Decision Making for Automotive-Platform Engineering: A Mixed-Methods Study on Practitioners' Requirements and Criteria

Philipp Zellmer[a,b], Jacob Krüger[c] and Thomas Leich[b]

[a] Volkswagen AG Wolfsburg, Germany
[b] Harz University of Applied Sciences Wernigerode, Germany
[c] Eindhoven University of Technology, The Netherlands

ARTICLE INFO

Keywords:
automotive
electrics/electronics platform
lifecycle management
product-structuring concept

ABSTRACT

With modern vehicles becoming increasingly software driven, long-standing automotive manufacturers face challenges in integrating software into their historically hardware-centered platforms. Even though hardware and software platforms leverage the same ideas, manufacturers must still unify hardware, software, and electrics/electronics components; as well as their intricate interconnections and variability. To address this challenge, automotive manufacturers are adopting product-structuring and variant-management concepts from different areas to develop a holistic platform perspective. Here, particularly decision making has manifested as a key problem to inform the involved stakeholders and assess different options. Specifically, simply adding software to a static hardware platform is insufficient to address the current digital transformation in the automotive industry: the new platform dimensions must be understood, changes balanced against each other, and necessary rework defined to achieve holistic platform management. In this article, we contribute to tackling this problem by presenting a mixed-method study through which we derived a set of requirements to support decision-making for today's automotive electrics/electronics platforms. We used requirements and insights from our previous work, which we refined and validated via expert workshops and a questionnaire with 76 experts from the automotive industry. Besides confirming and validating our previous work, we contribute a new consolidated overview of requirements and criteria together with a prioritization by practitioners. The findings of our work offer valuable guidance for automotive practitioners, particularly for adopting product-structuring concepts like electrics/electronics platforms and making decisions in the process. Our contributions further substantiate existing evidence and can guide research on developing decision-making techniques for complex electrics/electronics platforms.

1. Introduction

Automotive manufacturers continuously evolve their product portfolios through innovative vehicle features to remain competitive. In the past, automotive innovations built primarily on hardware. However, advances in technology, shifting consumer expectations, and new regulatory standards require more and more software features, which must be integrated into existing hardware platforms. Consequently, most modern automotive innovations are software-based, driven by trends like autonomous driving, driver assistance, electrification, or connectivity (Baumgart et al., 2014; Broy, 2006; Pelliccione et al., 2016). In turn, vehicles are increasingly digitized, transforming into software-driven cyber-physical systems that depend on effective hardware-software interaction to enable new features (Gustavsson and Axelsson, 2008; Lind and Heldal, 2012). This software-centric nature of modern vehicles poses challenges for automotive manufacturers; especially for long-standing ones that have historically built large hardware-driven product portfolios and need to integrate new concepts into their grown platform engineering, management, and tools. (Graf et al., 2014; Holsten et al., 2023; Zellmer et al., 2024c).

philipp.zellmer2@volkswagen.de (P. Zellmer); j.kruger@tue.nl (J. Krüger); tleich@hs-harz.de (T. Leich)

ORCID(s): 0009-0004-8217-8781 (P. Zellmer); 0000-0002-0283-248X (J. Krüger); 0000-0001-9580-7728 (T. Leich)

Managing the complexity of modern vehicle platforms is becoming increasingly challenging. In particular, the growing number of hardware, software, and electrics/electronics components with their intricate interconnections makes it difficult to handle the variability of such platforms. To address this challenge, automotive manufacturers constantly adopt new methodologies and product-structuring concepts. For instance, variant-management concepts from software product-line engineering (Clements and Northrop, 2001; Krüger et al., 2020; Pohl et al., 2005) are integrated into the established hardware platforms to incorporate a software perspective (Bandur et al., 2021; Thiel et al., 2009). Still, implementing a holistic platform strategy that fully captures all aspects of modern vehicles remains a practical challenge that has most recently led to the adoption of electrics/electronics platforms. When engineering and transforming their platform strategies, automotive manufacturers face complicated choices, requiring them to balance and assess their investments in the short and long run. To the best of our knowledge, there is currently no established technique that supports decision-making during such processes that is informed by current needs of practitioners.

This gap has become increasingly critical as automotive platforms shift towards software-centric architectures, which demand faster, more transparent, and lifecycle–aware decision making. For example, in our previous research (Zellmer et al., 2024c) practitioners at Volkswagen AG emphasized the need to improve criteria and processes to manage variant complexity, ensure platform compatibility, and address cost implications in a rapidly evolving environment. In this article, we contribute to closing this gap by building on this previous research. We present the results of a mixed-methods study for which we structured the insights we gained from our 26 previous expert interviews through group discussions to conduct a questionnaire (76 responses). Then, we integrated the findings from our previous interviews and new questionnaire, and validated them through further expert workshops. Thereby, we confirmed, refined, and extended our previous findings. Our goal was to derive a comprehensive set of validated requirements and criteria to support decision-making processes for automotive electrics/electronics platforms. In detail, we present the following, entirely novel, contributions in this article:

- We confirmed the insights we gathered in our previous interview study (Zellmer et al., 2024c) through a questionnaire survey and follow-up expert workshops.
- We discuss and prioritize the requirements we found to be important for decision making on (automotive) electrics/electronics platforms.
- We provide a validated and detailed set of criteria to support decision making for managing electrics/electronics platforms.

The results of our study can guide practitioners within the automotive domain in making decisions, especially when it comes to product-structuring concepts. Researchers can use our insights to design new techniques for managing complex electrics/electronics platforms. We hope that our contributions serve as a foundation for future research in software and systems engineering that is directly beneficial to practitioners.

2. Background and Related Work

Software as Driver of Complexity. The automotive industry faces significant challenges due to disruptive changes, including trends like digitization and the introduction of new software features. For instance, demands for functional safety, security, and onboard communication are contributing to an increasing number of vehicle features (Buckl et al., 2012; Wallin et al., 2009). Since software has become a key enabler of functionalities and innovative features, software and its management are also key to remain competitive within the automotive domain (Baumgart et al., 2014; Broy, 2006). Not surprisingly, the share of software in vehicles is expanding exponentially, powering approximately 80 to 90 % of all contemporary innovations in the automotive industry (Dajsuren and van den Brand, 2019; Pelliccione et al., 2016). Due to this trend, it is evident that modern automotive systems are increasingly complex, integrating various features to meet user demands, adhere to international regulations, or support environmental sustainability (Abel et al., 2016; Buckl et al., 2012; Wallin et al., 2009).

In fact, contemporary vehicles are evolving into complex cyber-physical systems, characterized by the seamless interplay between physical and software components, which dynamically adjust to their operating environment and conditions (König et al., 2018; Poudel and Munir, 2021). Consequently, automotive platforms today exhibit not only historically grown hardware variations, but also software and electrics/electronics variations. Managing all of these variations while identifying commonalities—a key goal of any platform strategy, has become immensely complex and challenging (Kato and Yamaguchi, 2011).

Automotive Electrics/Electronics Platforms. As software complexity increases, so does the number of electrics/electronics components in vehicles, such as Electronic Control Units (ECUs), sensors, and actuators; all of which are needed to enable an interconnected vehicle. The aggregation of all electrics/electronics components is referred to as an electrics/electronics platform, which serves as the basis for developing a modern vehicle-specific electrics/electronics architecture (Zellmer et al., 2024a). In this context, electrics/electronics platforms act as an intermediary layer, enabling the integration of hardware and software to create a cohesive cyber-physical system (Jaensch et al., 2010; Pohl et al., 2005). Notably, electrics/electronics platforms transcend individual hardware or software components. Instead, they aim to encompass the entirety of the electrics/electronics architecture to enhance standardization and promote synergies (Jaensch et al., 2010; Pohl et al., 2005).

Product-Structuring Concepts. Within our previous work (Zellmer et al., 2023), we conducted a mapping study of product-structuring concepts that have been explored for managing platforms in the automotive domain. We define a product-structuring concept as a methodology for systematically managing extensive product portfolios, encompassing hardware, mechanical, electrics/electronics, and software components. Through our mapping study, we identified three product-structuring concepts as feasible for addressing current needs in the automotive industry: electrics/electronics platform engineering, software product-line engineering, and product-generation engineering.

