed to reduce the number of projects significantly in the business processes area through cooperation with the controlling department and budget managers, Connected Car took a different approach. Consequently, we still work with seven budget pools, one for corporate processes and six from Connected Car."* (I.49)

4.3.2.6 Integrating OTA – The PremiumCar OTA Backend 2.0.

After the initial deployment of the first OTA backend for the initial vehicle releases of Model Delta, the OTA team had an opportunity to redesign their first OTA backend when a relaunch was planned for 2021. The decision to overhaul the backend stemmed from performance issues encountered with the microservice-based architecture used in the initial OTA backend. As explained by the Principal Product Owner:

> *"To execute a software update for the Model Delta, for instance, several technical steps are required. We must calculate which vehicles are affected, determine the appropriate package, encode it, deliver it, receive the result, evaluate the result, and apply it. This involves seven steps, and we initially implemented them using seven microservices. This approach had advantages, allowing us to scale individual components as needed. However, it introduced significant overhead. We experienced a high degree of communication between components, considerable infrastructure complexity within our business service, and poor availability. A failure in any component would result in a system-wide failure. If you calculate the availability, assuming each component is at 98 percent, you end up with an overall availability that more closely resembles 70 or 80 percent. This falls short of customer expectations."* (I.49)

In response to these performance challenges, the team aimed to transition to what they referred to as a "modulithic" approach, essentially a modular monolithic architectural strategy. The Principal Product Owner elaborated on this approach:

> *"We are moving away from the rigid microservice architectures. Our experience with the Delta project revealed that microservice architectures entail relatively high complexity and costs. Therefore, we are now primarily building monoliths, but these monoliths adhere to specific architectural principles. We call this approach a 'modulith.' When we consider how we would build the Delta today, we envision it as an application sliced by capabilities. The deployment artifact, which is what we intend to roll out and launch, represents the server—a single component. However, within this server, we slice it vertically into individual capabilities. This approach eliminates infrastructure complexities when these capabilities need to communicate. We deploy a single artifact, allowing us to scale services more efficiently. If a service becomes too large, which was a challenge in the past, we can easily extract a slice. For instance, we could isolate the software update package from an application and treat it as a separate deployment artifact. This way, we start with a modulith, a well-structured foundation, and adapt based on experience, making cuts if necessary. We no longer start with a microservice architecture only to realize it doesn't fit. Instead, we begin with a modulith and iteratively fine-tune it based on lessons learned."* (I.49)

To provide more clarity, the team categorized components based on capabilities that prioritize business value and integrated them into the IT architecture, as explained by the Principal Product Owner:

> *"We've taken the previous seven components (microservices) and divided them into slices, grouping everything related to a specific function into a service. Consequently, seven components have now merged into four. For example, we have a 'software update' component that encompasses all functions required for software updates, including vehicle calculation, package creation, package encryption, result reporting, and more. Each capability is represented within a specific service. We scale these services individually. If one component fails, such as the software update, other capabilities like live diagnostics, Function on Demand (FOD), and data collection continue functioning seamlessly. We do this technically, recognizing that there may be some overlap between services either through shared libraries or code duplication."* (I.49)

This architectural redesign resulted in a shift towards components that reflect actual business capabilities, creating a modular and scalable architecture.

4.3.2.7 Realizing OTA for Model Delta – Last Mile and Learnings

Model Delta commenced production in 2019. However, throughout the latter stages of the Product Development Process, the OTA team encountered challenges related to the integration and testing of their OTA components within the product development process, specifically within a practice known as "compound release." In a compound release, various vehicle components are tested together, including the entire collection of control units used in the car, ensuring an end-to-end test for the first time. In the context of OTA, this entails someone in Aftersales releasing a software update package, the OTA backend processing and transmitting the package to the vehicle, and the OTA FC (Flash Controller) flashing the software package to the target control unit. Compound releases were scheduled as part of the product development process on a three-month cycle. During these compound releases, teams received error lists to address any issues. The Head of OTA – Delta (IT) elucidated this practice:

> *"In the past, we used to conduct compound releases every three or four months. This involved coordinating all the control units within the network to form a network release. This meant that on a specific day, 120 control units with their new software and hardware versions were combined. These control units were then installed in the vehicle and subjected to a three-week testing period. If something didn't function as expected or as specified in the requirements, or according to the department head's wishes, you had to wait for another three or four months before revisiting the issue."* (I.70)

For OTA, this practice posed challenges as the three-month testing cycle was perceived as too infrequent by software teams accustomed to continuous testing and release practices. In response to this challenge, new practices were developed. The Head of OTA – Delta (IT) explained:

> *"In IT, we have more agility because we can deliver results in the next two-week sprint. This led us to realize the need for shorter iterations. We introduced what we call 'development drops' to address this challenge. Between official deliveries, we incorporate intermediate steps. We conduct smaller compound releases or post-integration compound releases. We perform 'DevDrops,' where a new software version arrives from the service provider, allowing us to focus on a specific control unit for testing within the development workshop."* (I.70)

This approach was also applied within the OTA context, enabling key components to be tested together without requiring access to a fully assembled vehicle. The Head of OTA – Delta (IT) provided an example:

> *"In the OTA context, consider a typical setup with aluminum boxes on a trolley. It includes a connectivity box for telecommunications control, a gateway for distribution, the OTA-FC (tester), and the infotainment system with a display. With this set of ECUs, you can test OTA functions without needing all the target ECUs installed in a vehicle or a car with all the components. Using this OTA setup, you can send a software package via the air interface. You observe the interaction on the infotainment system, such as prompts to 'Install software now' or 'Yes/No/Later.' Logs and traces capture the interactions between ECUs. This allows us to monitor precisely how the ECUs behave during the testing process."* (I.70)

The product development process, particularly the compound release approach with its set milestones, required the OTA software team and their backend to align with vehicle processes and adhere to specified timelines. Consequently, the OTA team had limited opportunities for testing, resulting in late testing cycles. The Principal Product Owner (IT) explained:

> *"The vehicle cannot perform OTA updates independently; it relies on the Backend. Thus, we needed to commit to specific milestones within the Vehicle Release (VR) compound releases, each involving a set of predefined features. However, this presented two challenges. First, vehicle development operates on a waterfall model, where requirements are compiled and sent to suppliers who deliver software for each milestone. Testing occurs after the delivery. If issues arise, you must wait for the subsequent VR compound release, typically three to four months later, to address them. This process posed difficulties for us because our development was exploratory. We only had the opportunity to integrate our work during the VRs, with no continuous development interaction with the vehicle. Therefore, we could not continuously test our software against the current vehicle version. To conduct tests, we required a specific level of vehicle component readiness. However, all vehicle components and software were built exclusively for VR milestones. Consequently, we only had testing opportunities every four to five months. Even when testing opportunities did arise, we sometimes couldn't utilize them because the product line teams prioritized other aspects of testing and didn't appreciate why we wanted to test the Backend at such an early stage. As a result, we started testing quite late. To provide a timeline: the project commenced in 2016, with the first software artifacts delivered in early 2017. Our first real testing opportunity came at the end of 2019 or the beginning of 2020, coinciding with the start of production in late 2019. Therefore, we began testing at the end of 2019, but we encountered multiple errors and issues that we were unable to address officially because, by that point, the vehicle was considered complete. In vehicle development, there is always a point where further integrations become challenging. Consequently, we devised a term within our team called 'Backaround,' which essentially means a workaround within the Backend. We had to resolve all vehicle issues in the Backend since we could continuously develop there. However, this approach introduced complexity into our system because we had to address any issues arising in our Backend. To address these within the vehicle system, we would have needed to submit formal change requests, which was a costly and bureaucratic process."* (I.48)

As a result, the OTA team and their developed backend had to integrate within a process initially designed for hardware development. The challenges encountered within this product development process and its compound release structure constrained the team's ability to pursue a practice of continuous release and integration, which is standard in software development. These challenges ultimately led to the launch of an OTA version that was not fully prepared, and the team continued to work on OTA updates even after the first vehicles were sold. Alongside technical challenges, these procedural issues posed significant challenges for the team. The Vice President heading the Delta product line emphasized the decision and summarized the issues:

"At the outset, the goal was to make all ECUs OTA update-capable. However, during the development process, we gradually had to abandon this vision. One reason was the realization that the volume of data transferred via the OTA interface was enormous. Another reason was the complexity of interactions between ECUs, which proved more intricate than initially estimated. Additionally, we needed to reconsider security requirements. To illustrate, just for the PremiumCar Communication Management module, which primarily encompasses the navigation system and the central head unit for radio and navigation functions, we were dealing with gigabytes of data that needed to be transferred. The control units were not originally designed to handle such large data volumes, and neither were the software and processes capable of efficiently managing them." (I.75)

4.3.3 New Architecture – New Beginnings?

With the Start of Production for Model Delta in 2019, the competitive landscape and the significance of software updates via OTA underwent significant transformations. By this point, delivering software updates via OTA had become an industry standard for PremiumCar's customers. The term "software beats spaltmaße [gap dimensions]" (Gerding, 2019) gained prominence, serving to contrast public perceptions and the strategies of emerging car manufacturers like Tesla and Polestar, who embraced software-defined vehicles. While traditionalists critiqued variations in gap dimensions in their competitors' cars, these newcomers leveraged OTA to continuously offer unique features that customers appreciated.

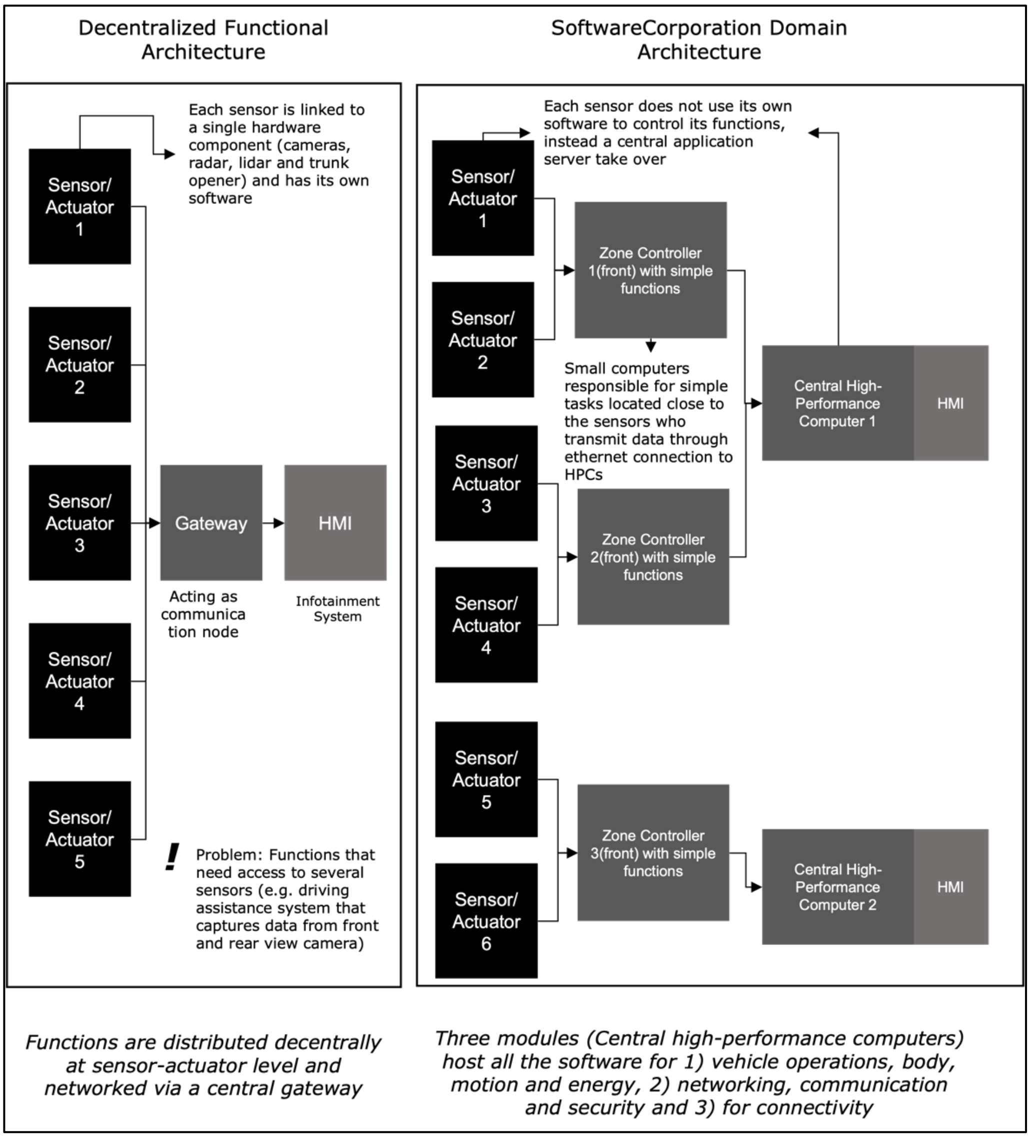
Furthermore, PremiumCar's management, as part of Mobility Group, recognized these shifts in the automotive landscape. Reflecting on their experiences with Model Delta, they made strategic decisions in response.

The management boards of Mobility Group and its affiliated brands made the strategic choice to consolidate numerous digital units within Mobility Group and integrate software teams from its brands. They initiated the establishment of a new subsidiary, SoftwareCorporation. This subsidiary was entrusted with spearheading the development of a novel vehicle architecture known as the Software-Corp. Domain architecture (refer to Figure 15). This architecture was designed to facilitate OTA capabilities from its inception and replace the outdated, decentralized control unit architecture that PremiumCar grappled with during the Delta project.

Central to this architecture, which SoftwareCorporation was tasked with crafting, were two high-performance computers, as detailed in an official document:

"Software-Corp. Domain Architecture stands for an end-to-end electronic architecture. It has two high-performance computers at its heart: ICAS1 and ICAS3, where ICAS stands for In Car Application Server. [...] The ICAS modules raise the performance capability of the hardware and software to a level that opens up a completely new spectrum of possibilities." (Appendix 8.2. - External Source 19)

Figure 15: Software-Corp. Domain Architecture (SoftwareCorporation, 2021)



SoftwareCorporation set out to reassign tasks that were previously handled by up to 150 control units within each car to a few centralized High-Performance Computers (HPCs). These HPCs were referred to internally by that name. To achieve this objective, the Software-Corp. Domain Architecture relied on three layers: a device layer, an onboard operating layer, and a backend layer.

On the mechanical device layer, physical components were equipped with sensors and actuators that would take over the functions previously managed by the control units. Zone controllers were introduced to oversee communication between different sensors and actuators based on the distinct zones within the vehicle. Thus, through the zone controllers a hardware abstraction layer is introduced into the product architecture.

Moving to the operating layer, high-performance computers were responsible for executing intricate computational tasks using a standardized operating system known as MobilityGroup.OS. This operating system also doubled as a development platform for applications run in the vehicle backend. As elucidated in a Software Corporation document:

> *"At the hardware level, at the heart of the unified architecture, is the consistent centralization of the control of functions via central high-performance computers. Sensors in the vehicle are then completely decoupled from the functions they perform. Instead, a few zone controllers will take over the computation of simple tasks. These are small computers located in specific zones of the vehicle, such as the front and rear. They sit close to the sensors to reduce the length of cables in the vehicle. They then transmit their data to new high-performance computers via an ethernet connection. The high-performance computers are at the core of the new unified architecture. They can control important sensors and also reliably calculate highly complex tasks [...]."* (Appendix 8.2. - External Source 19)

This new vehicle architecture was designed to enable PremiumCar, along with all other MobilityGroup brands, to seamlessly implement software updates via OTA. The Epsilon model from PremiumCar was slated to become the first model in which the initial version of the new Software-Corp. Domain Architecture would be integrated. To realize the Software-Corp. Domain Architecture, SoftwareCorporation employed five HPCs, with the third HPC designated to host OTA functionality. Consequently, functions previously managed by components like the OTA FC and the IIMs were relocated to one of the new central computers, namely HPC 3. Additionally, on the backend side, a new platform called Online Remote Update Next was introduced, replacing the multiple previous backends that had been used for software updates.

4.3.3.1 OTA Backend Development - Software-Corp. Domain Architecture

While the management team laid out the strategic plan for the Software-Corp. Domain Architecture, middle management was tasked with figuring out how to realize this vision by decoupling different components and refactoring functions. The Head of Connected Car explained the task of refactoring functions:

> *"A significant challenge lies in refactoring the functions. In other words, how can we redistribute functions that are currently procured in a highly decentralized manner, following the classic OEM principle, in a different way? Today, we acquire a function combined with the control unit, encompassing both hardware and software, from suppliers like Bosch or Continental. In the future, we will need to decouple this arrangement. This entails separating the software through an abstraction layer and then overlaying an application framework that operates on one or a few central computers."* (I.73)

This refactoring of functions also implied a different distribution of tasks in the value chain of vehicle manufacturing. This was due to the highly integrated communication architecture in the past, in which many services ran on only a few control units. The Head of Connected Car gave an example of the connected gateway, a key component used to operate OTA:

"If I want to perform a software update on a relatively complex control unit, such as the Connected Gateway, it's challenging because nearly 70 services are running on it. The Connected Gateway essentially serves as the network gateway in the car, mediating communication between various networked Ethernet control units. Updating the software on the Connected Gateway requires securing the entire process in isolation. This control unit has been typified, which means it contains data that needs to be reported to regulatory authorities for vehicle homologation. This tight coupling of hardware and software in a control unit makes it difficult to update because so much is dependent on it." (I.73)

Thus, the tightly integrated communication architecture necessitated the decoupling of functions from control units and reallocating those functions. PremiumCar's approach involved two stages: first, decoupling functions through refactoring to create partitions that could be updated in isolation, and second, reducing the number of ECUs in the vehicle.

"Currently, our primary challenge arises when a function requires access to numerous ECUs (Electronic Control Units). In such cases, we encounter a dependency issue, where a single ECU that cannot be updated can disrupt the entire update process. Therefore, our objective is to minimize the overall number of control units and reduce the number of control units associated with each function. We are pursuing this goal in two stages. Initially, we aim to decouple functions through refactoring, creating partial partitions that can be individually updated. This might result in updating not just one control unit, but possibly six. However, these six units would be self-contained, allowing us to secure and update them in isolation. Subsequently, in the second stage of this process, we will focus on reducing the overall number of ECUs." (I.73)

These changes had significant implications for overall value creation with key suppliers, as they now needed to integrate new interfaces into their components. The Head of Connected Car illustrated this with an example:

"Consider the example of opening the convertible roof. This is a typical function that we source from a supplier, encompassing everything from anti-trap protection to button control, including hardware and software. Another supplier may provide remote vehicle status, allowing you to check whether the roof is open or not via a mobile app. Now, we first need to integrate these functionalities. There should be a documented interface, something like an API which is today often not there. In the old paradigm, we'd simply install a control unit for opening and closing the roof and another one for interfacing with the app, containing all the logic for vehicle status and service control. For instance, if a thunderstorm was approaching and you wanted to close the convertible roof using your smartphone app, it should happen without any safety issues. Achieving such functionality requires discussions with both control unit suppliers, convincing them to decouple their software and provide an interface, essentially relinquishing part of their business." (I.73)

The ambitions for the Software-Corp Domain Architecture were bold, and PremiumCar's Epsilon model served as a pilot to pioneer and test this innovative architecture. Although SoftwareCorporation developed the entire technology platform, the OTA team was also assigned the task of developing a subcomponent of the platform called Online-Research Update Next (ORU Next), an ongoing endeavor.

4.4 FINDINGS: PREMIUMCAR'S OTA INITIATIVE

PremiumCar encountered substantial organizational and technical challenges during the implementation of OTA across various vehicle generations. Based on inductive data analysis, four central concepts emerged, revealing the disparities[12] between PremiumCar's aspirations and the tangible outcomes achieved with OTA. These four concepts (see Table 18) are 1) product architecture, 2) product development, 3) organizational structure, and 4) resource allocation.

Table 18: Key Concepts

Concept	Unit of Analysis	Evident in the Case
Product Architecture	Architectural design choices	Design choices for OTA architecture (e.g., decision for the OTA FC)
Product Development	Product development routines	Routines part of PremiumCar's product development process (e.g., compound releases)
Organizational Structure	Organizational design decisions	Decision for restructuring existing organizational arrangements that affect the OTA initiative (e.g., Virtual Product Organization))
Resource Allocation	Funding distribution practices	Practices to allocate resources (e.g., portfolio process) and to measure success (e.g., metrics).

Product architecture revolves around the architectural decisions made during the OTA initiative, encompassing choices related to the integration of the OTA FC, among other considerations. These decisions span both the selection of onboard vehicle components essential for OTA and the configuration of the offboard IT landscape within PremiumCar's IT systems.

The product development encompasses a set of routines within PremiumCar's product development process. It includes routines for both hardware and software development. Notably, it involves practices such as compound releases as part of the product development process at PremiumCar.

The organizational structure concept relates to decisions concerning the design of the organization. This includes changes made to existing entities, as seen in the transition within the Virtual Product Organization. It also involves the establishment of new organizational entities like Software Corporation.

Lastly, the resource allocation concept pertains to the practices for distributing budgets and funding the OTA initiative. It encompasses resource allocation practices, such as portfolio processes, and changes in metrics to assess the progress of the OTA initiative. The following sections introduce each of these concepts. We first provide a comparative analysis of the various OTA generations, outlining the alterations that occurred. Subsequently, we employ an inductive analysis to elucidate the underlying reasons for these changes.

[12] Following Robey and Boudreau (1999) the analysis focuses on discrepancies evident in the data.

4.4.1 Product Architecture

Product architecture, defined as “the arrangement by which a product's functionality is allocated to physical components" (Ulrich, 1995, p. 419), forms a crucial foundation of the product and is the focal point for the recombination efforts required to achieve digital product innovation (Yoo et al., 2010).

In the context of the OTA initiative, where the car and its various components constitute the actual product, OTA can be considered a digital product innovation enabling a generation of new product features. PremiumCar identified four key capabilities (see Table 19) facilitated by OTA technology: running software updates, conducting remote diagnostics, offering new Functions on Demand, and accessing vehicle life data for data analysis opportunities.

Table 19: OTA Capabilities

No	OTA Capability
1	**Software Update** involves the ability to update control unit software within the vehicle over the air, which, for example, affords bug fixing of existing software artifacts.
2	**Life Diagnose** allows PremiumCar’s engineers to help customers with issues remotely over the air with access to critical parameters of the car.
3	**Function on Demand** allows selling new features and services over the air. That means customers can purchase additional features (Extended range, more horsepower, etc.).
4	**Data Analysis** involves PremiumCar’s internal opportunity to remotely gather data on their cars on the road to learn and improve components and functions.

OTA technology enabled PremiumCar to remotely install software updates across various vehicle components, eliminating the need for customers to visit workshops for bug fixes. The Live Diagnosis capability empowered PremiumCar's engineers to assist customers remotely, addressing any issues they encountered. Functions on Demand presented PremiumCar with an opportunity to generate additional revenue by remotely offering new services and features to customers. This could involve features like temporary horsepower boosts or extended battery range. The data analysis capability allowed PremiumCar to remotely collect data on specific components, enabling them to learn and optimize these components and functions for the benefit of their customers.

The product architecture that could afford those capabilities in the OTA context encompasses all the components necessary to facilitate an OTA update, including the various layers of the product architecture.

To provide readers with an overview of the intricate changes in the product architecture, a comparative analysis offers insights into the different layers involved and introduces modifications made to the product architecture. Subsequently, in the inductive analysis, the mechanism known as “Product Architecture Enablement” is introduced to elucidate how these changes impact the product architecture and how PremiumCar endeavors to achieve a fundamental aspect of digital product innovation – a layered modular architecture (Yoo et al., 2010).

4.4.1.1 Comparative Analysis

Over the four generations of OTA updates, the product architecture consists of four different layers which are a content layer, a service layer, a network layer, and a device layer involved in the layered digital technology architecture (Table 20 and Figure 16). The content layer pertains to services carried out through OTA technology, such as the transmission of a software update package to the control unit or the provision of a Function on Demand package to the customer.

The service layer, also internally referred to as the OTA backend layer, encompasses components external to the vehicle responsible for providing, calculating, and transmitting the software package to the vehicle. In the 1st and 2nd generations, this involves the IBM, in the 3rd generation, the IBM, OTA Backend Start-Up Solution, and PremiumCar's first OTA Backend (PremiumCar Backend Platform 1.0), and in the 4th generation, the ORU Next platform.

Table 20: Product Architecture Layers of OTA

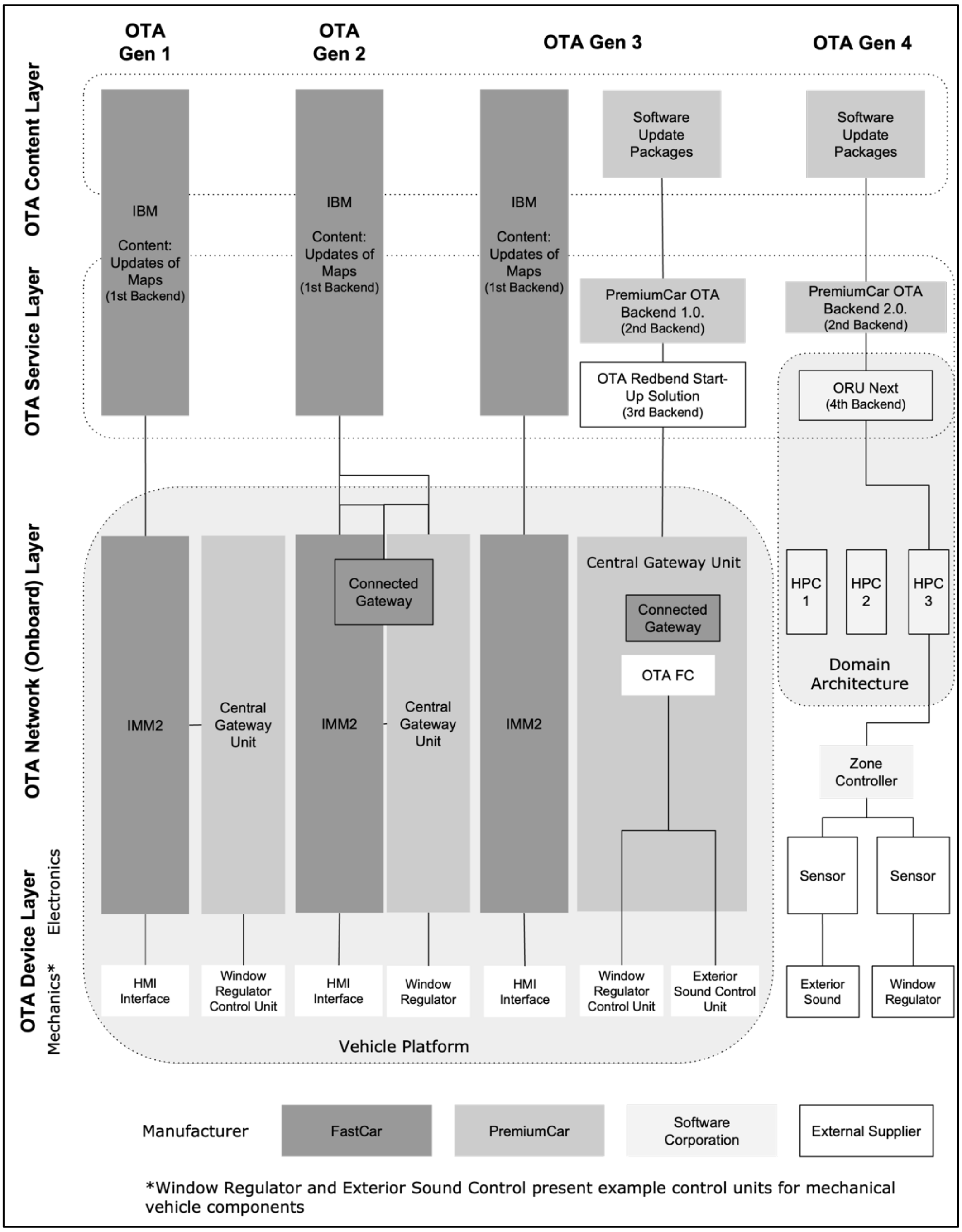
Layer (Yoo et al. 2010)	**Explanation**	**Evidence in the Case**
Content Layer	The content layer involves actual services being performed through the OTA technology, such as the software update of a control unit or the provision of a Function on Demand.	- 1st and 2nd generation: Software updates of Navigation Maps - 3rd generation: Software Updates of 23 control units and first Functions on Demand - 4th generation[13]: Software updates for all control units and Functions on Demand
Service Layer (OTA Backend)	The service layer refers to the actual OTA backend layer and the components outside of the vehicle that provide, calculate, and transmit the software packages to the vehicle.	- 1st and 2nd generation: IBM - 3rd generation: IBM, OTA Backend Start-Up Solution, and PremiumCar Backend Platform 1.0 - 4th generation: PremiumCar Backend Platform 2.0, Online Remote Update Next Platform
Network Layer (Onboard)	The network layer involves components part of the vehicle that receive and distribute software packages to OTA target control units.	- 1st generation: direct update - 2nd generation: Connected gateway - 3rd generation: Connected gateway and OTA FC - 4th generation: HPC and zone controller
Device Layer	The device layer involves the basic mechanical and electronic components that are supposed to receive an update. At PremiumCar, such components were often called OTA target control units (OTCU).	- 1st and 2nd generation: IIM - 3rd generation: Control units operating mechanical components (e.g., window regulator) - 4th generation: Mechanical components and sensors

The network layer, internally designated as the OTA onboard layer, includes components within the vehicle that receive and distribute software packages to OTA target control units. In the first generation, these components are unnecessary

[13] Not clarified as the vehicle was still in development, so only based on announcements.

as the IIM OTA directly receives OTA updates. In the second generation, the connected gateway is integrated, while the third generation sees the addition of the OTA FC. In the fourth generation, the OTA onboard layer is built by the HPC 3.

Figure 16: Scheme of Product Architecture Changes OTA



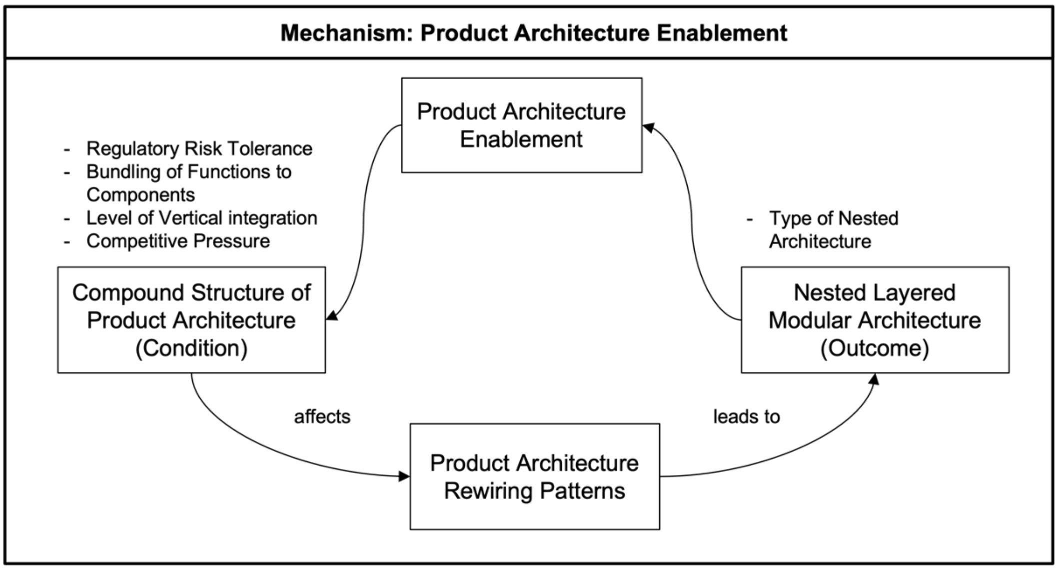
Lastly, the device layer refers to the fundamental mechanical and electronic components slated to receive an OTA update. These often consist of control units or components, also known as OTA target control units (OTCU). In the first and second generations, this involves the IIM, while in the third generation, a set of control units is responsible for operating various mechanical components like the window regulator. In the 4th generation, it encompasses mechanical components and sensors.

Regarding the OTA product architecture, two significant shifts are discernible. The first shift occurred with the integration of the OTA FC and OTA Backend Start-Up Solution in the third generation. In light of PremiumCar's ambitions to substantially expand OTA capabilities, particularly for the new model Delta, PremiumCar made the strategic decision to enhance the vehicle architecture. This involved the integration of a dedicated control unit, the OTA FC. Additionally, PremiumCar opted to incorporate a solution from an external vendor. However, non-compliance with cybersecurity policies necessitated the development of a new internally developed PremiumCar backend. The second shift in product architecture revolved around the development of the Software-Corp. Domain Architecture and the introduction of the HPC 3, which assumed responsibilities previously handled by other onboard components for OTA tasks. The Software-Corp. Domain Architecture represents MobilityGroup's and PremiumCar's response to the prevailing decentralized architectures and PremiumCar's aspiration for a layered vehicle architecture that would enable separate layers to be updated relatively independently. However, achieving this layered vehicle architecture required PremiumCar to decouple the electronic communication architecture and reassign tasks previously managed by control units to the HPCs. The rationale behind these two primary shifts in product architecture is elucidated in the subsequent inductive analysis.

4.4.1.2 Inductive Analysis

To explain the shifts in product architecture, the inductive analysis revealed a mechanism referred to as "Product Architecture Enablement" (Figure 17).

Figure 17: Mechanism Product Architecture Enablement



Product architecture enablement explains how industrial-aged incumbent firms with highly integrated product architectures dominated by design principles of physical components, engage in digital product innovation by rewiring their integrated product architectures, leading to a form of a nested layered modular architecture. The mechanism explains the conditions under which Product architecture enablement operates, the practices involved, and the resulting outcomes.

In terms of activating conditions, the compound structure of the preexisting product architecture becomes an essential prerequisite for the move toward digital product innovation. Here, the concept of the compound structure of the product architecture has four properties (see Table 21).

Table 21: Dimension Compound Structure of Product Architecture

Dimension	Properties of Dimension	Representative Quote
Compound Structure of Product Architecture (Condition)	The level of vertical integration describes the extent to which the firm manufactures key components within its boundaries, resulting in the firm's component architectural knowledge about the product architecture.	*"That means a big challenge is this refactoring of the functions [...]. In other words, how can we distribute the functions that are currently purchased on a very decentralized basis according to the classic OEM principle in a different way Today, we buy a function together with the control unit, hardware and software combined from a Bosch or Continental. And in the future, we will have to decouple this."* (I.73)
	The level of bundling of functions to components describes the number of components required to perform a single function.	*"If we just look at the unit in the center console with the control concept and modify it, it has an impact on many functionalities in the car. For example, I change the control of the seat heating with a new icon. I can no longer slide a trackbar from left to right; now I have to somehow turn it in a circle. [...] All of this affects many functionalities that are interconnected in the vehicle. [...] It may be that the seat heating works perfectly. But what happens when I also set the seat cooling to level three at the same time? What are the consequences, what cross-dependencies does that have on other functions?"* (I.86)
	The level of regulatory risk tolerance describes the willingness to engage in practices with insecure outcomes and regulatory insecurity.	*"In principle, even when enhancing an existing function through an OTA update, you must provide evidence that the legal requirements and homologation will continue to be upheld. If you introduce entirely new functions, this is not initially permissible. For example, a new driver assistance function that you have developed for new generations and want to deploy in older vehicles is currently not allowed in Germany."* (I.67)
	Level of competitive pressure pertaining to other firms' competitive advantage due to product architecture choices.	*"Tesla was certainly a crucial dimension as a challenging partner in the market. They were already quite early with OTA, which increased the pressure. Because the demand suddenly becomes much more pronounced when a competitor has it. As soon as a competitor has market-ready features and actively sells them, the pressure on all other competitors to retrofit something similar becomes many times greater."* (I.86)

Firstly, the level of vertical integration, which refers to the extent to which the firm manufactures key components within its boundaries, affects the firm's component architectural knowledge about the product architecture. In the OTA case, many core components of the product architecture were outsourced (e.g., OTA Backend Start-Up Solution), increasing the level of coordination, consuming time for coordination, and leading to misunderstandings. Over the course of the OTA initiative, PremiumCar noticed that it would have to strengthen its in-house capabilities, which it did by partially taking over the development of OTA within its own IT department and the newly established entity SoftwareCorporation.

Secondly, the level of bundling of functions to components, which describes the number of components required to perform a single function, is a key property of the compound structure condition. In the existing product architecture, PremiumCar's vehicle product architectures are closely integrated, requiring involvement with many control units and clarifying the interdependencies of each control unit to implement a software update via OTA. In the PremiumCar case, the bundling of functions to components was relatively high. This means that to integrate a new function (like OTA), PremiumCar's engineers needed to work on multiple components and untangle the interdependencies involved.

Thirdly, the level of regulatory risk tolerance, which describes the willingness to engage in practices with uncertain outcomes and inherent insecurity, presents another property of the compound structure product architecture. Given the complexity of the product architecture, each integration attempt presented a risk to the current working product architecture. Furthermore, since it was approved by regulatory bodies, interfering with the existing product architecture also posed a regulatory challenge. There was high regulatory insecurity, for example, in deciding whether a software update of an existing component turned it into a new one, triggering the need to go through lengthy approval processes again.

Lastly, the level of competitive pressure pertaining to other firms' competitive advantage due to product architecture choices is a key property of this compound structure condition. As new competitors in the market could deliver value to their customers more quickly, the product architecture became a key source of competitive (dis)advantage for PremiumCar, necessitating immediate action from the management team.