Electrics/electronics platform engineering focuses on the seamless integration of software and hardware components within an overarching electrics/electronics architecture (Holsten et al., 2023; Jaensch et al., 2010). To enable this integration, the electrics/electronics architecture incorporates an electrics/electronics platform that serves as a connection layer; thereby establishing a close interconnection between software and hardware components while considering the vehicle as a cyber-physical system. By considering all relevant components as parts of a holistic electrics/electronics platform, this concept aims to enhance the performance and efficiency of engineering as well as managing a vehicle portfolio. So, the electrics/electronics platform engineering concept aims to expand on the benefits of hardware and software platforms like improved reuse, customization, and faster time-to-market (Krüger and Berger, 2020; van der

Linden et al., 2007; Robertson and Ulrich, 1998; Simpson, 2004; Vietor and Stechert, 2013).

Software product-line engineering has emerged as a methodology for managing variability in software-intensive systems (Kato and Yamaguchi, 2011; Krüger et al., 2020; Li et al., 2016; Pohl et al., 2005). It enables organizations to achieve reuse and standardization across software artifacts, creating synergies between different software variants. Although software product-line engineering offers significant benefits, such as reduced costs, improved software quality, and accelerated time-to-market (Krüger and Berger, 2020; van der Linden et al., 2007), its focus on software limits its use in automotive practice due to the need of hardware components. Specifically, other forms of variability, for instance, in hardware or electrics/electronics components, may cause variability in the software, but are typically not integrated into a holistic view. Similarly, distinguishing between physical and functional variability within software product-line engineering can be challenging (Eklund and Gustavsson, 2013; Fischer et al., 2015; Queiroz and Braga, 2014).

Product-generation engineering refers to the systematic development of mechatronic systems across different generations starting from an existing reference product (Albers et al., 2015, 2020; Fahl et al., 2019). In this concept, engineers create new product generations by integrating carryovers with newly designed system parts (Albers et al., 2015). There are two fundamental hypotheses that guide product-generation engineering:

(1) Products are defined using a reference system, built on existing or planned socio-technical systems.

(2) Subsystems are developed through processes like carryover, embodiment, and principle variation.

This concept has been extended in recent research by addressing the growing importance of software and digitization in modern systems. For this purpose, it utilizes overarching functional road-maps to enable the mapping of functional evolution across an entire product portfolio and life cycle (Albers et al., 2020; Fahl et al., 2019; Holsten et al., 2024). So, this concept focuses on the evolution of a system and researchers are still investigating how to reflect on the increasing digitization.

Through our systematic mapping study (Zellmer et al., 2023), we found that all three product-structuring concepts follow similar ideas and aim for the same benefits. However, they focus on different aspects that are relevant for digitizing automotive and cyber-physical product portfolios: integrating all components (electrics/electronics platform engineering), accounting for the increasing importance of software (software product-line engineering), and managing continuous change (product-generation engineering). Thus, each of the concepts aligns with current trends in the automotive industry. Yet, all of them are also connected to various challenges and obstacles when it comes to implementing them in practice. For our work in the automotive industry, electrics/electronics platform engineering has manifested as the starting point into which we integrate ideas from the other two concepts. The primary reason for this is that electrics/electronics platforms emphasize a holistic view on the components that are relevant in the automotive industry.

Related Work. As we have explained, software has become a key driver of innovation and complexity in the automotive industry. While different product-structuring concepts have been explored to provide a holistic platform-management concept, the decision making involved when transforming and managing a platform has received little attention. For instance, Siyun et al. (2013) discuss three perspectives of purchasing quality. These dimensions include various decision-making patterns, but focus on the goal of developing a comprehensive framework for quality management. Reddy et al. (2021) conducted a literature review to evaluate the best decision-making methods for creating a make-buy decision framework for product-introduction processes in automotive manufacturing. Mauser and Wagner (2025) have proposed seven qualitative criteria to evaluate the centralization potential of automotive E/E architectures. Kaluza et al. (2016) have introduced first ideas and requirements for developing tools that provide reliable decision support during component development. Unfortunately, all of these works focus on a very specific aspect of (automotive) platform management.

In addition, Colombari et al. (2023) have investigated the relationship between data-driven decision making and the degree of digitalization at the company level in the Italian and US automotive industries. Similarly, Brown (2013) have explored how data-driven decision making can enhance software-development productivity, providing empirical evidence that the systematic use of metrics supports process improvement. However, neither study addresses electrics/electronics platforms or other product-structuring concepts. Consequently, neither of these studies contributes a detailed, systematic analysis of decision-making practices for managing complex electrics/electronics platforms, to which we contribute with our work.

Other researchers have investigated current challenges in the automotive industry, including topics related to product-structuring concepts. For example, Hohl et al. (2018) explored the challenges of integrating agile software development with software product-line engineering. In the end, they offer recommendations for a hybrid development process for vehicles. Broy (2006) presents an overview of the state of automotive software engineering, highlighting issues, challenges, and opportunities. Thiel et al. (2009) provide an overview of temporary challenges faced by automotive manufacturers, focusing on different product-structuring concepts. Similarly, we have investigated practitioners' current needs around product-structuring concepts (Holsten et al., 2023; Zellmer et al., 2024a, 2023), transitioning towards electrics/electronics platforms (Holsten et al., 2024), electrics/electronics platform release strategies (Holsten et al., 2026), and decision making (Zellmer et al., 2024c). Most of these studies are related to ours, but do not focus on decision making. The exception is our previous work (Zellmer et al., 2024c) that we built upon and extend with this article by validating and prioritizing our previous

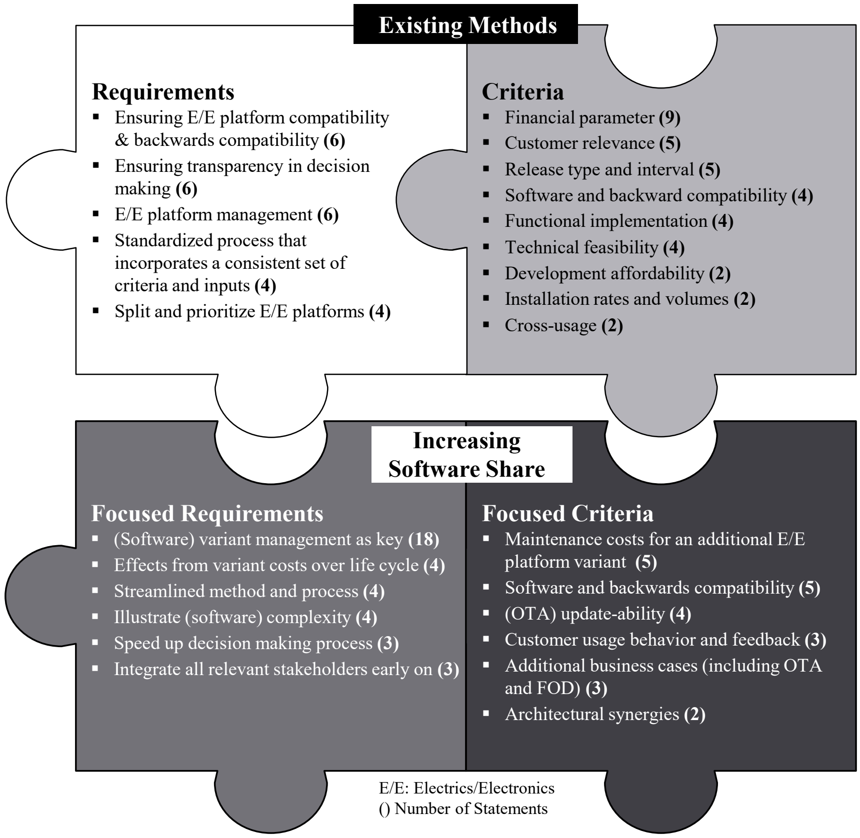

Figure 1: Most mentioned requirements and criteria in decision making for automotive platforms we elicited through our previous interview study (Zellmer et al., 2024c).

findings. Overall, we contribute novel and complementary insights compared to existing research.

3. Previous Interview Survey

In 2024, we (Zellmer et al., 2024c) conducted an interview survey with 26 experts from the automotive industry. We gathered practical insights and needs regarding existing product-structuring concepts and the decision-making methods around them. Specifically, we focused on decision-making methods that consider both hardware and software artifacts, and which are applicable or used within the automotive industry. So, the purpose of our interviews was to outline the current state-of-practice on decision-making for electrics/electronics platforms. To this end, we identified the requirements and challenges that different stakeholders perceive as important in this context.