The mechanism of Product Architecture Enablement revolves around the central practice of rewiring the product architecture. This practice encompasses PremiumCar's efforts to enable the existing architecture and has two key properties, the rewiring level and the rewiring pattern[14] (Table 22). Firstly, the rewiring level pertains to the decisions made regarding which level of the product architecture undergoes rewiring. Given the various existing layers, PremiumCar's OTA team had multiple options for integrating OTA. The decision for the layer on which PremiumCar’s team decided to integrate OTA is depicted by the rewiring level. Further, the decision for the rewiring level results in different rewiring patterns that describe the diverse strategies firms employ to incorporate digital components into their product architecture. The analysis of the PremiumCar case revealed five distinct patterns that PremiumCar employed to integrate OTA.

In the first two generations, PremiumCar added isolated components spanning different layers, such as the two components of the IIM and the IBM, which performed all tasks necessary for running OTA updates with minimal communication with other vehicle components. A second strategy involved enabling the device layer, requiring PremiumCar's engineers to modify the 100 control units within the vehicle to make them OTA-ready. However, this strategy,

[14] The term rewiring pattern is also known as software architecture patterns in computer science where different patterns have been identified (Gamma et al., 1995). For this dissertation it is understood as pattern for how product engineers approach the structuring of their activities, so as product design strategy (Baldwin & Clark, 2000)

although attempted by the team, was not successfully pursued due to the low level of vertical integration, which necessitated convincing external stakeholders to make changes to their components—an effort that was rejected by these external stakeholders. A third strategy involved adding a facade layer to the product architecture. In PremiumCar's case, this practice was instantiated through the integration of the OTA FC, allowing updates of other control units and creating a meta-level control unit. A fourth strategy involved relaunching a new middleware layer, a strategy pursued by PremiumCar as part of MobilityGroup and the efforts of SoftwareCorporation and the Software-Corp. Domain Architecture. A fifth strategy involved the integration of standards and interfaces into the product architecture, both within the hardware domain and in the software development process.

Table 22: Dimension Rewiring of Product Architecture

Dimen-sion	Properties of Dimension	Representative Quote
Rewiring of Product Architecture (Practice)	The rewiring level includes decisions on which level of the product architecture the rewiring takes place.	*"We also have different categories of control units. Some control units are highly integrated computers with a Linux operating system. There is also the possibility to revert to an older version if an update goes wrong [...]. However, if you are really writing directly into the memory of the electronic architecture because you have a microcontroller and maybe even an ancient processor architecture and there is significant cost pressure, for something as simple as a basic door control unit, it is then difficult to simulate the extreme cases where real errors can occur."* (I.65)
	Rewiring patterns refer to different strategies for how firms embrace integrating digital components into their product architecture.	a) adding isolated components that span different layers: *"When you have a new control unit, one issue is the complete networking within the vehicle. You need to include this control unit in the networking plan. This requires a full expansion. Actually, no vehicle had that. [...] You had to get into the networking because you always need for example an HMI for the customer during an update. And the IIM module is the only control unit that offers a direct update option because the module has everything it needs, such as flash capability, HMI, and so on."* (I.66)
		b) enabling the device layer: *"The existing vehicle stock architectures cannot do this. They are not updateable. Because for that, every control unit, every function must be capable of online updates. And one way to do this is to enable the control units individually."* (I.52)
		c) adding a facade layer: *"The Head of Department E/E wanted to integrate the OTA FC to allow flashing software packages of other control units. [...] To make sure that it is possible to flash an ECU from an external device."* (I.52)
		d) relaunching a new middleware layer*: "So far, we have a lot of control units in the vehicle, between 120 and 130 control units. All of them have a specific purpose and are extremely networked because they often come from different manufacturers and are only integrated in a meaningful way to a limited extent. And the idea of the Software-Corp. Domain Architecture is that I have high-integration computers, where I can combine many functions directly in 2-3 computers, and thus of course, map higher-value functions much more easily, which above all are of course networked."* (I.41)
		f) Integration of standards and interfaces: "*Let's take the example of opening the convertible roof. This is a typical function that we order from a supplier. Everything from anti-trap protection to button control is integrated, both hardware and software, which is then installed in the car. Another supplier may provide the remote vehicle status. You can use an app to check whether the roof is open or not. Now we first have to integrate these functionally. There should be a documented interface for this, something like an API. I'm deliberately using the subjunctive mood. Because currently there is no API."* (I.73)

An outcome of the Product Architecture Enablement mechanism is a form of Nested Layered Modular Architecture of the Product (Table 23).

Table 23: Dimension Nested Layered Modular Architecture

Dimension	Properties of Dimension	Representative Quote
Nested Layered Modular Architecture (Outcome)	Type of Nested Architecture between architecture levels pertains to the arrangement principles of old and new different components which can either be linear, lateral, or modular.	*a) Modular Arrangement: "Many existing components from old vehicles have survived in the new Software-Corp. Domain Architecture. In other words, what was there before has been adopted. That's why we still have the Device Backend ODP. Because these functionalities work with the backend."* (I.69)
		b) Lateral Arrangement: "Embedding OTA into Model Delta was a cross vehicle component endeavor as we tried through the OTA FC to touch upon multiple control units." (I.67)
		c) Linear Arrangement: "If you come from the software industry and think in terms of a modular system, OTA is actually a relatively trivial task. But if you think in terms of a monolithic system, as a vehicle still is today, with control units that have been tried, tested, and approved against each other end to end, it is a very, very big challenge to play individual code fragments into the vehicle." (I.86)

The case analysis reveals various types of Nested Architecture between architecture levels, which pertain to the arrangement principles of old and new components. These arrangements can be linear, as in the case of IIM and IBM, which present a linear integration approach for OTA; lateral, where the OTA FC serves as an example; or modular, as exemplified by the Software-Corp. Domain Architecture and the concept of zones. However, beyond these forms of arrangements, all OTA architectures are nested, as they comprise a mix of old and new components. This leads to a situation where the responsible team needs to manage different OTA architectures simultaneously.

To summarize, the mechanism "product architecture enablement" operates under the condition of the compound structure of the product architecture. The compound structure of the product architecture encompasses several factors, including regulatory risk tolerance, the degree of function bundling within components, the level of vertical integration, and the competitive pressures arising from the product architecture. The OTA ambitions given the conditions at PremiumCar led to the practice of rewiring, which is elucidated by the decision regarding the level at which product architecture rewiring occurs. This, in turn, impacts the specific product architecture rewiring pattern pursued. Concurrently pursued patterns subsequently give rise to distinct forms of nested layered modular architecture. Within these different forms of nesting, varying levels of architectural maturity become apparent, serving as a prerequisite for the overall mechanism to function effectively.

4.4.2 Product Development

The literature on digital product innovation development emphasizes distinctions in product development procedures between physical and digital products (Lehmann & Recker, 2022; Svahn et al., 2017; Wang et al., 2022). These differences are also evident in the context of the OTA initiative. PremiumCar, as an established automaker, had well-established product development procedures in place for their physical components. In this regard, PremiumCar effectively coordinated with suppliers responsible for developing modules and components, adhering to a product development process characterized by inflexible milestones and coordination practices.

The OTA initiative, positioned as a pivotal digital endeavor at PremiumCar, presented a challenge to the existing product development process. The team responsible for developing the OTA backend aspired to follow established software development practices, including continuous development, testing, and release. However, these practices clashed with the rigid product development process in place.

In response to these changes, PremiumCar implemented new product development procedures for digital services and also fine-tuned their existing product development process for physical components. Similar to the previous section, the alterations in product development routines will be presented through a comparative analysis before introducing the mechanism of "Attuning Product Development Routines" to elucidate these developments.

4.4.2.1 Comparative Analysis

Throughout the OTA initiative, the team executed a series of product development routines to create the OTA software update. It's crucial to note that while PremiumCar's development routines for physical components were highly sophisticated, the development routines for digital components were constructed and refined during the course of the initiative. This also applies to certain integration routines, some of which were pre-existing elements of the hardware development process, while others emerged during the OTA initiative, often in response to practical considerations imposed by the product development process for hardware components.

Significantly, the type of artifact and component being developed exerts a substantial influence on the product development routines. As the rigidity of material artifacts increases, making changes to such components becomes more resource-intensive, emphasizing the importance of careful planning to minimize the need for alterations. An overview of all product development routines is provided in Table 24.

Regarding physical components, PremiumCar relied on dedicated development routines for their vehicles. Typically, the product development process for a new component aligns with the launch of a new vehicle.

First and foremost, planning routines assume a pivotal role. They entail the establishment of milestone-based phases and deadlines, forming an integral part of PremiumCar's product development framework. These routines include key delivery dates, such as the Design Freeze deadlines and the Start of Production, representing the final point in time by which vehicle development must be completed. These milestones and deadlines serve as a structured roadmap for the systematic execution of tasks and the progression of projects.

Table 24: Product Development Routines for OTA

Type of Component	Product Development Routines in the Case
Physical Components (OTA Device and Network Layer)	- Planning routines include milestone-based phases and deadlines instantiated in the product development process. - Coordination routine unfolds through projects in which different departments collaborate to develop components. - Decision-making routines include committees in which decisions are being made.
Digital Components (OTA Service and Content Layer)	- Planning routines include agile practices following the SAFe framework in which feature requests and user stories are gathered, prioritized, and scheduled. - Coordination routines following the SAFe framework include daily scrum meetings and product increment plannings in which teams jointly identify and remove dependencies between different teams, but also collaboration routines with the vehicle teams. - Decision-making routines following the SAFe framework involve replacing committees by tying decision-making responsibilities to individual roles.
Integration Routines	- Compound Releases present frequent milestones for testing all vehicle components together. - Backarounds present a practice in the IT team where the team fixes bugs in the backend since they can’t access the device layer as the start of production does not allow it. - Development drops presents a practice in which IT teams perform testing of single compounds of components.

Secondly, coordination routines play a pivotal role in ensuring effective collaboration across various departments within PremiumCar. These routines manifest through the initiation of projects led by product line teams, involving experts from different departments working collectively to develop various components of a new vehicle.

Finally, decision-making routines constitute a critical aspect of PremiumCar's product development procedures. These routines entail the formation of committees or similar decision-making bodies where essential determinations are reached. For instance, PremiumCar maintained committees for IT architecture decisions, and significant changes in product architecture were discussed and approved within these committees. Additionally, changes in budget allocation required approval through these committees. These decisions steer the direction of vehicle projects, ensuring alignment with PremiumCar's profit goals and on-time product delivery.

For digital components, PremiumCar implemented a new operating model called SAFe (Scaled Agile Framework) for product development, and the OTA team iterated their development routines multiple times.

Concerning planning routines, the OTA team embraced agile practices and followed SAFe. SAFe encompasses multiple planning routines, with 3-month product increment planning being the most critical. These planning sessions, conducted over two days and attended by the entire OTA agile release train, allowed teams to plan for the next three months. Input for these plans came from team members who submitted features they deemed essential, which were then prioritized in pre-workshops involving product owners and leadership team members. The outcome of these workshops, a list of prioritized features, was subsequently handed over to the product increment planning team. During the product increment workshop, each development team planned their capacity for the next three months based on this list of prioritized features.

Coordination routines also played a pivotal role in PremiumCar's digital product development process. Scrum meetings within teams served as a platform for OTA teams to synchronize activities, share progress updates, and address any roadblocks. Additionally, Product Increment Planning workshops included dedicated timeslots for coordinating tasks between different teams and identifying and mitigating dependencies that could impede progress.

Moreover, PremiumCar's decision-making routines underwent a transformation during the OTA initiative. Leaders shifted away from traditional committees and instead delegated decision-making responsibilities to individual roles. For example, the IT architecture committee, responsible for approving IT architecture decisions, was disbanded, and this responsibility was transferred to the role of an IT architect. With each ART (Agile Release Train) having an architect as part of their team, decisions on IT architectural questions could be made within each team. This approach aimed to empower teams to make prompt and informed decisions, allowing OTA teams to move swiftly without long waiting periods for feedback.

Additionally, PremiumCar had a set of integration routines in place to align software and hardware development practices. Compound Releases were a key element, representing frequent milestones for testing all vehicle components together. Depending on the stage of the product development process, these Compound Releases occurred at intervals of weeks to months. During these releases, a few early prototypes of products or product components were presented and, ideally, successfully tested. Following each test, PremiumCar engineers often received a list of errors that needed correction before the next compound release. This practice effectively coordinated and aligned a product development ecosystem comprising multiple internal and external actors. However, it posed a challenge for the OTA team, as a software development team, they preferred more frequent testing opportunities.

In some cases, development drops served as a practice in which IT teams conducted testing of individual component compounds independently from end-to-end. For OTA, this involved testing the communication between the backend and the onboard component. While this practice helped identify issues early on, it could not fully address the need to test the OTA solution in the actual vehicle communication context, where it interacts with other control units and components.

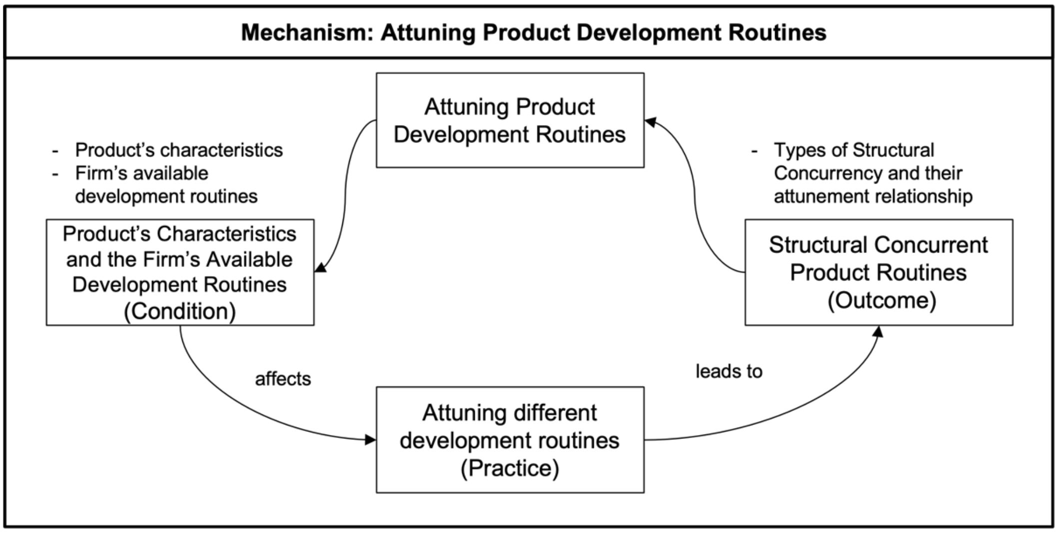
Furthermore, backarounds emerged as a last-minute development routine within the OTA team. Faced with constraints that prevented last-minute changes due to the Start of Production milestone, the team had to find a way to address software bugs within the OTA backend. As a result, the term "backaround" was coined to describe a backend workaround as a last-minute practice to rectify software bugs.

Regarding product development routines, a significant shift occurred during the OTA initiative with the introduction of SAFe and the establishment of the virtual product organization as a central framework for product development. For the OTA team, this shift meant that a set of standardized development routines became an integral part of their development process. The rationale behind this shift is explained in the subsequent inductive analysis.

4.4.2.2 Inductive Analysis

The inductive analysis revealed a mechanism referred to as "Attuning Product Development Routines" (Figure 18).

Figure 18: Mechanism Attuning Product Development Routines



"Attuning Product Development Routines" elucidates the process through which established incumbent firms, characterized by traditional product development routines primarily oriented toward physical components, transition to developing routines suitable for products necessitating both physical and digital components. This entails aligning various development cycles and routines to accommodate the hybrid nature of these products. Concerning activation conditions, the firm's product characteristics and its existing product development routines serve as critical factors influencing the mechanism's operation (see Table 25).

Table 25: Dimension Product's Characteristics and Development Routines

Dimen-sion	Properties of Dimension	Representative Quote
Product Characteristics and the Firm's Available Development Routines (Condition)	The customer's changing product expectations refer to the customer's desires triggered by offers from competitors.	*"And the customer wants [...] more digital services integrated into the vehicle, and more interaction with their smartphones.[...] This is especially true with regard to customer developments around age and geography. China is by far our strongest market. China is much more digital than Europe, and our customer base is also younger there. In Europe, the average customer is 55 years old, while in China, it's 35. And they want to use their car just like their smartphone."* (I.40)
	The firm's internal product understanding and identity refers to how the firm's historical success shapes its understanding of the future.	*"We have an extremely well-oiled machine with top-notch processes for the world of vehicles. It's a machine that functions smoothly with clearly defined governance structures and processes where every last detail is worked out, providing a great deal of security. Now, we are entering a world with a lot of uncertainty, and I believe the entire team is somewhat uncertain. We have been living in this structure for many years, and it is slowly being dismantled. [...] Vehicle development and the development of digital services operate at extremely different speeds and within different cultures [...] and this is where worlds collide."* (I.1)
	The product lifecycle refers to the firm's understanding of how long the product will serve the customer and the stages involved in maintaining it.	*"We always say Car for Life. That means that the vehicle can improve over the course of its life. Through software updates. Through Functions on Demand. And so on. And that of course works very differently than I sell my car once to the customer and then that's it."* (I.69)
	The malleability of product components refers to the resource investment necessary to incorporate changes in the component.	*"When I build a car body, I need pressing tools to bend sheet metal. I can't change that quickly, because a press tool like that costs a few million. And if I'm constantly making changes, it takes a lot of money. That means I have to work at a different speed and with a different model. [...]. But the customer doesn't look at the car as a product separately and say, sure, the sheet metal looks like this and the software is that. The customer says I have a product from you. It consists of hardware and software."* (I.8)
	The failure sensitivity of the product components refers to the risk for the firm if the component does not work properly.	*"There are a few concerns. For example, during a software update, parts like windows may move without the user or driver initiating such an action. This could render the corresponding anti-pinch protection ineffective. Imagine if the software device is controlled by the door. If the calibration routine is then executed, which raises and lowers the windows, there may be a failure of the anti-pinch protection during this calibration routine. And, of course, such a thing must not occur."* (I.65)
	Existing product development planning routines.	*"And in the development department, yes, there's the PEP (Product Engineering Process), [...]. And there's actually a feature freeze one year before SOP (Start of Production), and then it takes another year until it's SOP. Then, it's another three to six months until it's available at the point of sale. So, it's about a year and a half before it reaches a larger quantity. That means you effectively have a feature freeze a year and a half in advance. Of course, this is challenging for software."* (I.62)
	Existing product development coordination routines.	*"We have always developed in projects. The services that we want to provide are requested by the product line team, i.e. by the vehicle. And then there is a project with the corresponding committees and project structures where different development partners work together."* (I.60)
	Existing product development decision-making routines.	*"In IT, we used to have an architecture steering committee where all IT architecture decisions were approved. People went there with decision proposals: They were planning things like moving to the cloud here, or we want to make an architecture adjustment here."* (I.86)
	Existing product development integration routines.	*"We have the compound releases that take place in certain cycles. [...] But OTA has always been a side issue only relevant in the late composite releases. This has to do with the fact that the control units have to be ready first. So, you can only test late when the vehicle is ready for OTA. So, we develop quite a lot in advance in the back end, but we don't really know whether it will work in the vehicle in the end. And then we notice concept gaps or concept errors very late."* (I.60)

This entails addressing customers' evolving product expectations, which describes how changes in the market, driven by new competitive offers, create an activating condition for aligning various product development routines. Additionally, the firm's internal understanding and identity, influenced by its historical success, represent another facet of this dimension. Similarly, the product lifecycle, encompassing an understanding of the product's lifespan and the stages required for its maintenance, plays a role in this context.

In PremiumCar's case, the company had an established ecosystem and corporate culture centered around its core product, the car. This product had a fixed point of sales in time, was regarded as a physically engineered device, and demanded a high degree of sensitivity to potential failures during development, as any flaws could jeopardize customer safety. Moreover, the adaptability of individual product components, indicating the resource investment needed to incorporate changes in these components, represents another property of the condition that activates the mechanism.

Furthermore, the existence of preexisting product development planning, coordination, decision-making, and integration routines serves as a crucial condition for activating this mechanism. PremiumCar had excelled in developing the physical components of vehicles through effective collaboration with its supplier network, establishing a well-coordinated system around specific routines for planning, decision-making, and integration within the product development process, including the management of compound releases. In response to changes in the market landscape, PremiumCar adopted the practice of attuning different development routines (Table 26).

Table 26: Dimension Attuning Product Development Routines

Dimen-sion	**Properties of Dimension**	**Representative Quote**
Attuning different development routines (Practice)	Attuning practices which involve practices pursued by the firm to attune one product development approach with the other.	a) Standardizing Component Development: "*And that's why we broke up all the teams and mixed up all the people, which means that each team has a certain amount of domain expertise available. […] That's why we are moving towards standardizing our technology stack. We now try to do everything with Java.*" (I.49)
		b) Decoupling of material-induced routines through product architecture changes: "A big challenge is this refactoring of the functions []. In other words, how can we distribute the functions that are currently purchased on a very decentralized basis according to the classic OEM principle in a different way? Today, we buy a function together with the control unit, hardware, and software combined from a Bosch or Continental. And in the future, we will have to decouple this [....]." (I.73)
		c) Redesigning rigid hardware practices: "So if you tell the software developer that he can test things every three months in a composite release, but he would rather test things continuously, that's hard. This becomes clear from the bug lists from the composite release tests. These tend to get bigger and bigger because the scope and complexity of the software increase so much from release to release. So even with this linear composite testing every few months, you don't get the bug lists correspondingly smaller, as it used to be. This is simply due to the complexity. So, the calls for Continuous Testing and Release are getting louder and louder." (I.86)

PremiumCar had well-established hardware development routines and, over time, also developed agile development practices for applications. However, as software solutions matured, they required closer integration into the actual vehicles, as exemplified by the OTA initiative. During the OTA initiative, three attuning practices were observed, which involved efforts by the company to align one product development approach with the other.

The first practice aimed at harmonizing both development routines through standardizing component development. This standardization is applied to both hardware and software components. The introduction of the Software-Corp. Domain Architecture platform, intended for use across various MobilityGroup brands including PremiumCar, necessitated commitment to specific standards. These standards covered hardware development aspects, such as agreeing on temperature resistance standards for components, as well as software development, where an industry-standard framework (SAFe) was adopted to introduce agile methodologies into the IT organization, including SoftwareCorporation and other entities. At a more granular level within software teams, the establishment of additional standards was chosen to enhance flexibility, evident in decisions such as adopting Java as the standard development language. The driving force behind this alignment practice of setting standards was that such standards in both domains fostered greater flexibility for integration and coupling, thereby enabling the scalability and reusability of components (Software-Corp. Domain Architecture, microservices of OTA).

PremiumCar implemented a second practice to harmonize varying development cycles and routines, which involved decoupling material-dependent routines through product architecture adjustments. The company aimed to transition to a pace-layered architecture that would permit different layers to operate at their own individual speeds. This decoupling process entailed disentangling former interdependencies at the product component level, along with addressing the absence of standardized interfaces between these components, which had previously posed coordination challenges. As part of this endeavor to establish the pace-layered architecture, PremiumCar sought to create distinct and more independent rhythms for each product layer. This approach was coined “pace-layered architecture.”

While PremiumCar had already made significant progress in refining processes related to hardware development through its Product Development process, achieving the pace-layered architecture required additional measures. Specifically, the company introduced a dedicated rhythm for software development known as the “PremiumCar Clock Speed.” Under this rhythm, software teams engaged in a three-month cycle during which they developed, tested, and presented their product increments, all aligned with three-month milestones. The driving force behind this practice stemmed from the recognition that the close coupling and extensive integration of hardware and software within single components had led to increased product complexity in prior product architectures.

Another practice undertaken by PremiumCar's teams involved a combination of improvisation and a partial redesign of their well-established but rigid hardware practices. For instance, within the context of developing the OTA backend for the model Delta, the OTA team introduced a new practice called “backarounds.” This approach allowed the team to address backend issues that arose after the car had been produced, as these issues couldn't be accommodated within the existing product development process. Additionally, during later stages of development, the team enhanced the practice of “DevelopmentDrops“, enabling them to pretest a set of subcomponents earlier in the process compared to traditional Compound Releases. Furthermore, the Compound Release practices were also adapted, with shorter cycle times and increased testing capacity, allowing the OTA team to test their artifacts more frequently. The driving force behind these adjustments was the recognition of the rigidity inherent in the product development process, often stemming from security concerns. Many vehicle components required approval from regulatory bodies once they were deemed finished, creating a stark contrast with the OTA team's ambition to continuously develop their products.

These practices resulted in the establishment of various structural concurrent routines at PremiumCar, each tailored to address the unique conditions and challenges encountered during the OTA initiative (Table 27).

Table 27: Dimension Types of Structural Concurrent Routines

Dimen-sion	**Properties of Dimension**	**Representative Quote**
Types of structural concurrent routines (Outcome)	Temporal planning concurrency	*"Currently, we have this model-based view and also the digital view. And it's challenging, for example, to think about both simultaneously, like incorporating OTA into traditional releases[...] and the idea of continuously improving and integrating everything that belongs together into the organization.[...] This is evident, in the fact that we're often asked when the OTA solution will be finished. And we say, it's never finished. This often leads to understanding."* (I.44)
	Coordination concurrency	*" OTA is something that you need to plan and develop specifically so that you also have the content. So, it's no use just building the road, you also need the cars that drive on it. There are many who have started to build the road and make it nice and wide and all kinds of things. And then they said, now we're waiting for the cars to drive on it. But they didn't come on their own. And the cars they had were not compatible with the roads they had built and the destination. That's why content and services are two different things that I have to develop separately but also together.[...] In the infotainment area, for example, we developed an update that we would have liked to have rolled out backwards. But the infotainment component strongly networked with all areas of the vehicle these days. There were problems with interaction with an all-wheel-drive system and the new all-wheel-drive system required changes in the infotainment system. This was then developed, but no consideration was given to the fact that this software should also work in older vehicles with the older all-wheel drive system."* (I.67)
	Decision-making concurrency	*We are successively reducing committees. Decisions are deliberately no longer made by committees because the committee is being removed and decision-making processes are deliberately delegated to the appropriate roles. But if you look closely at day-to-day business, everyone who works in a SAFE organization at PremiumCar also has a line manager. [....] How the line manager then deals with his or her role varies greatly. If I position someone in a new role and give them new responsibilities, rights, and duties, I have to detach these rights and duties from where they were before. I have to do that consciously. Often we see that only the first part is done consciously, namely the giving of rights and duties to a role, but not the detachment from the existing role. Of course, this leads to conflicts. Of course, if the head of the department is still of the opinion that the technical functionality of the product is his responsibility, that he is measured by it, and that he has to take responsibility for it, and at the same time the product manager is given this responsibility, then conflicts are inevitable."* (I.86)

This encompassed several aspects of concurrency planning, coordination, and decision-making. Temporal planning concurrency signifies the coexistence of various development routines simultaneously within the same organization at PremiumCar. Coordination concurrency pertains to the simultaneous utilization of diverse coordination mechanisms, including products and projects. Decision-making concurrency involves the simultaneous presence of two distinct decision-making mechanisms: committee structures for the vehicle domain and a role-based model for the digital space.

In summary, the elements presented collectively constitute the mechanism of “Attuning Product Development Routines.” This mechanism is initiated by specific activation conditions, encompassing the product's characteristics and the firm's existing development routines, which influence the decision to attune different development routines. A set of practices is subsequently pursued to achieve this attunement, resulting in the simultaneous execution of various product development routines.

4.4.3 Organizational Structure

The literature on digital product innovation highlights the effects of digital innovation on organizational structure (Dremel et al., 2017; Nambisan et al., 2017; Sebastian et al., 2017; Yoo et al., 2010). It is argued that the boundaryless nature of digital innovation requires new forms of cross-boundary collaboration between different entities (Nambisan et al., 2017; Yoo et al., 2010). This also held true for PremiumCar’s digital initiative around OTA.

Over the course of the time period, PremiumCar adjusted its pre-existing organizational structure to accommodate the organizational requirements for realizing OTA. This involved refinements of existing organizational structures within IT and Product Development but also the creation of new organizational structures such as Software Corp.

Similar to the previous section, changes in the organizational structure at PremiumCar will be presented through a comparative analysis before introducing the mechanism of “Organizational Expansion based on Mirroring of Product Layers” that explains these changes.

4.4.3.1 Comparative Analysis

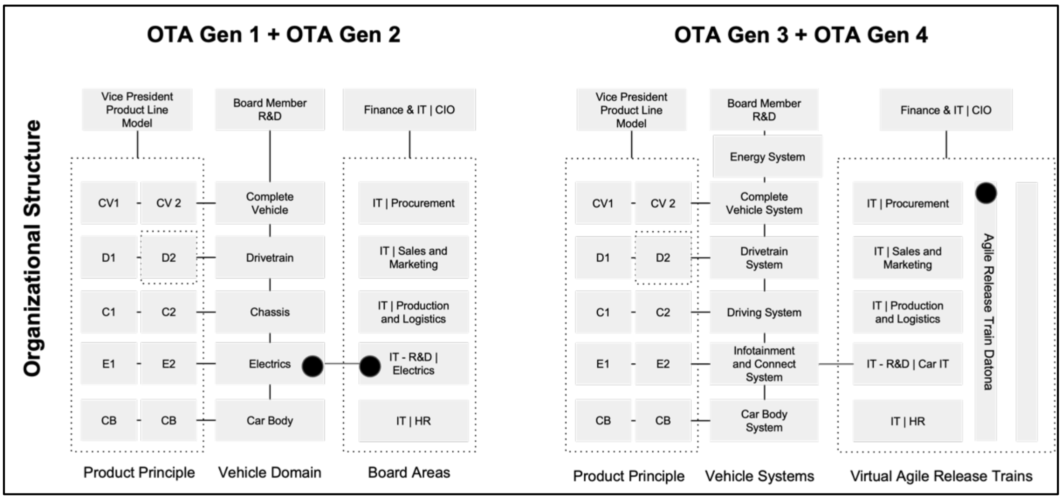
Next to the changes in product architecture, PremiumCar also initiated several organizational changes over the different generations of the OTA initiative. These changes affected the location of OTA within the organizational structure and were, to a certain extent, responses to challenges or experiences encountered during earlier OTA development efforts.

Initially, the organizational structure for OTA required close collaboration between three organizational entities: product development, IT, and SoftwareCorp.

In terms of product development, PremiumCar's organizational structure focused on product lines. These product lines were supported by teams from the R&D department, which, in the first two generations, followed the KEFAG structure across different components (e.g., drive train, chassis) or domains of the vehicle. Each product line had a responsible team for the development of specific components or modules, often co-developed with suppliers. The product line held expertise in each vehicle, while the R&D department possessed functional expertise for designing specific components and modules.

Regarding IT, which fell under the board area of finance and IT, its function was to support the R&D and product line teams, primarily by maintaining the company's existing IT tool landscape. This was organized as a functional structure, with each board area having a representative team in IT. Concerning OTA, the IT team became relevant as it developed and supported the necessary IT tools for performing software updates. This was handled within a specific sub-team within IT, responsible for the R&D department, particularly its electrics and electronics team. This team's role was to provide the necessary tools for operating software updates, such as the business connector (Figure 19).

Figure 19: Changes in PremiumCar's Organizational Structure



The third entity relevant to the organizational structure is SoftwareCorporation, which became prominent in the 4th generation of OTA when developing the central new vehicle platform necessitated close collaboration with the IT team.

In terms of organizational structure, three shifts occurred during the course of OTA (Table 28).

Table 28: Shifts Organizational Structure

Unit	Shifts including Practices	Example Quote
IT	Move from OTA operated in cross-functional projects towards OTA as a product instance requiring an explicit virtual organizational entity (ART OTA Data).	*"OTA Data has a value stream that extends across departmental boundaries. [...] This extends from the R&D department to the sales and production department. This makes it necessary to treat this value stream as a product, or now as an ART, in order to work together across departments. OTA Data is not an IT topic. OTA Data is an ART of PremiumCar."* (I.44)
R&D	Move from electro-mechanical component orientation (KEFAG) to electro-mechanical and digital systems engineering structure.	*"And what is now coming along in the R&D department is a transformation in the direction of systems engineering. And that we will then try to sow more systems, a combination of hardware and software."* (I.43)
Software Corp.	Moving the development of parts of the OTA onboard and backend development into a new external organizational entity.	*"And the other thing is that Software Corporation is supposed to become a kind of platform supplier. For OTA, this means that many onboard and offboard components are created together there. The brands build their vehicles around it, so to speak."* (I.45)

The first organizational shift occurs within the IT department itself. While in the 1st and 2nd generations of OTA, the OTA direct updates (IIM) were entirely managed by FastCar teams, in the 3rd generation, especially with the introduction of model Delta, the IT team in R&D – Electrics took on more responsibility. They collaborate with various stakeholders from R&D, after-sales, production, and the product line to develop the OTA backend.

During the development of model Delta and the expansion of OTA beyond the single component (IIM), the OTA team realized that achieving software updates for OTA requires a more cross-functional approach than just supporting IT tools. What was previously organized with different IT teams for different functional departments (one IT team for sales, one for production, and one for R&D) now needs to collaborate as one entity. This realization motivates the team to move away from the project approach, where different stakeholders from different departments collaborate, and transform themselves into a product. An internal initiative known as the Virtual Product Organization provides an opportunity for them to become an Agile Release Train.

The virtual product organization is not considered a new organizational structure but rather an additional "organizational layer" to the existing structure, focused on a set of agile release trains for product development. A subset of people from the initial IT-electrics team, in collaboration with employees from other departments, forms such an agile release train, internally referred to as "OTA Data".

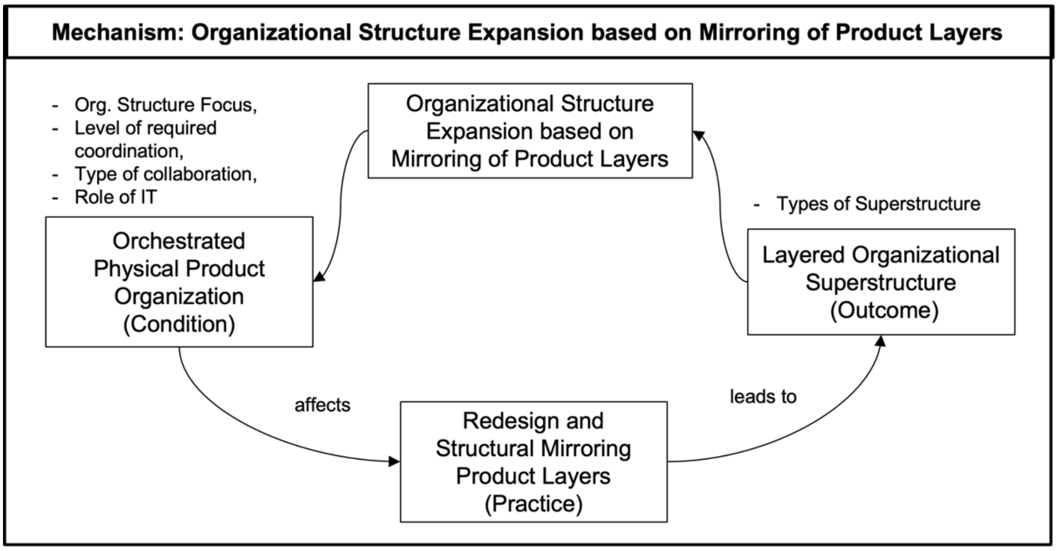
The second organizational shift involves moving away from the electro-mechanical component orientation (KEFAG) in R&D's organizational structure toward a systems engineering approach that incorporates the digital aspect into the product development and engineering structure. For OTA, the vehicle system infotainment and connect unit emerges as an organizational entity where OTA is managed from the vehicle development perspective. This shift is driven by the increased integration of digital technologies into components and the greater level of integration required in component development.

The third shift pertains to the establishment of a new entity, SoftwareCorporation, in the 4th generation. Central development efforts for components of the OTA onboard and backend development infrastructure are centralized within this new external organizational entity. This shift is driven by the product complexity of the established product architecture, where multiple brands (including PremiumCar) require a new product architecture developed as a cross-brand effort that aligns different development activities into one entity. Consequently, a significant portion of development efforts related to OTA is moved to this new entity, with the OTA team becoming an important stakeholder in this process.

4.4.3.2 Inductive Analysis

The inductive analysis revealed a mechanism referred to as "Organizational Expansion based on Mirroring of Product Layers" (Figure 20).

Figure 20: Mechanism Organizational Structure Expansion



Organizational expansion based on the mirroring of Product Layers refers to the process by which traditional industrial companies adapt their organizational structures to accommodate digital product innovation, aligning their structures with the layers of their digital products. Several activating conditions play a role in this transformation, such as organizational structure focus, level of required coordination, type of collaboration, and the role of IT (Table 29).

The concept of focus of organizational structure pertains to the fundamental guiding principles that shape an organization's structural decisions. In the case of PremiumCar, the product line principle serves as an illustrative example of such a guiding paradigm. This principle becomes evident throughout the OTA initiative, including instances like the separation of OTA teams according to product lines.

The level of required coordination refers to the extent to which different internal and external units need to collaborate and coordinate their efforts when working on individual product components. Within PremiumCar's established setup and during the first few OTA generations, this level is relatively low and characterized by clearly defined boundaries between teams and organizational entities, each responsible for specific tasks. For example, the decision to outsource the development of OTA components to an external supplier (e.g., OTA Backend Start-Up Solution) by the product line is an illustration of this approach.