In brief, we contributed the following:

- We conducted interviews with 26 practitioners to identify challenges of managing variants through automotive electrics/electronics platforms.
- We elicited the current state-of-practice in decision-making on platforms in the automotive industry.
- We synthesized a set of requirements and criteria to guide the (re-)design of decision-making processes for managing electrics/electronics platforms.

As part of our interviews, we identified and discussed various automotive challenges and requirements that influence decision-making for electrics/electronics platforms.

For instance, we found that variant management remains a key challenge in the automotive industry. In the past, variations primarily stemmed from different hardware components used across vehicle models that allowed for customizations. Over time, software has become the most important driver for innovation and customization, adding an additional layer of complexity. Thus, software and digitization have caused a major transformation when it comes to automotive platforms. Practitioners are still working out best practices to integrate the added complexity into historically grown platform management and decision making. So, it was not surprising that our interviewees indicated existing processes, methods, and tools to pose overarching challenges in decision making for transforming platform engineering. For example, the majority of our interviewees emphasized that the increased complexity poses new requirements and needs to improve transparency, speed up processes, and derive a structured method for decision making that effectively and consistency accounts for software.

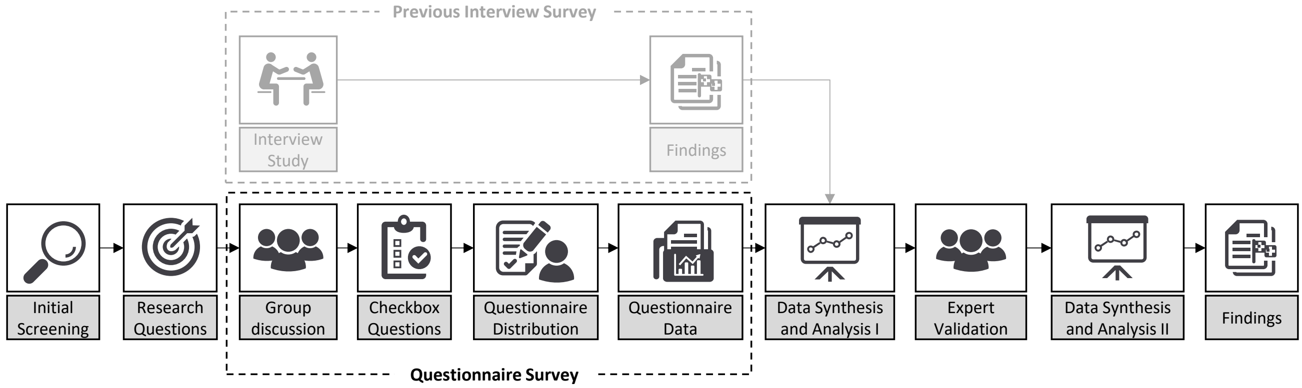

Figure 2: Overview of our research methodology.

In addition, most of our interviewees recognized that redesigning decision-making processes, tools, and methods would help them address customer needs, stay competitive, and manage the challenges of software maintenance throughout the life cycles of platforms and vehicles. To achieve this redesign, systems and processes must be seamlessly integrated, streamlined, and enhanced along new criteria that account for software. In Figure 1, we summarize requirements and criteria that we identified from our interviews as key for improving decision making in the automotive industry.

Within the top part of Figure 1, we display requirements and criteria that should be integrated into existing methods. For example, our interviewees mentioned electrics/electronics (backwards) compatibility, transparency in decision making, and electrics/electronics platform management most often. To inform decisions, we synthesized that particularly financial, customer, and release consideration were perceived as important criteria. Within the bottom part, we summarize the requirements and criteria that focus on the increasing relevance of software. For instance, we found that variant-management, especially for software, was the predominant requirement to develop future decision-making processes. This requirement should involve criteria for decision making, such as the maintenance costs of electrics/electronics platform variants, software compatibility, or over-the-air (OTA) updates. Overall, we identified clear gaps regarding a practically applicable decision-making framework for holistic automotive platform management.

4. Research Methodology

The goal of our work was to quantitatively validate our qualitative interview survey (Zellmer et al., 2024c) and to contribute new insights into the state-of-practice as well as needs regarding decision making on automotive platform-engineering. For this purpose, we conducted a mixed-method study using the framework by Nair and Prem (2020) and the data-triangulation methods by Creswell et al. (2003). In the following, we explain our methodology in detail, following the overview we illustrate in Figure 2.

4.1. Research Questions

By validating and extending our previous findings on automotive-platform engineering, we intended to inform new decision-making techniques in the domain. To achieve this, we defined two research questions (RQs):

RQ_1 *What are current challenges and requirements for decision making in the automotive industry?*

First, we empirically identified and validated current challenges and requirements for decision making in the context of software-defined automotive platforms through an online questionnaire followed by expert workshops. While the challenge of variant management has been widely acknowledged before (van der Linden et al., 2007; Pohl et al., 2005), the rapid shift towards software-based vehicles—— together with rising product complexity and major organizational transformations——has introduced new decision-making pressures in the automotive industry. Establishing an updated understanding is key to inform research, and it provides the empirical basis for RQ_2, for which we extracted, prioritized, and validated criteria to guide the development of future decision-making techniques.

RQ_2 *What criteria and requirements must be addressed to manage automotive electrics/electronics platforms?*

Second, we extracted criteria and requirements from our data that are key for effective decision-making. We prioritized and validated these criteria with experts to ensure their feasibility. So, we contribute a comprehensive set of criteria to guide the development of future decision-making techniques for practitioners managing (automotive) electrics/electronics platforms.

By tackling these research questions through our mixed-method design, we contribute insights from temporary automotive practice. Thus, our primary objective is to help automotive manufacturers understand the complexities and requirements that shape their decision-making processes on electrics/electronics platforms. In addition, our insights can guide researchers in refining existing or designing new decision-making techniques. We emphasize that these techniques must be applicable to product-structuring concepts, especially electrics/electronics platforms, to effectively manage large-scale automotive and other cyber-physical product portfolios.

4.2. Study Design

Our mixed-methods study involved a questionnaire to collect quantitative data, which we then combined with our previous interview survey (Zellmer et al., 2024c) and validated with experts through a series of workshops. In the following, we detail the design of our questionnaire and expert validation.

Questionnaire. We started designing our questionnaire by inspecting the findings and questions of our previous interview survey (Zellmer et al., 2024c). Through discussions among all authors, we iteratively refined our questionnaire to align it to our new research questions. Specifically, confirming and extending our previous findings served as guiding principles for refining our questionnaire. Furthermore, we tried to improve the quality of the questions and completeness regarding the topics we covered. To keep the questionnaire manageable for participants, we removed and merged redundant or irrelevant questions throughout these iterations. We further narrowed down, removed, or abstracted questions to prevent confidentiality or ethical concerns. For instance, we did collect a minimum of personal data and planned for an anonymous conduct to prevent that individuals could be identified.

With our completed draft version, we organized group discussions with employees of Volkswagen AG to further improve the quality of the questions and confirm that we gathered all relevant data. After updating and clarifying our questionnaire based on the feedback, we asked for and received internal approval by the communications department and the union of employees ("Betriebsrat") of Volkswagen AG to execute the questionnaire. While we did not design our interview based on recent methodological recommendations, such as those by Strandberg (2019), a retrospective cross-check confirms that we addressed the key aspects in these, such as consent, anonymity, and researcher neutrality.

Our questionnaire covered a minimum of background information necessary to understand our participants' characteristics through closed questions. As we display in Table 2, the respective questions covered a participant's field of activity, experience in the automotive domain, and familiarity with product-structuring concepts. To address our actual research questions, we used 26 closed questions (statements to agree or disagree with) across three parts, asking participants regarding their agreement on a series of statements on variant-management challenges (VQ*X* in Figure 3), decision-making practices (DQ*X* in Figure 4), and future decision making (FQ*X* in Figure 5). In Table 1, we summarize all questions from our online questionnaire as a complete overview. We used 4-point Likert scales (plus an "abstain" option) to keep the data quantitative and to get participants to provide an indication of their preference (i.e., not having a "neutral" option). Please note that we moved from abstract to more detailed questions within each part of the questionnaire.