The type of collaboration refers to the relational elements used between different internal and external units to work on single product components. In the OTA case, this becomes relevant in the relationship between IT and the product line or also in collaboration between product lines, IT, and external suppliers. Here, the product development process at PremiumCar is used to coordinate these different actors with a rather transactional approach.

Table 29: Dimension Orchestrated Physical Product Organization

Dimension	Properties of Dimension	Representative Quote
Orchestrated physical product organization (condition)	Organizational structure focus refers to the underlying paradigm that guides organizational structure decisions.	*"So, we are essentially vehicle project agnostic, in other words, we are actually independent of vehicle projects. Whereas, in the PremiumCar organization, they are always very focused on vehicle series. In the management department, there is a separate OTA separation for each vehicle series. And this naturally manifests the idea of thinking within these series and not thinking across them."* (I.44)
	The level of required coordination means the number of different organizational units collaborating on one product component.	*"At some point we realized that we had many projects that were changing the same system. And then, at the beginning, we had of course run it project by project, had of course also different environments, had different teams in each project. [...] And then we somehow realized that we couldn't get it synchronized. So, we had to merge a lot of source code, also different data models. And then, as a first step, we said that we would bring all these projects together and harmonize the requirements and bundle them together, and practically create a stream of requirements in the direction of this system. And that has already brought an incredible amount by not, let's say, having different teams change the same system."* (I.41)
	The type of collaboration refers to the relational elements used between different internal and external units to work on single product components.	*"If we look at the current collaboration model with traditional suppliers, their business model is to sell us the hardware, including the software. As long as this is the case, we have to order everything, specify it, and so on. We then receive exactly what we ordered and install it. And now, we need to change this business model of these suppliers as well. They should sell us the hardware and maybe the software. Or perhaps someone else sells us the software. This is, of course, a problem in the value chain structure in the industry."* (I.72)
	The role of IT refers to the position of the IT department in the design of product components.	*"In a dealer system or a departmental system, you can simply roll out a release. Vehicle development is a bit slower by default due to the product development process, as well as type approvals and issues with the Federal Motor Transport Authority [...]. But still, it was also a mindset issue, and also a matter of trust towards IT because IT was historically somewhat on the sidelines at traditional OEMs. In that context, IT was historically more of a cost factor and not an innovator or driver. However, gradually, it was also noticed that the things that were running in our program were good, and trust came along with the delivery and the quality that ultimately emerged."* (I.70)

Additionally, the role of IT within the organization involves providing support and ensuring the effective functioning of IT applications required by product development teams, such as the maintenance and development of the business connector.

These elements collectively describe the existing organizational condition, which serves as the starting point for PremiumCar's OTA initiative. The practice central to the mechanism is the "redesign and structural mirroring of product layers," which involves the creation of digital organizational entities that represent digital product components and an expansion of the understanding of existing organizational structures (Table 30).

Table 30: Dimension Redesign and Structural Mirroring of Product Layers

Dimension	Properties of Dimension	Representative Quote
Redesign and structural mirroring of product layers (practice)	Setting up multiple digital organizational entities representing (components of) digital products	*"[....] In the future, we needed to ensure that all relevant individuals involved in the entire software update process via OTA were part of a single team. That's how we defined our product OTA Data in 2019. [...] OTA Data is now synonymous with OTA because it encompasses the essence of OTA."* (I.46)
	Expansion of understanding of existing organizational structures	*"In response (to OTA), we changed our vehicle development structures and moved to systems engineering approaches. Before, our vehicle development was organized based on the KEFAG structure. Today we use systems engineering, which means we try to think from end-to-end with a system. Let's take a good example of the main headlight of a car. In the old structure, this main headlight was developed in the Electric section of KEFAG because it has a core electrical component. In the systems engineering approach, it's part of the car body system. That means where formerly the car body people had responsibility for sheet metal bending and painting and so on, they now also have a responsibility for the computing parts, air conditioning, and headlights."* (I.75)

The first practice, which involves establishing multiple digital organizational entities to represent components of digital products, encompasses activities at both the micro and macro levels of the organization. This practice is exemplified in the case through the transformation of teams into product-focused entities like OTA Data, which take responsibility for specific aspects of OTA backend activities, treating them as distinct product components. Additionally, the introduction of SoftwareCorporation, tasked with providing the central operating platform, is another manifestation of this practice.

The second practice, expanding existing organizational structures, encompasses activities where the company extends or enhances its current organizational frameworks. For instance, in this case, PremiumCar undergoes changes in its R&D department as it shifts towards a systems engineering approach aimed at incorporating digital components within its existing product development structure.

These two practices reflect PremiumCar's response to the need for organizational adjustments to accommodate digital product innovation, with a focus on establishing dedicated entities for digital product components and evolving its existing structures to better integrate digital aspects into its product development processes.

In essence, PremiumCar's OTA initiative is driven by a shift in its organizational focus, the need for enhanced coordination across various units, and the evolving role of IT in the context of digital product development. These factors prompt the organization to redesign its structure and mirror the layers of digital products to effectively accommodate digital innovation.

As an outcome, the company has built a layered organizational superstructure (Table 31).

Table 31: Dimension Layered Organizational Superstructure

Dimension	Properties of Dimension	Representative Quote
Layered organizational superstructure (outcome)	Units for each product layer (component).	*"Well, there is the Software Corporation. One that was founded precisely to increase our own share of development. The software for the control units was previously made by suppliers. [....]. And it will be like this: we will do the requirements management and the integration, and Software Corporation will build the platform centrally. In the end, the result must be a whole car and not just the software. Nevertheless, there are of course areas where the brand develops software itself. For example, in differentiation on the application layer. We build this ourselves at PremiumCar and FastCar."* (I.72)
	Integration relationship describing the organizational embeddedness of either the digital or the physical tasks into organizational arrangements.	*"Currently, the hardware clock and the organization dominate, that's clear and will remain so for a few more years. But the platform will become more relevant and we will have to adapt and change the hardware clock so that it matches the software clock. And for that, we have the Virtual Product Organization in which the software pact happens as a layer on top of the established organization."* (I.4)

The term "layered" refers to the distinct levels or components within the product's architectural design, while the "organizational superstructure" describes the unique organizational framework that exists within the company. This superstructure includes individual units for each product layer (component) and various forms of integration relationships that define how digital and physical units are integrated into the overall organizational structure.

An example of the former is SoftwareCorporation, which represents a dedicated entity for managing digital product components. A prime example of the latter is the virtual product organization, which acts as a "virtual layer" atop the existing organizational structure. Unlike SoftwareCorporation, the virtual product organization is not an entirely new entity but rather an approach to organizational coupling, where individuals assume different roles within different organizational setups to facilitate integration between digital and physical units.

In summary, the elements presented collectively constitute the mechanism of "Organizational Structure Expansion based on Mirroring of Product Layers." This mechanism is activated by the orchestrated physical product organization, which influences the decision to redesign and structurally mirror product layers. The outcome of this process is a layered organizational superstructure.

4.4.4 Resource Allocation

The literature on digital product innovation also emphasizes the importance of resource allocation in established organizations (Lee & Berente, 2012; Svahn et al., 2017). In the context of the digital initiative related to OTA at PremiumCar, securing long-term funding for a dedicated digital product conflicted with the project-based funding approach typically followed in established vehicle and IT projects. One contributing factor to PremiumCar's strong financial performance was its stringent budget culture, where financial resources were allocated based on a rigid business case logic with a clear return on investments. The OTA project presented challenges to this established logic.

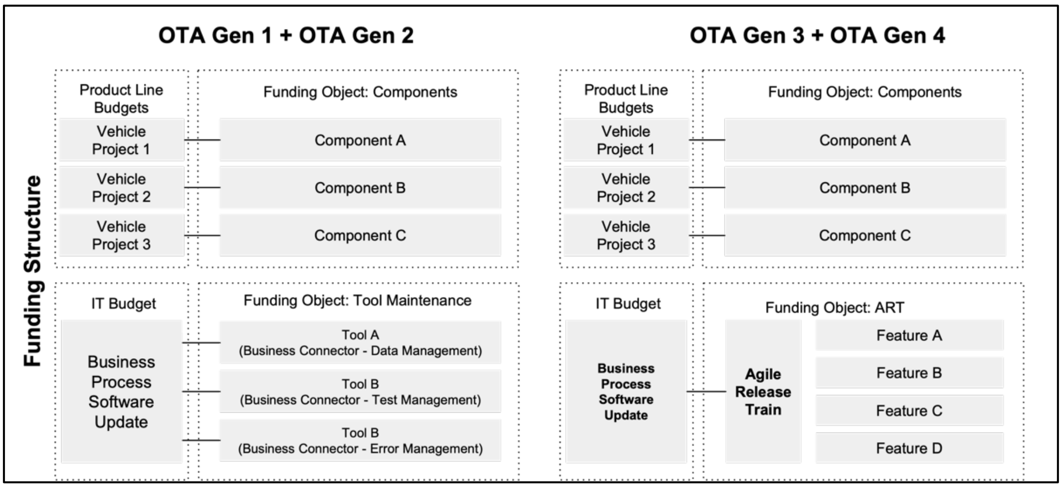
In response, and as part of the virtual product organization initiative and the implementation of SAFe, resource allocation practices at PremiumCar underwent changes.

As in the previous section, changes in PremiumCar's resource allocation practices will be presented through a comparative analysis before introducing the mechanism "Redesign Resource Allocation Mechanisms" that explains these changes.

4.4.4.1 Comparative Analysis

In addition to the changes in organizational structure, PremiumCar made the decision, as part of the virtual product organization initiative in 2020, to revise its approach to budgeting and funding for digital initiatives, including the OTA initiative and the OTA team (Figure 21).

Figure 21: Budgeting of OTA Initiative



The OTA team had previously received its funding from two sources. The first source was a central IT budget, which allocated funds for specific projects aimed at further developing existing or new IT tools (such as the business connector components). The second source of funding came from the budgets of vehicle projects, where the introduction of a new vehicle sometimes required changes or extensions to the IT landscape. These changes would translate into individual projects focused on specific components. The application and decision-making process involved creating detailed project applications, including cost estimates, funding allocation, and deliverables related to new components or IT systems. These applications were then submitted to a committee (often the IT architecture committee), where department heads would either approve or reject them. Once approved, the team could proceed with the project until its funding was exhausted. This funding approach was also applied to OTA, where the addition of new features for a vehicle project triggered corresponding IT projects, resulting in the development of new IT components for existing tools.

However, this funding approach posed challenges for the OTA project. It lacked flexibility, tying teams closely to their specific deliverables and impeding the realization of synergies between projects. It also led to duplicate development efforts, as teams within IT often lacked full transparency about ongoing projects, and resource allocation became a challenge due to the sheer number of projects, forcing teams to prioritize.

In response, PremiumCar's digital transformation office, through the virtual product organization, aimed to change this budgeting approach. While it had worked well for traditional vehicle projects, it created obstacles for digital product development, as OTA had experienced. Instead of binding a product team to a specific project with limited funding, the transition to a product-focused and subsequently Agile release train approach signaled a shift in the funding structure. The IT leadership team moved away from funding individual projects and adopted a cost-center approach through portfolios. For OTA, two portfolios were established: one for software updates and another for infotainment and connectivity. In the case of software updates, funding was allocated to the Agile Release Train (ART), with a basic resource provision, and additional funding was distributed based on the team's work on specific features, providing greater flexibility. These changes in the budgeting approach unfolded through three key shifts in specific budget practices (Table 32).

Table 32: Shifts Budgeting of OTA

Budgeting	Shifts including Practices	Example Quotes
Budget allocation	Moving away from allocating funding to projects towards allocating continual funding to products and features.	*"We are currently funded on 14 different projects that need approval in committees. Each project has a defined score, with work packages and budget. And we got this million to realize a feature for production. Then they expect us to invest into their feature, no matter what we do."* (I.44)
Budget effect measure-ment	Moving away from funding outcomes like components or tools towards funding features and their impact on business metrics.	*"And the budget must also fit more clearly with Important topics for us as a company. So it must not be written in the project description. Build me this backend system. Instead, it must include topics such as 98 percent successful software updates for the new Alpha. [...] The goal is not to build backends, but to generate successful software updates for the customer."* (I.48)
Budget decision making	Moving decision-making for changes that require reallocation of funding away from committees into roles within decentralized teams.	*"No one has to run somewhere and release a budget anymore. And the decision can be made by a product owner or product manager and no longer by some hierarchy."* (I.6)

The first budget shift was aimed at changing the budget allocation process. PremiumCar's digital leadership team recognized that the traditional approach of allocating funding to individual projects, similar to the process used in vehicle projects, was not suitable for developer teams in need of continuous funding for their products and features, which often extended beyond the scope of single vehicle projects.

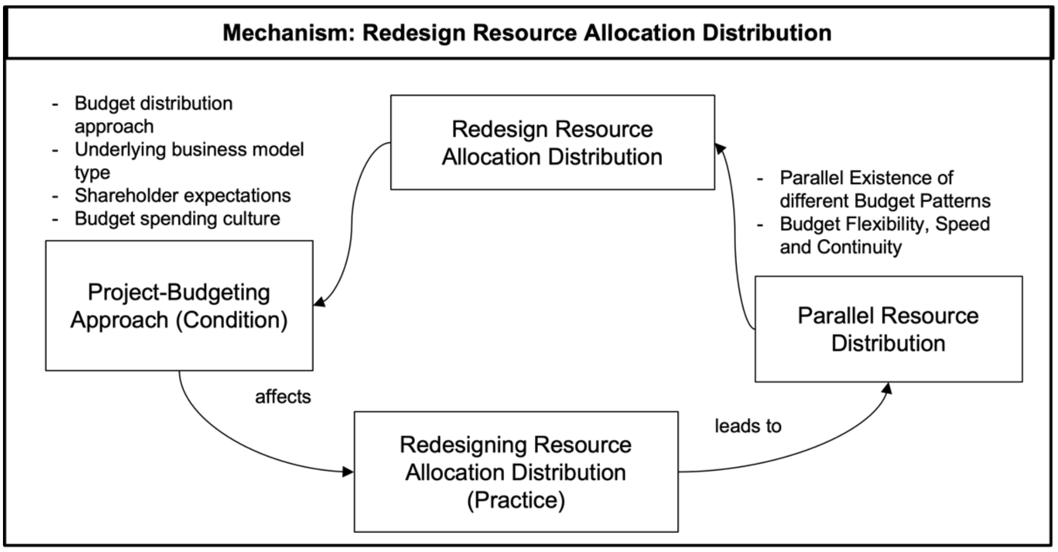
The second shift in budgeting focused on the evaluation of the budget's impact. It entailed a departure from funding-specific outcomes, such as components or tools, and a shift towards funding features and assessing their impact on key business metrics. In the case of the OTA team, they sought to be evaluated based on business metrics related to OTA success, like the software update success rate. Instead of emphasizing the development of tools and components, the team aimed to prioritize the development of artifacts that directly contributed to measurable improvements in relevant business metrics.

The third budget shift pertained to the decision-making mechanism and the time required for decision-making. Within the virtual product organization, the digital leadership team aimed to expedite decision-making for changes requiring budget reallocation. This involved moving decision-making away from committees that required approval for such decisions and toward roles and decentralized teams. The rationale behind this shift was to reduce the prolonged waiting times for feedback that teams experienced during their development efforts. By streamlining committee structures and approval stages, the goal was to accelerate the development timeline for features.

4.4.4.2 Inductive Analysis

The inductive analysis uncovered a mechanism referred to as "Redesign Resource Allocation Distribution" (Figure 22).

Figure 22: Mechanism Redesign Resource Allocation Distribution



The mechanism "Redesign Resource Allocation Distribution" explains how established industrial-age companies, primarily focused on physical product development and project-driven budgeting, adapt and modify their budgeting practices to enable the continuous development of digital products. This mechanism operates under specific activating conditions, involves various practices, and leads to distinct outcomes.

The project-driven budgeting approach serves as the starting point for this mechanism and faces challenges when applied to digital initiatives such as OTA (Table 33).

Table 33: Dimension Project Budgeting Approach

Dimension	Properties of Dimension	Representative Quote
Project-budgeting approach (condition)	The budget distribution approach refers to the currently used approach for providing budget decisions.	*"Then everyone enters their needs, then the portfolio is shuffled back and forth until it somehow fits into the budget framework and then it is logged in and then it is implemented for a year and then the process is opened up for it. And that is not a satisfactory process, because the budget is always already distributed. So we don't have any breathing space because so many projects are running. They have durations of three, four, five years, and logically, the topics for which money has already been spent for two years are not being put up for discussion now, but are being continued."* (I.5)
	The underlying business model type refers to the different monetization logics of products or services in their delivery.	*"The area of tension at this point is clearly still procurement and the financial goals that are set. You say that you want to achieve this and that margin with the vehicle. This is where the points come into play with the electric vehicle, that a high-voltage battery is very expensive and therefore you actually have a higher cost pressure. And if I save €0.20 on the RAM, then I have saved €0.20 per vehicle and that is actually still the way of thinking. And then you rather save on the hardware and then you have massive difficulties to use the hardware efficiently or not to overload the hardware."* (I.65)
	Shareholder expectations refer to the firm's profitability expectations and their implications for resource investment.	*"We as a company are very much business case-driven and lean-oriented. [...] So, we are in the automotive industry, the company with the best margin. I think Ferrari used to be one of them, and we've now caught up with them, if I remember correctly, with the sixteen percent that our CFO always communicates publicly. And we're investing here in topics that we're not convinced will be successful, because we don't know whether we'll make any money with them, yes. So that means one thing, the margins are shrinking rather to a comma X topic, yes, so earning money digitally means normally long volume. For us, volume is not anchored in our DNA. [...] So we're getting away, we have to get away from selling a piece of product towards a digital product in a given use case, that means the business model completely changed, but that also means the business case doesn't run for three years, but rather for fifteen years, perhaps, but it also means, if the business case has completely changed in the forecast perhaps after three to five years, sometimes even after one year, to stop something, yes, that's also part of it."* (I.1)
	Budget spending culture refers to the mindset and values that guide budget decisions.	*"But it's not like other tech players like Google or something like that where you get play money and say do what you want one day a week and you also have a small budget and then we'll see what you come up with. Instead, we have a process that is always very strongly driven by controlling and we constantly question whether we need it and always approve it with a 30 percent discount. So you never work consistently with all the resources that would have been needed to make it even better."* (I.52)

In the project budgeting approach, budget allocation occurs within the vehicle domain by applying for funding from an annual IT budget pool. Once a project is approved, it often limits flexibility, as ongoing projects must continue to deliver value, leaving little room for new initiatives. Additionally, the organization's business model type plays a crucial role, as PremiumCar primarily focuses on selling hardware (e.g., cars) with a strong emphasis on cost efficiency. This can lead to decisions against investing in additional hardware required for OTA, as it may negatively impact the economic viability of the vehicle component.