Expert Validation. We first analyzed the questionnaire results ourselves and synthesized insights by also considering our previous interview survey. Then, the first author created presentations to communicate our work and findings to experts in the field. This included mapping the requirements and criteria we identified to the four dimensions of the Weighted Shortest Job First (WSJF) method (Leffingwell, 2018). With these artifacts, the first author organized a series of workshops at Volkswagen AG in which we asked experts to validate our findings based on their experiences. Moreover, we defined optional questions to prompt discussions if needed to elicit elaborations from the experts. To keep the workshops concise, we tracked the time we used and aimed for a maximum of one hour. For this expert validation, we selected participants with substantial professional experience, typically at least five years in their respective area. Also, these participants were recognized as subject-matter experts within Volkswagen AG.

Besides open discussions about the results, we asked the experts to rank the decision-making criteria we derived from our previous interview survey and questionnaire results. For this purpose, we used the WSJF method to categorize and prioritize criteria within fitting scopes (explained in Section 5.3). We asked the experts to define a ranking regarding the importance of the criteria within a section. At this point, multiple criteria could share a position, in case the expert perceived them as equally important. To build an average and to better understand how important the criteria were perceived in relation to each other, we then assigned points to them. Specifically, we rewarded points in reverse order (i.e., first place received points equal to the last rank, last place received one point). For shared places, we used the average of the respective scores. Then, we scaled the ranking to 100 points (or 100 %) based on the ratio of points each criterion received within its category.

We remark that the plain results of our questionnaire and workshops address primarily RQ_1, which we present in Section 5. Essentially, we elicited the state-of-practice and temporary challenges on decision making in the automotive industry. In turn, our discussion of the results in Section 6 primarily addresses RQ_2. Through this question, we sketch what we learned for advancing current decision-making practices. Nonetheless, please note that a clear distinction was not always possible, since current challenges (RQ_1) inform and define what is needed in the future (RQ_2). Thus, the distinction between both questions is inherently vague in some parts of this article.

4.3. Conduct

Next, we outline the conduct of our questionnaire and expert validation. For both, our target group of participants were employees from different brands of Volkswagen AG. In the end, we gathered responses from experts at Volkswagen (VW), Volkswagen Nutzfahrzeuge (VWN), and CARIAD.

Table 1
Overview of all questions in our online questionnaire.

ID	Question	Section
BQ1	What is your current field of activity?	Background information (Section 4.3)
BQ2	How many years of experience do you have in your current field of work?	
BQ3	Are you familiar with product structuring concepts such as platform management, (software) product lines, E/E platforms, and product generation engineering?	
VQ1	The automotive industry faces significant challenges due to the growing share of software and E/E components, with software set to play a key role in the future.	Variant-management challenges (Section 5.1)
VQ2	electrics/electronics platform management is central to overseeing and controlling software platforms throughout their life cycle.	
VQ3	The new challenges and requirements related to software-based platforms and architectures have significant impact on your daily work.	
VQ4	Platform strategies and concepts are significantly influenced by the increasing importance of software and the growing number of electrics/electronics components.	
VQ5	In the traditional approach, product development and platform management still place a stronger emphasis on hardware elements.	
VQ6	New challenges, such as the growing share of E/E components and software, have already been effectively integrated into product development and platform management.	
VQ7	The management of software-based platforms and architectures differs significantly from traditional hardware-focused platforms.	
VQ8	Variant management is significantly impacted by these new challenges and requirements, particularly due to overlaps with platform management, lifecycle management, and integration management.	
VQ9	New innovations, such as the continuous software maintenance of modern vehicles throughout their lifecycle, significantly impact the variant management of E/E architectures and platforms.	
DQ1	Effective decision-making for change initiatives is crucial in managing E/E architectures and platforms across various vehicle projects throughout their life cycle.	Decision-making practices (Section 5.2)
DQ2	The increasing importance of software and new software-driven features, like over-the-air updates, strongly influence decision-making for change initiatives.	
DQ3	Dependencies between hardware and software elements in E/E platforms and architectures can play a crucial role in shaping decision-making.	
DQ4	Both hardware and software components of the E/E architecture are currently given equal consideration in the decision-making process for change initiatives.	
DQ5	Adequate methods and tools are available to assist in decision-making for managing E/E platforms.	
DQ6	Existing methods and tools for evaluating changes effectively address the current challenges and requirements of the automotive industry, including variant management.	
DQ7	Certain inputs, criteria, and requirements for decision-making in E/E platform management are either underrepresented or entirely absent.	
A comprehensive decision-making method ...		Future decision making (Section 5.3)
FQ1	... must incorporate variant management throughout the entire life cycle of the electrics/electronics platform and architecture.	
FQ2	... must effectively support decisions on variant reduction and avoidance.	
FQ3	... must incorporate meaningful KPIs (key performance indicators) into the evaluation.	
FQ4	... must incorporate external factors, including competition, customer satisfaction, and usage behavior.	
FQ5	... must consider cross-platform financial effort and outcome metrics.	
FQ6	... must account for the impact on both software integration and the E/E platform and architecture.	
FQ7	... must consider additional criteria, such as Cyber Security and Safety (UNECE 155).	
FQ8	... must include positive influencing factors (such as effects on cost, manufacturing efficiency, and economic key performance indicators).	
FQ9	... must incorporate cross-business criteria in decision evaluations.	
FQ10	... must consider additional potential when implementing in existing as well as new regions (market potential).	

All three brands are organized and operate independently. While VW and VWN share platforms, they belong to different business units and are responsible for their own products, including distinct processes and tools. CARIAD is a younger company founded in 2020 that develops cross-brand software products for the entire Volkswagen group.

In detail, the three brands differ in several dimensions:

Market and Strategy. VW targets the mass market for private customers, currently emphasizing electrification and digital transformation. In contrast, VWN is specialized in light commercial vehicles for other companies. CARIAD drives group-wide software development, aiming for unified electrics/electronics platforms and achieving digital revenues.

Organizational Structure. VW operates as a traditional automotive brand within the group's multi-brand portfolio. VWN is a separate business unit with its own processes, but it shares platforms with VW. CARIAD functions as a more agile, software-focused organization that employs more software engineers, architects, and data specialists compared to the other brands.

Product LifeCycle. VW cars typically follow 5–7-year product cycles with periodic facelifts, while VWN vehicles have longer cycles (8–10+ years) due to the lower production volumes and higher durability requirements. CARIAD follows continuous software roadmaps, decoupling software updates from hardware cycles.

Platform and Software. VW builds on hardware-driven platforms in which software is being integrated. VWN adapts these platforms for commercial vehicles, which often adds further components and complexity. CARIAD develops a unified software platform that serves as the digital backbone for the entire groups.

Please note that participation in both parts of our study was voluntarily and no participant was in a dependent position to any author. We anonymized all data to protect the privacy of the participants and to avoid any negative consequences.

Questionnaire. We deployed our questionnaire online via a Volkswagen-internal cloud environment. This environment is intended for internal questionnaires at Volkswagen AG and supports typical features to prepare, release, and analyze questionnaires. Then, we promoted and distributed our questionnaire via email across Volkswagen AG. Additionally, we shared the link to the questionnaire within relevant departments to raise attention.

To prevent that the participants from our previous interview survey would participate in the questionnaire, we did not add them to our emails and also mentioned in these emails that these experts should not be participating. Instead, we asked all 26 participants from our interview survey to distribute the questionnaire to relevant colleagues within their departments. Please note that while these participants could still have participated in our questionnaire, their results would be equally valid. We only tried to not have them participate to cover new and different points of view, validating and extending our findings through others' perspectives.

In total, we received 76 valid responses from participants with diverse fields of expertise and varying levels of experience, as we summarize in Table 2. We discarded any response as invalid that was not completed or if only the option "abstained" was selected. Mostly, our participants worked as technical engineers (26) or product managers (14), but 19 have even been associated with departments not directly connected to the platform engineering. Roughly a quarter (20) of our participants had less than one year of experience in the automotive domain. Most (45) had between one to ten and ten participants more than ten years of experience. Similarly, 54 (71 %) of our participants were familiar with product-structuring concepts, and 22 did not know this term before. However, this does not mean that these 22 participants were not familiar with platforms and their engineering at Volkswagen AG.

Table 2
Participants of our online questionnaire.

Field of Activity	Number	Percentage
Technical Engineering	26	34
Product Management	14	18
E/E Platform Engineering	4	5
Sourcing Management	4	5
Portfolio Management	3	4
Systems Engineering	3	4
Configuration Management	1	1
Lifecycle Management	1	1
Other departments	19	26
Experience in the Domain		
$<$ 1 year	20	26
1–3 years	21	28
3–10 years	24	32
$>$ 10 years	10	14
Familiar with Product-Structuring Concepts		
Yes	54	71
No	22	29
Sum	**76**	**100**

Expert Validation. We divided our in-person workshops along the two stages we described in Section 4.2. First, the first author presented and discussed the analyzed and synthesized interview and questionnaire data with the experts. Second, the experts prioritized the criteria we identified and validated before using the WSJF method. To minimize bias, we deliberately included only participants who had not taken part in our previous interview survey or questionnaire. Participation was voluntary, we anonymized the resulting data, and participants could withdraw from the workshop at any time without any negative consequences.

To steer the workshops, we used presentations, which we used to present the data we collected from our previous interview survey and the questionnaire. The first author took notes during the workshops, which he checked with the experts for correctness before concluding a workshop. In the end, we conducted seven workshops (so, also seven rankings of decision-making criteria), each taking around 45 to 60 minutes and involving the first author as well as one or two experts. We stopped at this point, because we did not collect new insights in the latest workshop iterations, indicating saturation for our data analysis and interpretation.

4.4. Data Triangulation and Analysis

Since we built on a diverse set of data to answer our research questions (i.e., interviews, questionnaire, workshop discussions), we employed a combination of quantitative and qualitative analysis methods. More specifically, we used descriptive statistics to analyze and summarize the quantitative data from our questionnaire. To analyze our notes on the workshop discussions, we used open coding and card sorting, which we did also use in our previous interview survey. For these qualitative data analyses, the first author built on his experiences of working at Volkswagen AG for several years already. He has contributed to projects across various departments at Volkswagen AG, focusing on the areas of variant management, platform engineering, and software portfolio management. This expertise and understanding of domain as well as company terminology enabled him to systematically classify and organize the data. To enhance the results, we utilized the combined expertise of all authors, drawing particularly from our earlier research in this area (Holsten et al., 2023, 2024, 2026; Zellmer et al., 2024a, 2023, 2024b,c). In the end, we grouped the collected statements into themes and compared these to the results from our previous interview survey.

5. Results (RQ_1)

In this section, we present the results of our study to address RQ_1. Aligning to our questionnaire design and previous work (Zellmer et al., 2024c), we structure this section along three topics: variant-management challenges, decision-making practices, and needs for decision making in the future. For each, we first present the results of our questionnaire with 76 valid responses. As explained, our participants could answer each question through a Likert scale. We distinguish between the answering options using different colors in Figure 3, Figure 4, and Figure 5. Afterwards, we present the outcomes of validating the results through our expert workshops. At the end of each topic, we summarize our key insights, which we discuss holistically in Section 6 to answer our research questions. Note that, for clarity, we refer to *participants* if we refer to the practitioners answering our questionnaire. We refer to *experts* to refer to those practitioners participating in the validation workshops. Please note that some of our findings have been identified in previous research. Still, we (i) present a holistic overview of the current state-of-practice within a multi-brand automotive manufacturer; (ii) provide additional evidence for previous as well as new insights; and (ii) argue that Original Equipment Manufacturers (OEMs) with long-standing, process-heavy structures may face similar challenges—a hypothesis that warrants further investigation in other industrial domains.

5.1. Variant-Management Challenges

In the first part of our questionnaire, we aimed to elicit how the increasing share of software in automotive platforms challenges current platform-engineering and variant-management practices. We present the results for each question in this part in Figure 3. For the remainder of this article, we use the identifiers on the left side of a question in Table 1, Figure 3, Figure 4, and Figure 5 to refer to each question.

The responses for VQ1 show that all but one participant strongly agreed (64) or agreed (11) that software and electrics/electronics components pose new challenges for the automotive industry. A similar consensus emerged regarding the importance of electrics/electronics platform management throughout the life cycle of vehicle portfolios (VQ2). Fifty-seven participants strongly agreed, 14 somewhat agreed, and only two disagreed with this statement. Thus, it is not surprising that the majority of our participants either strongly agreed (58) or agreed (14) that these new challenges impact their daily work (VQ3). Only four participants disagreed with this statement. For VQ4, most participants indicated that existing platform strategies and concepts are significantly influenced by an increasing share of software and electrics/electronics components. This emphasizes the pivotal role of electrics/electronics platform management for organizing modern vehicle portfolios, with 57 participants strongly agreeing and 16 agreeing.

In contrast, our participants are divided regarding the current focus in product development and platform management (VQ5). A significant proportion of participants indicated that they no longer see a focus on hardware components, with eight strongly disagreeing and 22 disagreeing with our statement. However, the majority still strongly agreed (12) or agreed (28) that the focus has remained on hardware components, as seen in "classic" automotive-platform management. This discrepancy is also visible in the responses concerning the effective integration of new challenges and requirements (VQ6). Here, about one third of our participants (24) agreed that new challenges and requirements (e.g., the increasing number of software and electrics/electronics components) have been effectively integrated into product development and platform management. In contrast, approximately two-thirds of the participants stated that these challenges have not been effectively addressed, with 25 disagreeing and 23 strongly disagreeing.

For VQ7, most participants (36) agreed that software-based platforms differ significantly from traditional automotive platforms. Another 32 participants strongly agreed, with only one participant disagreeing and strongly disagreeing, each. We can observe similar results regarding the impact on variant management (VQ8). Only two participants disagreed that the changes in platform and lifecycle management that are caused by software and electrics/electronics components impact variant management. The rest agreed (24) or strongly agreed (49) with this statement. Lastly, for VQ9, the majority of our participants strongly agreed (50) and agreed (22) that innovations like continuous software maintenance throughout a vehicle's life cycle impact the variant management for modern vehicles—with only two disagreements.

Expert Validation. During our workshops, we first aimed to understand the challenges and requirements caused by the increasing share of software (VQ1, VQ2, VQ3). All experts found the results to be comprehensible. According to them, the results for VQ1 can be attributed to the widespread media coverage of e-mobility. However, other experts believed that the results stem from the fact that e-mobility is becoming increasingly similar to other smart devices, thereby facing similar requirements and challenges. For VQ2, all of our experts