This is also closely related to shareholder expectations, which refer to the firm's profitability expectations and their implications for resource allocation. PremiumCar's monetization approach heavily relies on selling cars at a single point in time with a relatively high-profit margin, making them a highly profitable investment. However, with OTA, PremiumCar can only achieve smaller returns through the sale of services, which become profitable with scaling. As a luxury OEM, the idea of selling a high volume of products is not deeply ingrained in PremiumCar's culture. Therefore, the shift to OTA necessitates a complete change in the business model, which also challenges high shareholder expectations. This relates to the condition of the budget spending culture, which refers to the mindset and values guiding budget decisions. PremiumCar's culture is often described as conservative, with cost control as a primary goal.

To establish the right funding structures, PremiumCar engages in the practice of redesigning various resource allocation distribution methods (Table 34).

Table 34: Dimension Redesigning Resource Allocation Distribution Practices

Dimension	Properties of Dimension	Representative Quote
Redesigning resource allocation distribution practice	Shifting the budgeting object from a focus on artifacts to one on impact metrics.	*"And the budget must also fit more clearly with Important topics for us as a company. So, it must not be written in the project description. Build me this backend system. Instead, it must include topics such as 98 percent successful software updates for the new Alpha. [...] The goal is not to build backends, but to generate successful software updates for the customer."* (I.48)
	Restructure the resource allocation prioritization process.	*"And we decided that we needed a new budget structure. And we want to allocate a budget for long-term capabilities that deliver value. Within these capabilities, we have some flexibility on which topics we want to work on. So, for example, you provide a budget for the OTA infrastructure development that builds a capability instead of having multiple projects, each doing a small part tied to a vehicle project."* (I.5)
	Shifting the decision-making process to increase speed.	*"No one has to run somewhere and release a budget anymore. And the decision can be made by a product owner or product manager and no longer by some hierarchy."* (I.6)
	Provide opportunities for long-term funding of product teams.	*"We have restructured the budgets for a part of the portfolio, namely for the virtual product organization, and brought them all into the general portfolio. This means moving away from project management to product management in which we want to finance corresponding products via a large pool instead of individual projects. That means continuous financing of operational teams that develop portfolio products instead of project structures."* (I.2)

PremiumCar strives to shift from budgeting based on the delivery of tangible objects (such as a new OTA backend) to measuring impact metrics (e.g., the percentage of successful software updates). Additionally, management restructures the resource allocation prioritization process, moving away from teams and projects applying for funding. Instead, they provide continuous baseline budgets for specific products and capabilities. Every three months, priorities and tasks are adjusted to respond to changing needs. Furthermore, PremiumCar transitions the decision-making process away from committees and empowers product owners within the teams, giving them more responsibility to accelerate decision-making processes.

Furthermore, PremiumCar now provides opportunities for long-term funding of product teams. In the past, teams were solely funded through discrete projects, and team members would often disband at the end of each project. However, for certain products like OTA, continuous funding is now available.

In terms of outcomes, this has led to the coexistence of Parallel Resource Distribution practices, as the prevalent project distribution mechanism still exists for vehicle-related projects (Table 35). PremiumCar essentially operates two budgeting approaches: one driven by the traditional vehicle projects based on discrete projects, and another for digital products that rely on continuous product funding. For initiatives like OTA, which sit at the intersection of these approaches, it means receiving funding from two different sources.

Table 35: Dimension Parallel Resource Distribution

Dimension	Properties of Dimension	Representative Quote
Parallel resource distribution (outcome)	Existence of different parallel budget patterns that focus on either discrete product funding or continuous product funding.	*"Today, we have two funding sources, each contributing half of the funding for OTA Data. One relates to business processes, now called Portfolio Products. The other is Connected Car, a separate portfolio. While we managed to reduce the number of projects significantly in the business processes area through cooperation with the controlling department and budget managers, Connected Car took a different approach. Consequently, we still work with seven budget pools, one for corporate processes and six from Connected Car."* (I.49)
	Budget flexibility, speed, and continuity refer to how flexible teams are, how budget effects are measured, how continuous budget is provided, and how fast the decision-making process is.	*"We are currently funded on 14 different projects that need approval in committees. Each project has a defined score, with work packages and budget. And we got this million to realize a feature for production. Then they expect us to invest into their feature, no matter what we do."* (I.44)

The coexistence of parallel budgeting approaches also impacts the flexibility, speed, and continuity of teams. Flexibility refers to how adaptable teams are in terms of budget allocation. Speed refers to how quickly budget decisions can be made, and continuity relates to the consistent provision of budget. In the case of OTA, the hybrid approach has increased flexibility, speed, and continuity. However, the persistence of the traditional project-based approach is still seen as a challenge by the team.

In summary, the elements presented collectively constitute the mechanism of "Redesign Resource Allocation Distribution," which elucidates how industrial-aged companies adapt their budgeting practices to facilitate digital product innovation. These companies typically lean toward project-based funding approaches due to their emphasis on physical products. While the physical component remains important, the organization undertakes the redesign of resource allocation distribution mechanisms, resulting in the coexistence of parallel resource distribution mechanisms stemming from both the vehicle and software domains.

5 DISCUSSION

This dissertation investigates how industrial-aged organizations achieve digital product innovation. Drawing on the digital product innovation and modularity literature (Baldwin & Clark, 2000; Colfer & Baldwin, 2016; Henfridsson et al., 2014; Lee & Berente, 2012; Svahn et al., 2017; Yoo et al., 2010, 2012) it attempts to answer this question based on a single case study of PremiumCar, an industrial-aged carmaker, focusing on their digital product innovation initiative related to OTA updates. Its findings result in four mechanisms that explain how industrial-aged organizations accomplish digital product innovation.

The discussion section situates those findings within the relevant research streams. Based on the introduced literature and grounded in the empirical findings, it proposes a process model of how industrial-aged organizations accomplish digital product innovation.

Before introducing the process model, it discusses some of the findings in the light of the modularity and liminality literature intending to situate the process model accordingly.

5.1 The Modularity and Liminality of Digital Product Innovation

Industrial-aged organizations draw on specific practices and activities to accomplish digital product innovation, both with regard to product architecture as well as organizational structures (Hylving & Schultze, 2020; Svahn et al., 2017). Such periods are shaped by their transitory "liminal" nature of activities (Henfridsson & Yoo, 2014; Orlikowski & Scott, 2021). Hence, the evolving nature of digital technology affords action opportunities that provoke tensions between the future and the status quo giving rise to such liminal periods that unfold between experimentation and implementation (Henfridsson & Yoo, 2014; Orlikowski & Scott, 2021).

Considerable attention has been paid to aspects of product architecture (Henfridsson et al., 2014; Hylving & Schultze, 2020; Lee & Berente, 2012; Yoo et al., 2010) as well as to required organizational tensions that industrial-aged companies need to address in order to succeed with digital product innovation (Svahn et al., 2017; Yoo et al., 2012, 2010). In particular, the tension between different physical and digitally dominated product architectures has been identified as a source of conflict that needs to be resolved (Henfridsson et al., 2014; Hylving & Schultze, 2020). One specific implication emerging from this is the practice of mirror-breaking, where the literature suggests that in order to accomplish digital product innovation, firms need to break the overlapping of product architectures with organizational practices (Hylving & Schultze, 2020).

The study uses the mirroring hypothesis to unpack that process and to unpack the dynamics. Thus, the PremiumCar case around the OTA initiative picks up the literature stream on mirroring in digital innovation but provides a contrasting picture to the literature.

While the integration of digital control systems like the OTA FC is certainly used as boundary-spanning objects that disrupt the previous product architecture mirror (Lee & Berente, 2012), our case study's findings reveal a series of shifts in the mirroring between product architecture and organizational structure. Thus, the findings would support another argument. Currently, mirroring as a product design strategy is depicted in a binary way – companies either mirror or not (Burton & Galvin, 2022; Colfer & Baldwin, 2016). The case suggests a more dynamic view. Rather than a single instance in time, mirroring and mirroring breaking seem to be practices situated in *mirroring as a process* (MacDuffie, 2013). To explain this in detail, consider the different shifts.

The case suggests that PremiumCar departed at the beginning of the OTA initiative from the status quo in which the product architecture and the organizational structure as well as the product development routines involved high levels of mirroring. For example, the different products and components were mirrored into the organization not only through the product line principle but also very specifically as teams within the product line were organized around components or modules following the KEFAG architecture. Then, with the expansion of OTA in the 3rd generation, and as suggested by the literature (Hylving & Schultze, 2020; Lee & Berente, 2012), PremiumCar engages in mirror breaking both on the product architecture level (with the integration of the OTA FC) as well as on the organizational level (where for example the IT unit formerly responsible for the software update tools evolves into a product team seeking cross-functional responsibility). However, towards the end of the initiative, the case also suggests – in contrast to the literature – that PremiumCar strives to mirror the layeredness of the digital product architecture in organizational design and practices (Yoo et al., 2010). For example, organizational entities are established that mirror product layers. Thus, rather than the current binary view of mirroring as a design strategy (Hylving & Schultze, 2020; Lee & Berente, 2012), the case suggests considering *mirroring as a process* that industrial-aged companies pursue to accomplish digital product innovation.

Further, the study highlights the liminality of the process that industrial-aged companies experience to accomplish layered modular architecture. Whereas the existing literature on the liminality of digital product innovation paints a picture of liminality as either a continuous accomplishment in practice (Orlikowski & Scott, 2021) or as transitionary process (Henfridsson & Yoo, 2014), the findings of the case suggest a third view. The process of accomplishing digital product innovation at PremiumCar is punctuated by specific decisions on the product architecture and organizational level, but also a continuous accomplishment in practice where actors need to confront and merge different realities at the same time. A valid example from the case is the situation with the Backend implementation for the OTA. What was outsourced in the beginning by the product line is for a short period of time developed in the IT team before it is then again moved to SoftwareCorporation. Different backends co-exist for different vehicle generations. Also, decisions for moving the responsibility for the backend development punctuate new liminal periods. Thus, in their pursuit of digital product innovation, the OTA development is constantly operating between implementation and experimentation.

To achieve digital product innovation in industrial-aged companies requires engaging in the process of mirroring and mirror-breaking. Here, liminality is a *state of simultaneity faced by actors when pursuing digital product innovation constrained by past architectural frames and related organizing practices that are blended with newly emerging architectural frames and related organizing practices.* These processes unfold within a liminal state*, where actors simultaneously contend with past architectural frameworks and organizing practices while blending them with emerging architectural frameworks and organizing practices.*

The state leads to a liminal period of improvisation between experimentation and implementation to succeed with digital product innovation.

5.2 A Process Model for Digital Product Innovation

The dissertation proposes a process model (Figure 23) that focuses on the a) contextual triggers that initiate industrial-aged organizations to pursue digital product innovation, b) the reciprocal liminal mechanisms that industrial-aged organizations pursue to accomplish digital product innovation, and c) the outcomes on the product architecture as well as on the organizational level.

Figure 23: A Process Model for Digital Product Innovation

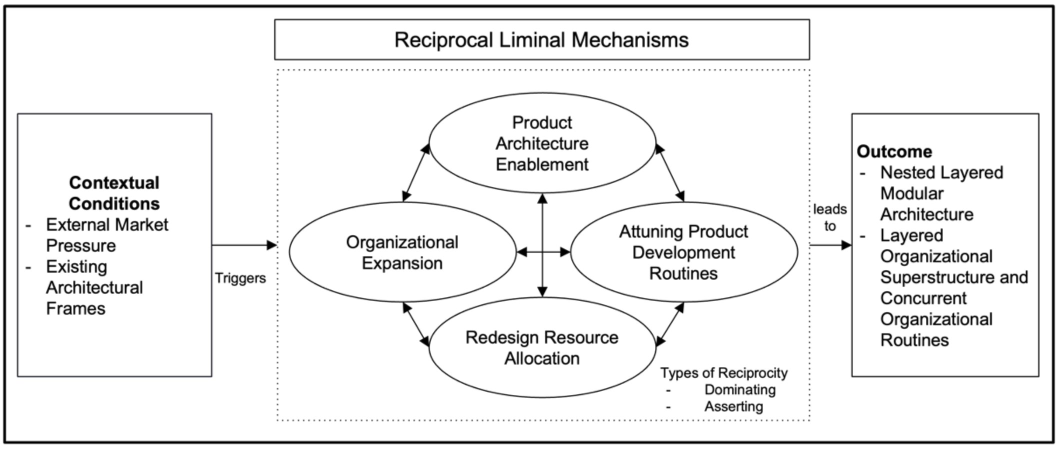


Table 36: Process Model Concepts

Concept	Definition
Contextual conditions	The starting point of the digital product innovation journey is a tension between external market pressure and conflicting architectural frames.
Reciprocal liminal mechanisms	Reciprocal liminal mechanisms describe transitional activities pursued by industrial-aged companies and their effects on each other which can either be dominating or asserting.
Product architecture enablement	The mechanism explains how industrial-aged organizations continuously decouple and rewire their product architecture to achieve modularity and layeredness in the component-task arrangement to succeed with digital product innovation.
Organizational expansion	The mechanism explains how industrial-aged organizations expand and refine their preexisting organizational structure to accommodate and incorporate organizational structures representing different modular components of product layers to accomplish digital product innovation.
Attuning product development routines	The mechanism explains how industrial-aged organizations refine their existing product development routines grounded in the different materiality of product components leading to a concurrency of performed routines at the same time.
Redesign resource allocation	Redesign resource allocation explains how industrial-aged organizations adjust their internal resource allocation practices and processes to accommodate continuous funding for digital product innovations.
Outcome	A nested layered modular architecture and an organizational superstructure with concurrent organizational routines that together form PremiumCar's digital product innovation capability.

5.2.1 Contextual Conditions

How do established, industrial-aged organizations embark on the path of pursuing digital product innovation? Both the existing literature and the findings from case studies suggest two critical contextual triggers in this endeavor.

The literature contends that shifts in consumer behavior and expectations, coupled with changes in the competitive landscape, play pivotal roles (Svahn et al., 2017; Vial, 2019). For instance, Svahn et al. (2017) noted that the connected car initiative at Volvo was catalyzed by the advent of Apple's iOS and Google's Android in 2008, which prompted Volvo to consider car connectivity seriously. These findings closely resonate with PremiumCar's efforts in Over-The-Air (OTA) updates. In this context, external market pressures, such as Tesla's launch of OTA services in 2012, drove new customer expectations that PremiumCar had to address with their Model Delta. Thus, PremiumCar responded to external market pressure by expanding the OTA functionality drastically with the new Delta model that was introduced in 2016.

Therefore, the first contextual trigger for the proposed process model is labeled "market pressure," encompassing the mounting external pressures and developments within the broader market domain that compel industrial-aged companies to take action.

However, unlike young firms, industrial-aged organizations cannot simply discard their past and create a new product from scratch to compete with emerging rivals. They must undergo a meticulous transformation of their existing product architectures and organizational practices.

Regarding product architectures, Henfridsson et al. (2014) highlight that the decision to embark on a transformation journey was motivated by the high product complexity characterized by tightly coupled components and the encapsulation of software within hardware (Henfridsson et al., 2014). This closely aligns with the OTA challenges faced by PremiumCar. PremiumCar confronted a product architecture deeply integrated into its vehicles, where the component-level communication architecture critical for OTA updates was intricately woven. In this study, the term "compound structure of the product architecture" (see 4.4.1.2) is employed to encapsulate these legacy product architecture challenges. Such an integrated architectural approach runs counter to the requirements of incorporating a digital service or product that adheres to a layered architectural approach (Yoo et al., 2010). The literature has delineated these conflicts in product architectures using terms such as "hybrid architecture" (Yoo et al., 2010), "architectural frames" (Henfridsson et al., 2014), and "conflicting configurations of modularity" (Hylving & Schultze, 2020).

Furthermore, following the theoretical premise of the mirroring hypothesis (Colfer & Baldwin, 2016), product architecture decisions were deeply intertwined with organizational structures and practices. In the case of PremiumCar, this was exemplified through the product line principle. The product line principle led to the replication of each vehicle and its components (e.g., control units) within the R&D

organization. When facing the implementation of OTA in the third generation, PremiumCar had dedicated OTA teams for each vehicle. Initially, OTA necessitated the enablement of device layer components (control units), which required the OTA team to engage with each component team (totaling over 100 teams) – a testament to the effectiveness of the mirroring hypothesis at PremiumCar.

The highly integrated product architecture mirrored in the organization's structure and practices elucidate PremiumCar's status quo and provides the second contextual condition. In alignment with the literature (Henfridsson et al., 2014; Svahn, 2012), and referring to both the preexisting integrated product architecture mirrored in the organizing logic, encompassing its practices and structures, the term "existing architectural frame" is employed as the second contextual trigger.

It is the interplay between these two contextual triggers – external market pressures on one hand and the constraints imposed by existing architectural frames on the other – that activate a set of reciprocal liminal mechanisms. Industrial-aged organizations must navigate these mechanisms adeptly to achieve success in the realm of digital product innovation.

5.2.2 Reciprocal Liminal Mechanisms

Mechanisms are defined as "causal forces that would have to exist in order to explain a given phenomenon" (Williams & Wynn, 2018, p. 318). Depending on the level of analysis, one can distinguish between different types of mechanisms, such as situational, action-formation, and transformation mechanisms (Hedström & Ylikoski, 2010). From the PremiumCar case study analysis, this study proposes four "reciprocal liminal mechanisms".

Reciprocity, in the sense of mutual dependence (Dictionary, 2023), implies that the activation of one mechanism relies on the activation of another mechanism. This concept also underscores the influence of the mirroring hypothesis (Colfer & Baldwin, 2016). For instance, the relationship between product architecture and product development routines is considered reciprocal because the product architecture initially dictates the product development routines, and the enforcement of additional product development routines, in turn, influences product architecture decisions.

Reciprocity manifests in two types of relationships. Firstly, a dominating relationship where one mechanism exerts dominance over the other. Secondly, asserting relationships which entail one mechanism claiming relevance through the other. These relationships are characterized by their liminal innovation practices, which refer to the transitional nature and the intermediary role of actors between experimentation and implementation (Mertens, 2018; Orlikowski & Scott, 2021).

For example, in PremiumCar's OTA backend product architecture, the lack of decoupling of the OTA product architecture dominates the product development routines. Thus, interdependencies in the product architecture result in dependencies in the product development routines. Thus, the design of OTA components, in this case, the first OTA backend is constrained by design decisions made due to constraints in the product development process. The OTA team mitigates the product development challenges through backaround practices, a new practice where issues supposed to be addressed in the onboard architecture are addressed in the backend, increasing product architecture complexity. Here, we can witness reciprocity as the product development practices and constraints – a structural element – influence the product architecture. Thus, the product architectural design decisions are also a result of the product development routines deployed. Thus, product architectures and social structures – like the product development routines – are interwoven and whereas the product architecture decisions often dominate the actual work practices and processes, such practices and processes assert themselves again in the product architecture.

5.2.2.1 Product Architecture Enablement

Overcoming conflicting product architecture types rooted in the different materiality of physical and digital components poses a significant challenge for industrial-aged organizations (Henfridsson et al., 2014; Hylving & Schultze, 2020; Lee & Berente, 2012; Yoo et al., 2010). This conflict is also evident in the PremiumCar case study.

The literature suggests that digital control systems play a key role in bridging different architectural frames (Lee & Berente, 2012). This notion was affirmed in the PremiumCar case, where the rewiring strategy of the OTA FC served as a facade to access and enable other control units that could not independently update themselves. In the most recent OTA generation, such digital control systems (referred to as domain controllers) seem to play a vital role in reorganizing various layers of product architectures. PremiumCar here restructures the entire task architecture of the Software Corp. Domain Architecture and moves task belonging together into five different domains. What was formerly largely distributed across the entire vehicle in terms of functions is now allocated closely to each other.

Secondly, the literature has identified that in moving from a highly integrated product architecture to a layered modular architecture, uncoupling from the old product architectures is a crucial practice (Hylving & Schultze, 2020). The case study findings regarding the practices of rewiring further develop this concept, suggesting that instead of merely uncoupling, industrial-aged organizations need to engage in decoupling to accomplish digital product innovation. These organizations do not simply abandon the old architectural frame; rather, they carefully consider how to rewire the communication architecture between different layers.

The literature emphasizes that digital product innovation requires layered modular architectures (Yoo et al., 2010). Layeredness, in this context, means having separate and loosely coupled layers of devices, networks, services, and content, all interconnected through standardized interfaces like APIs (Yoo et al., 2010). In the PremiumCar case, the aspiration to realize such layeredness in the product architecture was evident, with OTA having a device layer (control units), a network layer (OTA FC and Connected Gateway), a service layer (OTA backend), and a content layer (software updates or functions on demand). However, while the literature suggests that this is a transitional process of transformations (Hylving & Schultze, 2020), the findings indicate a continuous process where, over different generations and gradually, components are decoupled and new layers are introduced (e.g. Software-Corp. Domain Architecture introduces a new middleware layer).

Furthermore, this process is of a liminal nature (Mertens, 2018; Orlikowski & Scott, 2021), as product architecture teams must handle both old architectural components and new architectural components simultaneously, as seen in the presence of multiple backends at the same time. Thus, the product enablement mechanisms also interact with the organizational structure mechanism: initially, product architecture decisions dominate how work is distributed among component teams. However, the emerging social structure around different teams responsible for various backends resulted in multiplicity, which was resolved at the MobilityGroup level with the establishment of a central actor responsible for a central platform.

Changes in product architecture around decoupling also necessitated changes in the redistribution of work and tasks with suppliers, providing evidence that product architecture changes affect the entire value architecture within the product's supply chain (MacDuffie, 2013). Through the decoupling of control units and their components on the device layer, suppliers who previously provided both hardware and software for the component were now tasked with delivering only the device layer, along with an interface specification to integrate the component into the OEM's operating layer infrastructure.

In summary, in line with the modularity literature (Baldwin & Clark, 2000), it can be argued that achieving modularity in product architecture for digital product innovation should be considered a process in which product architectures are reassembled and redesigned, and modular elements (such as components) are introduced gradually over different generations. Additionally, the concept of information hiding (Baldwin & Clark, 2000), a key principle for managing complexity across different layers, seems to be a central principle in this process. This results in the decoupling of different layers, allowing organizations to express different product architecture logic, each with its own cycling times. At PremiumCar, this concept was referred to as "pace-layered architecture." It also reflects the generativity of digital innovation, as digital products are by design in-complete and continuously in the making (Lehmann & Recker, 2022). The decoupling of different layers serves as a significant premise in this context. Now, with independent decoupled layers, product components can evolve at their own speed.

Based on the case study findings and consistent with the literature, such developments are summarized as the liminal and reciprocal mechanism of product architecture enablement. This action-formation mechanism describes how industrial-aged organizations continuously decouple and rewire their product architecture to achieve modularity and layeredness in the task distribution of their products to succeed with digital product innovation.

5.2.2.2 Organizational Expansion

The literature underscores the significance of altering the organizational structure in industrial-aged companies as a prerequisite for successful digital product innovation (Drechsler et al., 2020; Vial, 2019).

PremiumCar adhered to these findings and undertook two types of activities to reshape its organizational structure. Firstly, it established multiple digital organizational entities, each representing different components of digital products. This was exemplified by the OTA service, where initially a product team emerged, subsequently evolving into an Agile Release Train. A similar transformation occurred with SoftwareCorporation, which became a distinct entity responsible for developing the central Software Corp. Domain Architecture platform and its components. So, different entities emerged taking over different product architecture layer tasks. This also holds true on the component organizing level where the literature discusses the difference between feature teams vs component teams (Zorin & Hahn, 2020). PremiumCar's OTA team also moved away from component teams towards feature teams to mirror the emerging OTA capabilities into their system architecture. Thus, it seems that the mirroring hypothesis (Colfer & Baldwin, 2016) also holds true here, mirroring the different product architecture layers into the organizational structure surrounding digital product innovation.

The literature also points out that industrial-aged organizations frequently create dedicated organizational units alongside the main organization, tasked with developing digital innovations (Haskamp et al., 2023; Holotiuk, 2020; Lorson et al., 2022; Woerner et al., 2022). Although PremiumCar also had such a unit in place (PremiumCar Digital), it appears that the organizational structure required for achieving digital product innovation must be more nuanced and cannot be outsourced to isolated external units. Each element of the virtual product organization represented various digital product streams. PremiumCar's virtual product organization, where product development was meant to take place, was not an external digital unit but rather another "organizational layer" superimposed upon the existing organizational structure. This meant that employees who had a role in the established organizational structure at PremiumCar as project leads also had a second different role as product owner etc. in the virtual product organization. It appears that "multi-capping" (Van der Meulen et al., 2022) - a practice discovered in a Toyota case involving connected cars, where "executives assume multiple concurrent leadership roles throughout the company" (p. 4) - also extends to the employee level as an integration practice for representing the needs of different perspectives. Thus, PremiumCar's employees were simultaneously part of their established functional roles within the organizational structure and played a role in the virtual product organization. This closely intertwined setup seemed to be a necessity due to the close collaboration required between the physical vehicle product teams and the digital product teams to ensure the success of digital product innovations like OTA. While this collaborative approach broadly aligns with other studies aimed at facilitating digital product innovation, which necessitates increased cross-functional teamwork and collaboration (Hylving & Schultze, 2020; Lee & Berente, 2012), it nevertheless extends the scope of collaboration and the set of practices required to do so.

Secondly, PremiumCar also refined its existing organizational structure and the way it perceives itself, particularly in the realms of IT and product development. A prime example is the reconfiguration of the product development organizational structure, transitioning from the KEFAG structure to the systems engineering concept. Whereas KEFAG represents the physical components of the car, the systems engineering encompassed both physical and digital components. Hence, the organizational structure also seems to undergo a merging of physical and digital organizing logic.

The literature has also vividly discussed how digital product innovation alters the role of the IT department, requiring it to serve as both a service provider and a product development entity (Urbach et al., 2019). However, with the emergence of OTA and, in the most recent OTA generation, it seemed that IT at PremiumCar assumed at least three roles. Firstly, as the traditional IT department responsible for maintaining day-to-day operations; secondly, as the primary entity within the virtual product organization tasked with providing digital products; and thirdly, within the new board area for infotainment and connected services. In this new role, alongside the CIO, a new board member was entrusted with overseeing topics at the intersection of electronics and information technology. Thus, not only do digital initiatives expand and exceed existing understanding of IT (Kaganer et al., 2023), but this example also demonstrates how IT entities begin to influence the development of physical devices. For instance, the new domain overseeing infotainment and connectivity services now plays a significant role in shaping the physical product architecture. The establishment of the new area for infotainment and connected services exemplifies the growing significance of car connectivity and its associated effects, including the emergence of various services such as software updates, which manifest as product streams within the virtual product organization. This could be interpreted as what the literature has called the "ontological reversal" (Baskerville et al., 2020) where digital technology not only represents physical realities but becomes an active player in shaping such physical realities.

Viewed through the lens of the mirroring hypothesis (Colfer & Baldwin, 2016), one could argue that the various adjustments and changes in the organizational structure were precipitated by shifts in product architectures, with each product layer and domain being represented in the organizational structure at PremiumCar.

In summary, based on the developments observed in the case study, and partially corroborated by the literature, this study proposes the reciprocal mechanism of "organizational expansion" rooted in the mirroring of product layers. This mechanism elucidates how industrial-aged organizations expand and refine their preexisting organizational structures to encompass and integrate organizational units representing different modular components of product layers, ultimately facilitating digital product innovation. It is a situational mechanism since it furnishes the structural conditions that either constrain or enable certain activities (Hedström & Ylikoski, 2010).

5.2.2.3 Attuning Product Development Routines

In the management of digital product innovation, industrial-aged organizations need to manage different product development routines.

As the literature on digital product innovation highlights, physical and digital product development routines are fundamentally different (Hylving & Schultze, 2020; Lehmann & Recker, 2022; Svahn et al., 2017; Yoo et al., 2012). Physical product development relies on a pre-defined top-down logic where the product has to be fully known prior to product design (Hylving & Schultze, 2020). This stands in sharp contrast to the bottom-up logic where the product can be incomplete as it serves as a platform with generative capabilities (Hylving & Schultze, 2020; Weiss et al., 2023; Yoo et al., 2012). This has severe implications on the product development process, as digital product principles such as continuous integration and release are foundational whereas physical milestone-based product development tries to carefully avoid changes as they tend to be quite resource intensive (Antons et al., 2019; Berente, 2020). Thus, whereas digital product development routines strive for early testing and release to increase development speed, physical product development is, by design, somewhat slow and stable to make product architecture decisions carefully and avoid cost-intensive changes, resulting in different development speeds (Gerster et al., 2021; Svahn et al., 2017)

This was also visible at PremiumCar's OTA initiative where PremiumCar's rigid product development process undermined the OTA team's desire for continuous testing and release. PremiumCar had a practice in place to span the different development speeds called "compound releases", but such compound releases could only reflect the Dev/Ops spirit to a certain extent. In their digital product development activities, PremiumCar's OTA team part of the virtual product organization relied on the agile operating model SAFe with their 90-day cadence of new product increment releases. Thus, PremiumCar had different development speeds and corresponding practices in place depending on the type of materiality that was being developed. For fast-moving worlds, PremiumCar relied on established software development practices, for the physical product components it still used the milestone-based rigid product development process.

The literature highlights how industrial production development principles that are determined and linear conflict with agile development principles that are indeterminate and cyclical (Berente, 2020), leading to hybrid arrangements of agile and stage-gate approaches (Brock et al., 2020). This also held true for PremiumCar where the existing product development process was refined and the times between compound releases were shortened. However, an essential conflict posed was the idea of being "done". With the Start of Production part of the product development process at PremiumCar, often projects were considered finished, and people moved to different projects. This organizing pattern needed to be changed to accommodate the desires of the digital product development teams that wanted to further develop and release new digital products independent of the physical car development projects. This corresponds to the idea of digital products and services that are "ever in the making" (Lehmann & Recker, 2022).

The PremiumCar case revealed that industrial-aged companies somehow need to pursue structural concurrent routines when it comes to the traditional product development tasks of decision-making, planning, and coordinating different stakeholders revealing the in-betweenness of the activities performed. While the literature highlights how digital innovation invokes such tensions between the status quo and the requirements of digital innovation leading to liminal periods (Orlikowski & Scott, 2021) the findings from the PremiumCar case tie the emergence of liminal innovation practices back to the materiality of the product architecture. The fundamental differences in the product development routines are rooted in the different material natures and the lack of decoupling of those different forms of materiality which PremiumCar attempted to do.

In summary, based on findings around the OTA initiative and what the literature revealed about the product development routines required for digital product innovation, this study proposes the reciprocal mechanism of "Attuning Product Development Routines". The mechanism explains how industrial-aged organizations refine their existing product development routines grounded in the different materiality of product components leading to a concurrency of performed routines at the same time. It is an action-formation mechanism since it explains the actor's activities on the micro level (Hedström & Ylikoski, 2010).

5.2.2.4 Redesign Resource Allocation

Industrial-aged organizations have resource allocation practices in place to ensure that resources are spent efficiently. This was also the case at PremiumCar where the different practices and processes were in place responsible for the financial success story the company has become. Also, the literature highlights the central aspects of budgeting and pre-existing business model patterns (Berente & Yoo, 2012; Klos et al., 2021; Soluk & Kammerlander, 2021).

PremiumCar had an established business model and a clear monetarization logic that focused on the sales of physical products (cars) and in which the scalability and profitability of each vehicle component were considered critical for the overall financial success of the vehicle projects. With its high-profit ambitions, PremiumCar had put a set of practices in place such as a rigid business case approval scheme to decide where to invest its scarce resources. This led to a very frugal spending culture that became a challenge with OTA. Firstly, OTA had a different monetization logic, something already mentioned in the literature (Soluk & Kammerlander, 2021). Rather than in the sale of physical cars where the sales are generated at one point in time, OTA required a different revenue generation approach in addition to cost savings for software updates.

While Functions on Demand are predicted to be a quite profitable business model (Koster et al., 2021), it nevertheless requires the sale of high numbers of service until the initial cost investment becomes worthy. Selling large volumes of something was at odds with a luxury carmaker that was used to sell low numbers of products for high prices.

The resource allocation logic was also internalized in the practices where the virtual product organization at PremiumCar intended to break with the project-funding approach that undermined the continuously required investment into stable digital products. The virtual product organization's leadership team allocated a large portion of their available budget towards newly established products that now received continuous funding for their teams. However, parts of the funding were still acquired from vehicle projects that stuck to the pre-existing budgeting scheme, leading to concurrency and the parallel existence of budget distribution practices.

From the case study, the mechanism of "Redesigning Resource Allocation" is proposed where industrial-aged organizations adjust their internal resource allocation practices and processes to accommodate continuous funding for digital product innovations.

5.2.3 Outcome

As an outcome of this process and the four liminal mechanisms operating, the study proposes two main outcomes. On the product architecture level, a "nested layered modular architecture" emerges and on a structural level, an "organizational superstructure" as well as "concurrent organizational routines" are emerging.

On the product architecture level, the digital product innovation literature highlights how accomplishing digital product innovation requires embracing layered modular architecture (Hylving & Schultze, 2020; Yoo et al., 2010). Thus, to no surprise, the outcome of the process is a form of layered modular architecture.

Indeed, with each OTA generation, the digital layered architecture becomes increasingly prominent, culminating in the Software Corp. Domain Architecture. Here, PremiumCar fully embraces layered modular architecture which also changes the relationship and presents a shift away from an architectural frame that was guided by the physical architecture towards an architectural frame that fully embraces digital innovation and dominates the physical world as a design principle (Baskerville et al., 2020; Yoo et al., 2010).

However, this layered modular architecture appears in a nested form since the layeredness and the rewiring activities of the modular architecture that are performed under time pressure during product development of existing cars leads to a product architecture that is assembled of existing components where gradually new forms of components are introduced. Different configurations and types of nesting can be observed.

Thus, the outcome is a nested modular architecture that is understood as a form of layered modular architecture assembled of pre-existing components and newly integrated components that lead to different forms of nesting. The literature finds that nesting is used as a product architecture strategy (Ulrich, 1995). For example, as highlighted by Ulrich, "Geometric nesting is a design strategy for efficient use of space and material and involves the interleaving and arrangement of components such that they occupy the minimum volume possible, or, in some cases, such that they occupy a volume with a particular desired shape" (Ulrich, 1995, p. 433). The study understands nesting in the form of different arrangement principles of old and new or different components and finds three types of nesting, linear, lateral, or modular. Linear nesting here refers to an allocation of functional elements to different product layers in a linear way, as seen in the IIM and the IBM in the study. Lateral nesting refers to refers to an allocation of functional elements to one product layer in a lateral way through a facade layer, for example, visible through the OTA FC and lastly, modular nesting is where functional elements are allocated as encapsulated entities that are accessible through a standardized interface as it was the intention with the Software-Corp. Domain Architecture and the concept of zones. Importantly, the notion of nesting here highlights that all nesting types comprise a mix of old and new components, thus nesting is never a binary strategy but rather a constantly evolving pattern of pursued activities, requiring the team to master these different outcomes at the same time.

On the structural level, an organizational superstructure emerges that tends to mirror the product architecture layers. The preexisting organizational structure focuses on the device layer meaning the car components that are developed within the preexisting hardware organizational structure. With the expansion envisioned through OTA, the organizational structures are gradually expanded with different organizational structure elements being added responding to the different product layers. The OTA device layer is operated at PremiumCar, the OTA network layer, and the service layer at Software Corporation where PremiumCar is only responsible for incorporating components that are developed, and the application layer again is developed in a PremiumCar unit. Thus, per product architecture layer, PremiumCar set up different units. While the literature on organizational structure has observed the emergence of new organizational forms (Hanelt et al., 2020; Vial, 2019), this study advocates that such changes in the organizational structure are actually not tied to topics such as identity (Wessel et al., 2021), but more importantly, are explained by shifts in the product architectures required for digital product innovation. Leveraging the mirroring hypothesis, the study finds that industrial-aged organizations expand their organizational structures through different types of organizational arrangements which enables them to engage in digital product innovation.

Further, on the product development structures and process, another outcome is the concurrency on the structural routine level with both product development routines and resource allocation routines. In order to operate different product layers within the organization and their required organizing logic, PremiumCar needs to deploy different "concurrent organizational routines" such as budgeting or product development practices at the same time making this status another central outcome.

6 CONCLUSION

The dissertation attempted to investigate how industrial-aged companies can accomplish digital product innovation. To conclude this work, the answers to the initially introduced research questions are presented, followed by an outline of the theoretical contributions and their implications for the dissertation's literature. Then the practical implications of this work are outlined briefly as well as the boundary conditions and limitations of the findings presented before closing with a discussion of future research opportunities arising from this work.

6.1 ANSWERS TO RESEARCH QUESTIONS

The dissertation began by introducing key investigative research questions that the study intended to answer (see Chapter 1.3). Throughout the dissertation, those research questions were addressed accordingly (Table 37).

Table 37: Research Questions and Answers

Research Question	Research Answer
What is the current body of knowledge regarding organizational inertia in industrial-aged companies?	Framework on the antecedents, processes, and consequences of organizational inertia[15]
What are the practices of industrial-age organizations pursuing digital product innovation?	Four mechanisms and their conditions, practices, and outcomes
What is the process of how digital product innovation is accomplished in an industrial-age organization?	Process framework including triggers, mechanisms, and outcomes

On the first research question around the current literature on organizational inertia, a dedicated conference paper (Haskamp et al., 2021) was published. This includes a dedicated framework unpacking organizational inertia, its antecedents, dimensions theoretical lenses, and outcomes.