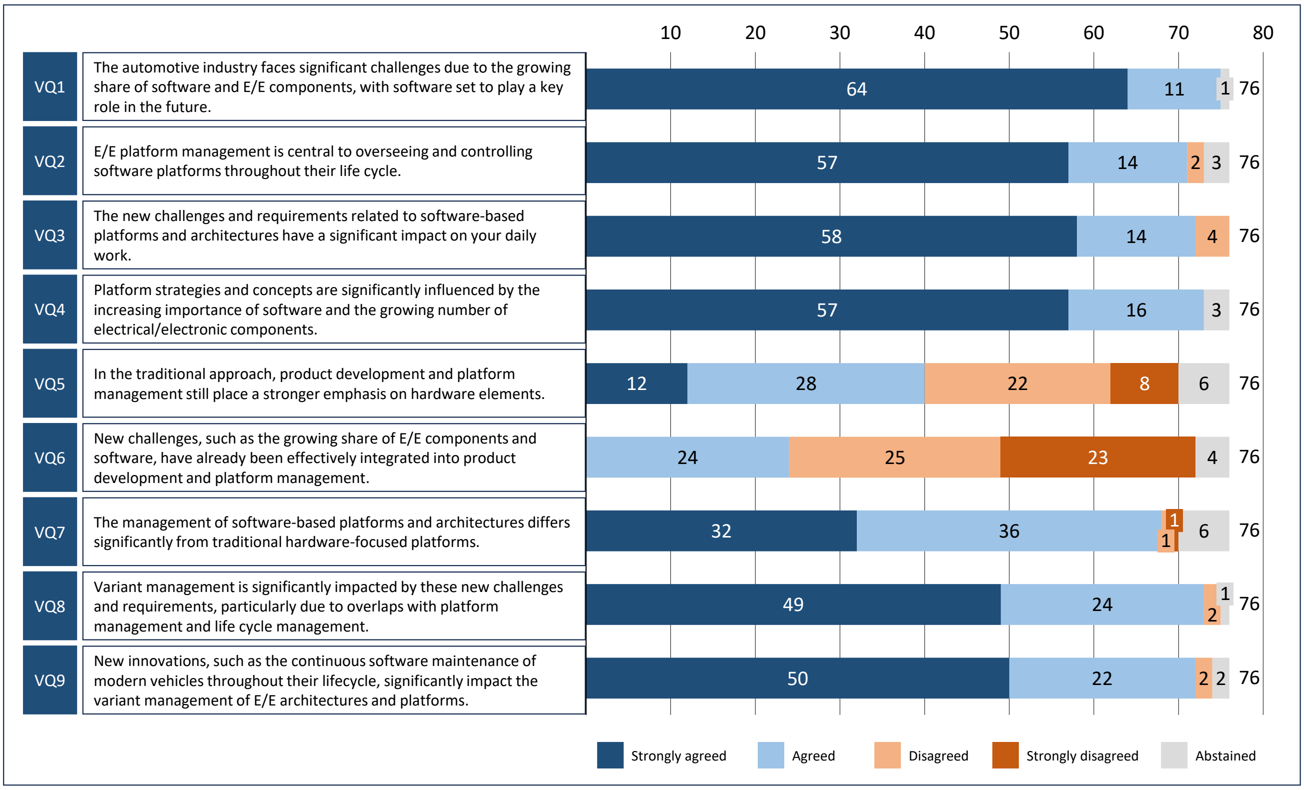

Figure 3: Questionnaire results on variant-management challenges (VQX).

agreed with the statement, emphasizing the importance of centralized platform management, especially to enable reuse of parts and modules. Additionally, some experts pointed out that the start-up phase for electrics/electronics platform management is equally important. In response to VQ3, the experts either agreed or strongly agreed with the statement. They emphasized that not all challenges and requirements have been fully addressed, and that the influence of the temporary changes on the daily work is evident. Moreover, some experts noted that the impact of higher proportions of software and electrics/electronics components are more strongly reflected in specialized areas, such as in managing software maintenance.

Similarly, all experts agreed on the results that automotive platform strategies are significantly impacted by the increasing shares of software and electrics/electronics components (VQ4, VQ5, VQ6, VQ7). Specifically, they support the notion that electrics/electronics platform management is pivotal for managing and controlling software-based vehicle portfolios throughout the platform's and vehicles' life cycles (VQ4). In contrast, discussing VQ5 revealed a broader range of opinions. While some experts believed that the focus in the automotive industry remains on hardware, others suggested that this focus depends on the specific work area. Additionally, some argued that the perception of a stronger hardware focus stems from history, as many processes and committees have been instantiated during the hardware-centric era. We observed a similar situation for VQ6, which addressed the efficient integration of current challenges and requirements. Most experts stated that the results depend on the specific work area, arguing that a holistic view is currently missing. For question VQ7, the experts agreed on the results. They noted that changes in traditional platforms seem to be recognized across different work areas.

For VQ8 and VQ9, which focused on variant management for software-based platforms and architectures, we received consistent feedback from the experts. Their perspectives largely aligned with the results of the questionnaire, confirming that the challenges posed by the current changes impact variant management. Most experts argued that this is connected to the ongoing emphasis on (hardware) variant reduction, which has historically been a key objective. Seeing the current software-based automotive platforms, the importance of variant management and addressing the integration of hardware and software is growing. Also, the experts emphasized the increasing significance of software variance, which is becoming a critical part of automotive variant management. In this context, the experts also highlighted that the integration of hardware and software has positive and negative implications. Notably, lifecycle management and variability are influenced by the shorter update intervals associated with software compared to hardware (Kuiter et al., 2021). Particularly the continuous maintenance of vehicles via over-the-air (OTA) updates marks a significant development. OTAs enable bug fixes and new features throughout the life cycle of a vehicle, which can be introduced even at

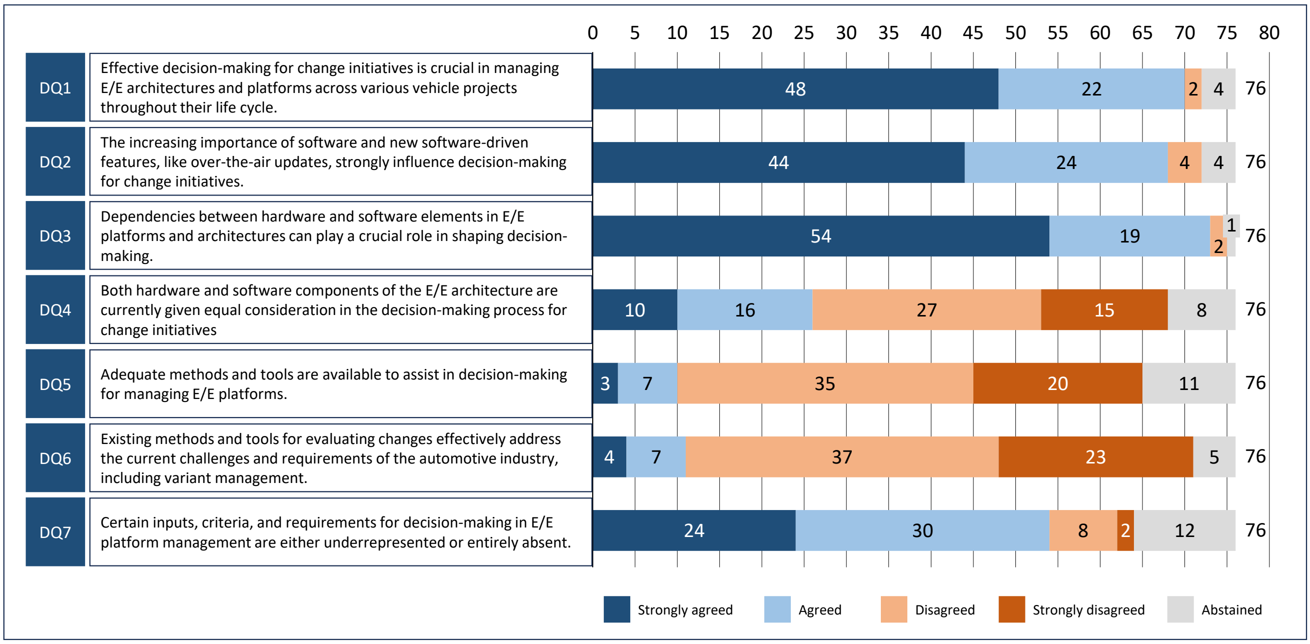

Figure 4: Questionnaire results on decision-making practices (DQX).

the customer's premises. However, using OTAs can also lead to even more software variance.

Variant-Management Challenges: Key Insights

Software has become the dominant factor in the automotive industry and its variant management. ● *Predominantly hardware-oriented processes impede the timely and coordinated integration of software-driven changes.* ● *Software-related requirements remain distributed across departments, resulting in redundancy and inconsistent decision making.* ● *Although electrics/electronics platform engineering and software maintenance are acknowledged as critical, unclear ownership and lifecycle criteria prevent a systematic solution.*

5.2. Decision-Making Practices

In the second part of our questionnaire, we aimed to elicit the state-of-practice on decision making for electrics/electronics platforms. We present the respective questions and responses in Figure 4.

First, we elicited the importance of overarching decision making for managing electrics/electronics architectures and platforms (DQ1). The majority of our participants either strongly agreed (48) or agreed (22) that decision making is key and is shaped by emerging challenges and requirements. Only two participants disagreed with this statement. A similar consensus emerged in response to DQ2. Here, we asked about the influence of software, with 44 participants strongly agreeing, 24 agreeing, and only four disagreeing. The results for DQ3 were even more one sided with 54 participants strongly agreeing and 19 agreeing that dependencies between hardware and software within electrics/electronics platforms can have decisive impact on decision making. Again, only two participants disagreed. In contrast, our participants' opinions diverged regarding the consideration of hardware and software components in decision-making processes (DQ4). Specifically, 26 participants agreed that both are equally considered when evaluating change proposals. Conversely, 27 participants strongly disagreed and 15 disagreed with this statement.