The second question concerns industrial-aged companies' practices to achieve digital product innovation. This was answered by proposing four mechanisms including their conditions, practices, and outcomes (Chapters 4.4. and 5.2.).

The third question aimed to unpack how digital product innovation is accomplished and addressed by developing a process model (Chapter 5.2.).

[15] The answer to this research question is not explicitly part of this dissertation but part of a conference paper in which the literature review findings are presented.

6.2 Theoretical Contribution

There is a set of academic papers published in the most prestigious journals in management and information systems (Baiyere et al., 2023; Fielt & Gregor, 2016; Gradillas & Thomas, 2023; Nambisan et al., 2017, 2020, 2019; Piccoli et al., 2022; Vega & Chiasson, 2019; Vial, 2019; Yoo, 2012; Yoo et al., 2010, 2012) that highlights the need to better understand how digital technology shapes organizing and how existing knowledge and theories on management and innovation are challenged by digital phenomenon.

This involves specifically the question of how to accomplish digital product innovation and integrate opposing architectural logic that also has implications for organizing. The research presented in this study attempts to contribute to this literature (Hylving & Schultze, 2020; Vial, 2019; Wang et al., 2022; Yoo et al., 2012, 2010). It offers four generative mechanisms (Hedström & Ylikoski, 2010) and a process model that serves as explanations for the liminality of the process and can be considered as organizational anchor points and levers to succeed with digital product innovation. Previous process models either only focus on organizational aspects (Henfridsson & Yoo, 2014) or take a more strategic level (Soluk & Kammerlander, 2021). The process model proposed in this dissertation attempts to link micro (OTA Team activities) and macro-level events (Virtual Product Organization initiative) to explain how industrial-aged organizations accomplish digital product innovation.

Second, the current literature on the digital transformation of industrial-aged companies (Chanias et al., 2019; Kaganer et al., 2023; Vial, 2019; Wessel et al., 2021) investigates the organizational side of digital transformation using constructs such as identity (Wessel et al., 2021) or business models (Klos et al., 2021; Soluk & Kammerlander, 2021) or value creation (Vial, 2019). Only recently, a stream of literature started to focus on the actual digital product architecture questions (Faulkner & Runde, 2013; Hylving & Schultze, 2020; Kallinikos et al., 2013; Piccoli et al., 2022) to trace back the underlying causes of transformation to the unique nature of digital artifacts. The dissertation and the process model developed tried to follow up on this stream. It attempts to express the socio-technical nature of the phenomenon by linking technical product architecture decisions with organizational changes. By leveraging the mirroring hypothesis as a means to do so, the dissertation attempts to shift the focus of attention beyond organizational behavior constructs to include product architecture aspects more proactively to explain organizational changes in the digital product innovation and transformation literature.

Third, a modularity research stream in the strategic management literature investigates the interplay of hardware and software in terms of whether mirroring is an effective strategy for digital product innovations (Cabigiosu & Camuffo, 2012; Colfer & Baldwin, 2016; Furlan et al., 2014; MacCormack et al., 2012). While for fully digital products or fully physical products, knowledge on the effects of mirroring exists, the dissertation attempts to fill the gap for products with both different physical and digital components and correspondingly, different development speeds. The findings of the dissertation indicate that mirroring has the potential to be an effective strategy for two reasons. Firstly, it provides the concepts and terms to unpack the differences between different physical and digital product layers, their components, and their required ways of organizing to accomplish digital product innovation. Second, next to outlining the particularities of different forms of materiality, it moves the center of attention to the management of interfaces between different product layers.

In summary, the dissertation’s theoretical contribution is that it leverages the mirroring hypothesis to unpack how industrial-aged companies pursue digital product innovation. Based on the findings of the single case study and the current body of literature, it proposes a process model for achieving this with an emphasis on architectural questions as a focal point for understanding how digital technology influences organizational structures.

6.3 PRACTICAL CONTRIBUTION

The CASE trends signal a fundamental shift for the entire automotive industry (The Economist, 2022). Mastering software becomes as important as managing hardware (The Economist, 2023a). Both newcomers and established companies need to learn how to master "mashup products" (Rigby, 2014) that involve both physical and digital components. The findings from the dissertation around the OTA initiative of an industrial-aged incumbent provide a few interesting lessons learned for executives and decision-makers of OEMs.

Firstly, it presents four critical levers (product architecture, organizational structure, product development process, and resource allocation practices) that can guide OEM executives' attention and focus while mastering this process.

On the product architecture level, modularity is key for both hardware and software components. Hardware-level product component design requires incorporating standardized communication interfaces. OEMs with their low vertical integration need to enforce such requirements more consistently in collaborating with their suppliers. Also in terms of software architecture, OEMs need to move away from their highly monolithic software architectures towards scalable and composable software architectures that rely on packaged business capabilities and data assets (Wixom, Piccoli, Rodriguez, 2021). The OTA teams shift between different product architecture approaches, for example moving from monolithic to microservice-based and then to modulithic architectures.

With regard to the product development process, thinking about where product development can differ and where it requires collaboration between completely different ways of working requires rethinking the existing product development and management toolset. Digital product management relies on a set of practices and tools (agile, design thinking, etc.) that can only be applied in limited ways to physical product development. Due to the relatively high resource investment, such physical product development follows different practices that rely on traditional waterfall processes. Mashup products like cars require a new approach that exceeds the current status-quo practices (e.g. Compound Releases).

In terms of the organizational structure, if one takes the mirroring hypothesis as a valid mental model for organizational design, it also provides a few normative implications for how industrial-aged organizations should pursue digital product innovation. Similar to the case organization, organizational entities need to be built to represent different product layers and once established, interfaces between the entities need to be defined, both on the product architecture level and also on the organizational level.

Lastly, in terms of budgeting executives should learn to operate different forms and types of budgeting accordingly. Executives need to confront loss of power in terms of budgeting when such decisions are shifted into teams. But by no means shifting budget decision-making to teams means higher decision-making autonomy. To steer and navigate different teams toward joint goals, specific metrics, and KPIs are required for evaluating the teams and their work.

Secondly, the integration of digital technology into cars will fundamentally impact the entire automotive value chain, with OEMs demanding higher shares of the actual value creation process to compete with newly emerging tech players. As the strategic relevance of physical hardware component development diminishes and other factors such as battery development gain prominence, OEMs must reevaluate their position in the ecosystem and explore available options. These changes in product architecture and OEMs' efforts to develop product architecture competencies themselves have significant implications for suppliers. They either can partner with OEMs to develop specific components of the different product architecture layers or they turn into simple device layer providers for OEMs.

It seems that the CASE transformation will become a long-term task executives will be confronted with throughout the 2020s. Thus, executives should be aware of the long transitionary period they face. In this period, decision-makers and employees need a high tolerance for ambiguity. They must be able to operate in multiple worlds simultaneously before these worlds decouple and function independently.

6.4 LIMITATIONS

While the dissertation attempts to contribute to the outlined research streams, it suffers some limitations that need to be mentioned.

Firstly, the theoretical development draws on a single case study of a luxury carmaker uniquely positioned in the market due to its incorporation into MobilityGroup and its relatively small number of cars produced and sold every year. While leveraging such a single case for theorizing on the dynamics posed by digital product innovation presents an established method (Yin, 2011), it also suffers some shortcomings in terms of generalizability. Thus, the theoretical ideas and concepts developed need to be considered in terms of their boundary conditions, which are a Western luxury carmaker uniquely embedded into the automotive ecosystem and part of MobilityGroup.

Also, the digital product innovation initiative evolved over a long period, and although the observation period was relatively long, the fourth generation of software updates via OTA was still ongoing. Thus, their outcomes were hard to predict, which is why normative statements based on empirical evidence are hard to make at this time, limiting the validity of the theoretical statements made to a certain extent.

This aligns with the study's data-gathering focus, which strongly represents the OTA team's perspective at PremiumCar's IT department. The researcher tried to mitigate this risk by focusing on actual events first and evidence around these events rather than opinions on certain developments. Thus, although the researcher attempted to reach representation of different stakeholder groups, access to specific affiliated entities within the case, such as FastCar, SoftwareCorporation, or supplier representatives, was hard to get. This needs to be considered when reading the findings.

Further, in the study, we focus on the changes in the product architecture and the organization due to the effect of digital product innovation, highlighting the digital aspects and their particularities for being responsible for the changes. For sure, the emergence of digital technologies through new competitors played a key role in PremiumCar's and MobilityGroup's actions. Still, we want to include that other ongoing technological shifts, like e-mobility, had a severe impact on the management team's organizational and product architecture decisions (Murmann & Schuler, 2022).

Also, a large part of the data gathering was conducted during an ongoing pandemic which only allowed data gathering via online tools (Zoom, MS Teams, Miro). The researcher tried to respond to the following literature guidelines (Prommegger et al., 2021) e.g., by highlighting the importance of robust theoretical anchoring and validating findings immediately after the pandemic has ended in person.

6.5 FUTURE RESEARCH

The study's findings and limitations offer a rich departure point for future research on how industrial-aged companies can achieve digital product innovation.

From the lens of layered modular architecture and digital product innovation (Hylving & Schultze, 2020; Lee & Berente, 2012; Yoo et al., 2010), further exploration of the relationship between product architectures and organizing practices is needed. Modularity theory (Baldwin, 2023; Baldwin & Clark, 2000) offers a rich set of instruments and constructs to unpack and track the changes that the unique nature of digital artifacts and objects present and how they affect the practice of organizing. Particularly tracing such changes through a design structure matrix (Baldwin & Clark, 2000) or identifying modularity in software architectures by using digital trace data could help advance our understanding of changes imposed by digital technology on different organizing layers. Further, exploring and validating the claims made in the dissertation on the role of mirroring and mirror-breaking as practices to pursue digital product innovation can be considered worthy since they offer both important theoretical and practical implications. Recognizing the fluid and malleable form of the digital artifact and object (Kallinikos et al., 2013) and investigating the effects of this on the mirroring hypothesis can be considered a rich field of study. The information systems community offers a rich body of theoretical concepts and work on unpacking the relationship between digital technology, materiality, and organizing (Bailey et al., 2012; Leonardi, 2011; Mutch, 2010; Orlikowski & Scott, 2008).

Further, the process framework developed in this dissertation provides a good departure point for further exploration. Specifically next to conducting more case studies but also deploying other methodological approaches such as configurational analysis (Furnari et al., 2020) to validate the process model could be considered an enriching way forward. The information systems and management literature offers a rich amount of case studies on industrial-aged companies pursuing digital product innovation (Hylving & Schultze, 2020; Svahn & Kristensson, 2022; Svahn et al., 2017), the current literature presents different narratives on how digital product innovation can be achieved. Rather than finding the "right" way of this, it might make sense to move towards configurational thinking (Furnari et al., 2020) to understand the different variables at play here and to provide more insights on the "pathways" (Woerner et al., 2022).

In summary, the findings of the dissertation and their implications hopefully contribute to reducing the high numbers of transformations that create insufficient value (Forth et al., 2020) and spark some new ideas about how incumbents in the automotive industry can rewrite their stories to sustain the industry's historical success in driving economic prosperity and innovation. With the pressing ecological sustainability challenges and the demand for sustainable mobility, there is an urgent need for strong players to address these issues.

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8 Appendix

8.1 List of Publications

Table 38: List of Peer-Reviewed Publications

Publications	VHB[16] Ranking
Haskamp, T., Hund, A., Raabe, J.-P., & Uebernickel, F. (2023). The Unfolding of Digital Transformation in Pre-digital Companies: A Meta-case Analysis. *ICIS 2023 Proceedings*. International Conference on Information Systems (ICIS), Hyderabad, India.	A
Wuttke, T., **Haskamp, T.**, Perscheid, M., & Uebernickel, F. (2023). On the Potential of Business Process Management for Digital Entrepreneurship: Findings from a Literature Review. *ICIS 2023 Proceedings*. International Conference on Information Systems (ICIS), Hyderabad, India.	A
Wuttke, T., **Haskamp, T.**, Perscheid, M., & Uebernickel, F. (2023). Understanding Business Process Evolution in Digital Ventures. *WI Conference Proceedings 2023*. WI 2023, Paderborn.	C
Sebastian, I., **Haskamp, T.**, & Fonstad, N. (2023, June). Generating Momentum in Digital Business Transformations. *MIT Sloan CISR Research Briefing*, *XXIII*(6).	Not ranked
Haskamp, T., Raabe, J.-P., Barthel, P., & Schirmer, I. (2023). The Digital Innovation Unit: A Silver Bullet for Digital Transformation? *ECIS Proceedings 2023*. European Conference on Information Systems 2023, Kristiansand, Norway.	B
Leser, L., **Haskamp, T**., & Uebernickel, F. (2023). A Matter of Legitimacy - Overcoming Organizational Inertia for Sustainability Transformation. *Conference Proceedings 30th IPDMC*. Proceedings 30th IPDMC, Italy.	Not ranked
Beermann, V., **Haskamp, T**., Marx, C., & Uebernickel, F. (2023, January 3). Addressing Inertia in Pro-Environmental Behavior	C

[16] Verband der Hochschullehrerinnen und Hochschullehrer für Betriebswirtschaft e.V. (VHB) (2023), https://vhbonline.org/vhb4you/vhb-jourqual/vhb-jourqual-3/gesamtliste

through Nudges: A Review of Existing Literature and a Framework for Future Research. *Proceedings of the Hawaii International Conference on System Sciences*. HICSS, Maui, Hawaii, USA.	
Haskamp, T., Dremel, C., Marx, C., Rinkes, U., & Uebernickel, F. (2023). The New in the Old: Managing Inertia and Resulting Tensions in Digital Value Creation. In G. S. D. A. K. C. D. Kathryn Brohman (Ed.), *Digitalization and Sustainability: Advancing Digital Value*.	Not ranked
Marx, C., **Haskamp, T.,** de Paula, D., & Uebernickel, F. (2022). The Nexus of Design Thinking and Intrapreneurship: Insights from a Large-scale Empirical Assessment. *Conference Proceedings HICSS 2022*. HICSS 2022.	C
C. Gerling, F. Bickel, T**. Haskamp**, F. Uebernickel. (2022). Collaborate to Innovate: Utilizing Design Patterns Cards for Accelerating the Digital Transformation of Small and Medium-sized Enterprises. *Conference Proceedings HICSS 2022*. HICSS 2022.	C
Haskamp, T., Mayer, S., Annalena, L., & Uebernickel, F. (2021). Performance Measurement in Digital Innovation Units - An Information Asymmetry Perspective. *ECIS 2021 Proceedings*. European Conference on Information Systems 2021, Marrakesh, Marocco.	B
Haskamp, T., Lorson, A., de Paula, D., & Uebernickel, F. (2021). Bridging the Gap - An Analysis of Requirements for Performance Measurement Systems in Digital Innovation Units. *Proceedings of the 16th International Conference on Wirtschaftsinformatik*. 16th International Conference on Wirtschaftsinformatik, Duisburg-Essen.	C
Haskamp, T., Breitenstein, A., Lorson, A., & Uebernickel, F. (2021). A Management Control Systems Perspective on Digital Innovation Units. *AMCIS 2021 Proceedings*. Americas Conference on Information Systems, Montreal, Canada.	D
Haskamp, T., Dremel, C., & Uebernickel, F. (2021). Towards a Critical Realist Understanding of Digital Transformation: Results of a Structured Literature Review. *AMCIS Proceedings 2021*. Twenty-Seventh Americas Conference on Information Systems, Montreal, Canada.	D
Uchenna, P., **Haskamp, T**., & Albizri, A. (2021). Meta for Faith – How Digital Technology is Reconfiguring Faith-Based Institutions. *Forty-Second International Conference on Information Systems (ICIS) 2021*. Forty-Second International Conference on Information Systems 2021, Austin, Texas, USA.	A
Mayer, S., **Haskamp, T.**, & de Paula, D. (2020). Measuring What Counts: An Exploratory Study about the Key Challenges of Measuring Design Thinking Activities in Digital Innovation Units. *Proceedings of the 54th Hawaii International Conference on System Sciences*, 4951–4960.	C
Gerling, C., Bosch-Herterich, A., de Paula, D., **Haskamp, T.**, & Uebernickel, F. (2020, June 8). Exploring Boundary Objects and their Affordances in the Context of Design Thinking Projects from a Multi-Stakeholder Perspective. *Conference Proceedings 27th IPDMC*. 27th IPDMC: Innovation and Product Development Management Conference, Online.	Not ranked

Further Non-Peer-Reviewed Publications part of the Dissertation

Table 39: List of Non-Peer Reviewed Publications

Publications	**VHB[17] Ranking**
Marx, C., **Haskamp, T**., & Uebernickel, F. (2023). Designing Innovation in the Digital Age: How to Maneuver around Digital Transformation Traps. In C. Meinel & L. Leifer (Eds.), *Design Thinking Research: Innovation – Insight – Then and Now* (pp. 323–345). Springer Nature Switzerland.	Not ranked
Marx, C., **Haskamp, T**., de Paula, D., & Uebernickel, F. (2021). Design Thinking Diffusion Model: Empirical insights into the status quo. Event Proceedings. The ISPIM Innovation Conference –Innovating Our Common Future, Berlin, Germany.	Not ranked
Haskamp, T. (2021). Performance Measurement of Design Thinking: Conceptualizations, Challenges, and Measurement Approaches. In C. Meinel & L. Leifer (Eds.), Design Thinking Research Translation, Prototyping, and Measurement (pp. 273–297). Springer.	Not ranked
Haskamp, T., Paul, A., Stöckli, E., de Paula, D., & Uebernickel, F. (2020). Implementing Design Thinking for Non-Designers: Learning Profiles from a Q-Methodology Study. *The Proceedings of "ISPIM Connects Global 2020*. ISPIM Connects Global - Celebrating the World of Innovation, Virtual.	Not ranked

[17] Verband der Hochschullehrerinnen und Hochschullehrer für Betriebswirtschaft e.V. (VHB) (2023), https://vhbonline.org/vhb4you/vhb-jourqual/vhb-jourqual-3/gesamtliste

8.2 DATA COLLECTION AND ANALYSIS REPOSITORY

Access to the virtual data collection and analysis is given to reviewers and can be requested with the author's permission.

8.3 STATEMENT ON THE USE OF GENERATIVE AI TOOLS

Recent literature (Davison et al., 2023; Dwivedi et al., 2023) vividly discusses the role of generative AI in information systems research and suggests guidelines for the responsible usage of AI-supported tools (Susarla et al., 2023). Such guidelines highlight the role of transparency in using such generative AI tools in research endeavors. Accordingly, the author provides an overview of how generative AI tools have been used in accordance with those guidelines (Susarla et al., 2023) for the context of the dissertation.

Table 40: Use of Generative AI Tools

Generative AI Tool	Use for the Dissertation
DeepL (deepl.com)	Translation of interview quotes
Grammarly (app.grammarly.com)	Refinement of language issues and sentence structure
ChatGPT (https://chat.openai.com/)	Refinement of language issues and sentence structure