Via DQ5, we asked how adequate current methods and criteria are to address emerging challenges and requirements of software-focused platforms in the automotive industry. A majority of our participants disagreed (35) or strongly disagreed (20) that effective methods for decision making around electrics/electronics platforms exist. Only three participants strongly agreed and seven agreed. Similarly, regarding whether existing tools and methods sufficiently address temporary challenges in the automotive industry (DQ6), most participants expressed dissatisfaction. Namely, 37 disagreed and 29 strongly disagreed, while only four strongly agreed and seven agreed with our statement. Lastly, when we asked about the sufficiency of current decision-making criteria (DQ7), most participants indicated that criteria are missing or underrepresented (24 strongly agreed, 30 agreed). Only a minority disagreed (8) or strongly disagreed (2) with our statement that the current set of criteria is insufficient. We remark that this question received the highest number of abstentions among all of our questions. Likely, this is because the number of participants being exposed to or working with such criteria is smaller than the total number of participants.

Expert Validation. During the follow-up workshops, we started again from the fundamentals about the role of decision making (DQ1, DQ2), which led to a quite consistent picture. All experts agreed with our results, emphasizing that decision-making processes must become more agile and flexible. For example, the increasing number of changes at shorter intervals caused by software requires a clear and transparent decision-making framework. Additionally, it was noted that the flexibility of deploying and updating software compared to hardware introduces new decision criteria (Brown, 2013).

For DQ3 and DQ4, several experts found it surprising that most participants understood the impact of hardware–software dependencies on decision making. We found this notable, seeing the different perspectives and criteria through which decisions are made and prioritized in practice. Some experts also explained the discrepancy by pointing to variations in work areas, suggesting that perspectives shift depending on the phase of a development project. For instance, participants involved in early stages, such as requirements elicitation, may be more inclined to agree. In contrast, those working in later stages may be less likely to share this perspective. Other experts attributed the results to the hardware-focused past of long-standing automotive manufacturers.

The experts had different opinions on DQ5 and DQ6. Most emphasized that there are sufficient tools and methods, but the current processes lack the integration and transparency needed to effectively support decision making (Colombari et al., 2023). In contrast, other experts argued that current tools and methods have not been updated to address the needs of a software-driven domain. They noted the limited availability of methods to evaluate software and its functions, including the complexity of variants and associated costs throughout vehicle life cycles. Regarding the importance of introducing new criteria and requirements for decision making (DQ7), the experts agreed with our participants. Through the discussions with the experts, we also noted that the larger proportion of abstentions may be explained with the complexity and difficulty of defining feasible decision criteria.

Decision-Making Practices: Key Insights

Decision making is recognized as pivotal for managing electrics/electronics platforms. ● Software increasingly drives key decisions in the automotive industry, which confirms previous work by Brown (2013). ● Gaps in tool integration hinder decision making for electrics/electronics platforms and impact the operational level, which refines previous work by Colombari et al. (2023).

5.3. Future Decision Making

In the last part of our questionnaire, we investigated what should be changed to facilitate and improve decision making for automotive electrics/electronics platforms in the future. For this purpose, we changed the style of our questions, as we display in Figure 5. Instead of defining a statement to agree or disagree with, we now asked participants to judge ten requirements regarding their relevance. We derived these requirements based on our previous interview survey (Zellmer et al., 2024c) and incorporated respective decision criteria into their wording.

A majority of our participants either strongly agreed (51) or agreed (20) that a comprehensive decision-making method must cover variant management and the entire life cycle of an electrics/electronics platform (FQ1). Only one participant strongly disagreed and two disagreed. Similarly, the importance of supporting decisions on variant reduction and avoidance was widely acknowledged (FQ2). In fact, 57 participants strongly agreed and 15 agreed to this requirement, with only two participants disagreeing. Integrating meaningful Key Performance Indicators (KPIs) into decision-making processes received wide support (FQ3). Overall, 49 participants strongly agreed and 21 agreed with this requirement, while only one strongly disagreed and one disagreed. External factors such as competition, customer satisfaction, or usage behavior received the strongest endorsement (FQ4) with 60 participants strongly agreeing and 13 agreeing. A similar consensus emerged for FQ5 regarding the inclusion of cross-platform financial metrics. Here, 52 participants strongly agreed, 19 agreed, and two disagreed.

For FQ6, most participants strongly agreed (58) that a comprehensive decision-making framework must account for software as well as electrics/electronics platforms and architectures. An additional 14 participants agreed, while only one disagreed. Furthermore, including criteria like cyber security and safety (UNECE, 2021) was emphasized (FQ7), with 55 participants strongly agreeing, 14 agreeing, three disagreeing, and one strongly disagreeing. Criteria like costs, efficiency, or other economic KPIs also received strong support (FQ8). A total of 43 participants strongly agreed, 23 somewhat agreed, and only five disagreed on these criteria. We can observe similar patterns for FQ9 on cross-business criteria, with 40 participants strongly agreeing, 27 agreeing, and five disagreeing on their importance. Only one participant strongly disagreed here. Finally, the importance of considering market potential in existing and new regions was strongly supported (FQ10). Namely, 41 participants strongly agreed, 30 agreed, and only three disagreed with our statement.

Expert Validation. We also adjusted our workshop discussions to validate the requirements and criteria we derived. Besides open discussions, we now also employed the WSJF method (Leffingwell, 2018) to prioritize requirements and criteria. This method involves four scopes: *user and business value*, *time criticality*, *risk reduction and opportunity enablement*, and *job size*. In Table 3, we map our criteria to these four scopes. Note again that we defined these criteria based on our previous interview survey and questionnaire.

Beginning with *user and business value*, the experts attributed the highest importance to **customer added value, benefits, and satisfaction**. In our scoring, this criterion received the most points with 152. **Sales/profit** was ranked second highest by experts, scoring 135 points. The criterion **cost reduction** received 112 points (3rd), while **frequency and behavior of use** ranked fourth with 101 points. **Availability of the scope/ scope affected** followed with 98 points (5th) and **complexity reduction** was ranked sixth with 65 points. **Market share and new business areas** ended up in

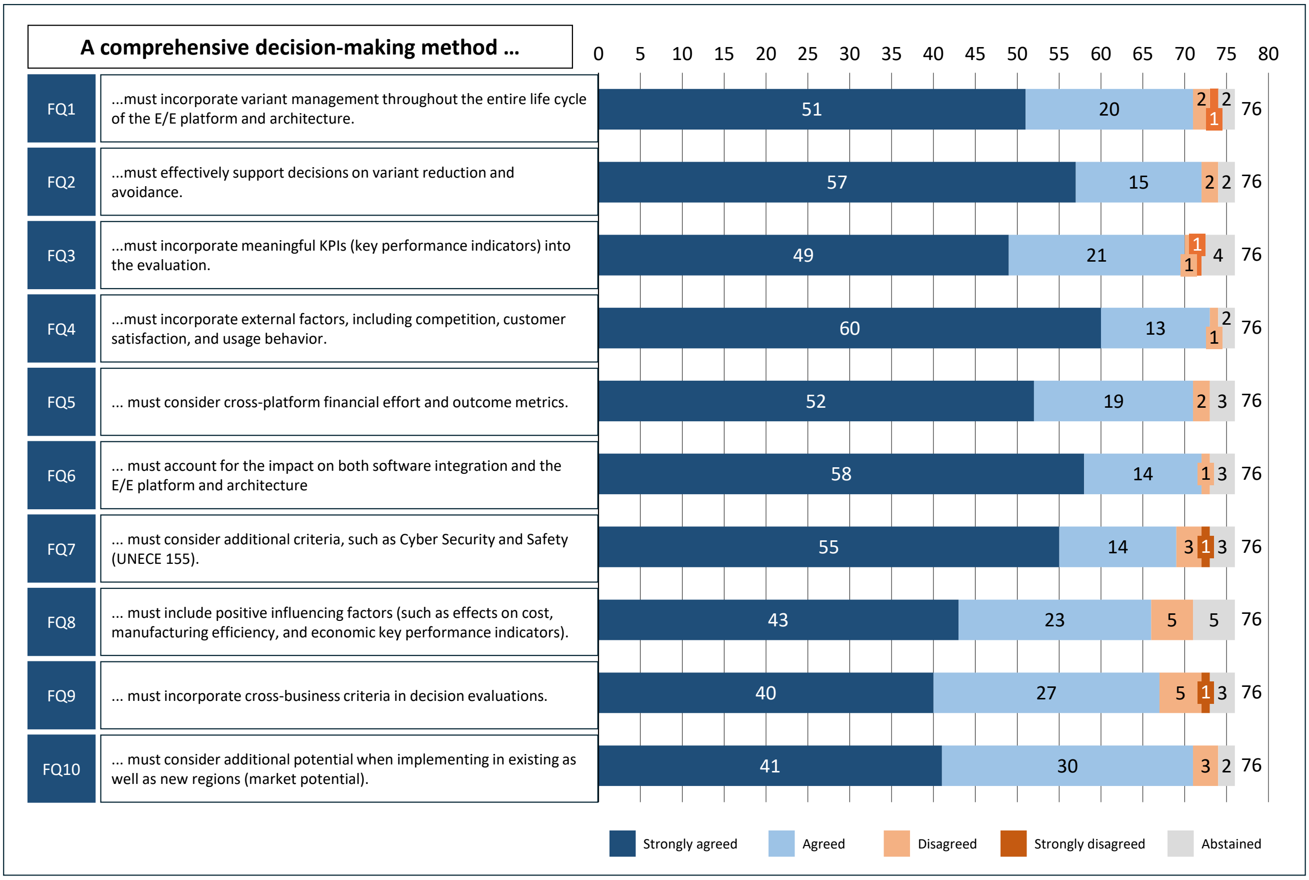

Figure 5: Questionnaire results on future decision making (FQX).

last place with 37 points. Overall, the top ranks underpin the importance of assessing financial performance in industry.

Among the criteria on *time criticality*, **internal and external dependencies** scored the highest, with some distance to the other two criteria. This highlights that dependencies are important in determining the urgency of tasks or projects. In second rank, **market opportunities and competitive relevance** received 217 points. **Influence on sales and business development** was ranked third with 183 points.

Among the criteria for evaluating *risk reduction and opportunity enablement*, **reduction of technical risks** received the highest score with 154 points. **Reduction of legal and regulatory risks** ranked second with 139 points, emphasizing the relevance of compliance and legal safeguarding. **Reduction of financial risks** followed in third place with 110 points, reflecting the importance of ensuring financial stability. Fourth, **improving efficiency** received 98 points and connects particularly to operational efficiency. In fifth place, **improvement of scalability/ availability** scored 87 points, while **improving system security** ranked sixth with 81 points. Lastly, **new business opportunities and markets** was ranked seventh with 54 points.

Regarding the criteria for evaluating *job size*, the criterion **electrics/electronics platform effects (compatibility)** scored highest with 220 points. This underscores that the experts perceived it as critical for decision making to understand whether a electrics/electronics platform is compatible with the product portfolio. With 162 points, the second rank was attributed to **development effort (capacity)**, while **development effort (costs)** closely followed in third place with 134 points. The last two criteria, **implementation risk** (5th with 96 points) and **complexity of implementation** (6th with 89 points), ended up below the average score. This indicates that these two criteria have comparably low priority according to our experts.

Future Decision Making: Key Insights

All key requirements and criteria for decision making we defined were perceived as relevant. ● The most important criteria connect to customer value, costs, risks, dependencies, and platform compatibility.

6. Discussion (RQ$_2$)

Next, we discuss our results to address RQ$_2$.

6.1. Variant-Management Challenges

Software Transforms the Automotive Industry. The questionnaire results reveal a strong consensus among our participants regarding the transformative impact of software and electrics/electronics components on the automotive industry.

Table 3
Validated criteria using the WSJF method.

Scope	Criteria	Points	Rank
User and business value	Customer added value, benefits and satisfaction	152	1
	Sales/profit	135	2
	Cost reduction	112	3
	Frequency and behaviour of use	101	4
	Availability of the scope/ scope affected	98	5
	Complexity reduction	65	6
	Market share and new business areas	37	7
Time criticality	Internal and external dependencies	300	1
	Market opportunities and competitive relevance	217	2
	Influence on sales and business development	183	3
Risk reduction and opportunity enablement	Reduction of technical risks	154	1
	Reduction of legal and regulatory risks	139	2
	Reduction of financial risks	110	3
	Improving efficiency	98	4
	Improvement of scalability/ availability	87	5
	Improving system security	81	6
	New business opportunities and markets	54	7
Job size	Electrics/electronics platform effects (compatibility)	220	1
	Development effort (capacity)	162	2
	Development effort (costs)	134	3
	Implementation risk	96	4
	Complexity of implementation	89	5

This is particularly visible for VQ1 to which 75 out of 76 participants agreed or strongly agreed and VQ2 to which 71 participants strongly agreed or agreed. These results are in line with our previous interview study (Zellmer et al., 2024c), in which we explored challenges related to software-oriented platforms in the automotive industry. Challenges commonly mentioned in the interviews (e.g., managing software, ensuring reliability) align with vehicles shifting towards complex cyber-physical systems. In this regard, the experts now also pointed out that customer demands are shifting towards mobile devices, resulting in similar challenges and requirements. The challenge of integrating software may be more prominent for long-standing automotive manufacturers that have historically grown hardware platforms. Whether newer manufacturers face identical or different problems regarding software requires future work with such manufacturers.

Complexity is Continuously Increasing. Other challenges occurred due to software-induced complexity. Our new results align with our previous study, emphasizing that the increase in software-driven functions, ECUs, and connectivity represents a key challenge in the automotive industry. Particularly the additional efforts in testing, validation, and safety assurance during the platform and vehicle life cycles are of concern according to the experts. In turn, this highlights the need to harmonize hardware and software life cycles already in development—an issue also occurring in other domains like embedded systems (Kuiter et al., 2021). Thus, it is not surprising, that the majority of our participants (58 strongly agreed and 14 agreed) reported being significantly impacted by such new challenges in their daily work (VQ3). During the workshops, we found that not all challenges and requirements have been addressed, yet. Moreover, the details of how to address the challenges depend on the different work areas impacted. As the experts remarked, the higher proportion of software and electrics/electronics components are more visible in certain specialized areas, which explains why some participants disagreed with the question.

Maintaining and Updating Software has Changed. To address such challenges, the interviewees in our previous interview survey mentioned several requirements, especially software maintenance throughout the entire platform and vehicle life cycle. In addition, the interviewees stated that customer expectations regarding software have changed, for instance, due to the widespread use of mobile devices. For such reasons, flexible software deployment strategies like OTA updates are needed, while automotive manufacturers must reflect on the impact on all stakeholders when deciding on such strategies. These trends are supported by the results of our questionnaire (VQ4). Our participants clearly indicated that software poses new challenges and requirements that strongly impact the existing platform strategies. During the workshop, the experts further confirmed these findings, highlighting electrics/electronics platform management as key for engineering modern vehicle portfolios.

Shifting from Hardware to Software Impacts Stakeholders Differently. In contrast, the interviewees' opinions in our previous study varied regarding the extent to which new requirements and challenges had already been addressed in the automotive industry. Some reported that such an integration was already piloted, while others noted that it had only been partially implemented. A similar pattern emerged in our questionnaire (VQ6). However, most participants actually disagreed (25) or strongly disagreed (23) that the new requirements and challenges had been addressed—drawing a much more negative picture. During the workshop discussions, most experts stated that this result could depend on the participants' specific work areas. They noted that some areas are more advanced in addressing software requirements and challenges, while certain areas are also less impacted by such changes. Nevertheless, the participants seem to be aware of the differences between traditional hardware platforms and modern software-based platforms in the automotive domain (VQ7). This was further confirmed by the experts during our workshop discussions.

Holistic Variant Management is a Challenge. Our questionnaire revealed a clear consensus that variant management is significantly impacted by new software-related challenges and requirements (VQ8, VQ9). The experts in our workshops confirmed this assessment, claiming that this is a consequence of the continued focus on (hardware) variant reduction. We received similar statements during our previous interview survey. For instance, interviewees highlighted that a focus on hardware variants can negatively impact electrics/electronics platform management, harming the maintenance of software and complexity. Moreover, new business models, such as continuous software maintenance via OTA updates, enable more frequent updates and bug fixes. In parallel, these new business models are highly dependent on systematic variant management. Consequently, software-based platforms require effective variant management that ensures a manageable number of variants within an electrics/electronics platform. The focus must shift towards a holistic view on hardware and software together. According to the experts, the continuous growth of software in modern vehicles will mean that software and its variant management are becoming a critical factors for decision making. So, software variance is also becoming more important, but since adequate integrated tool support is missing, further research on managing and deciding on electrics/electronics platforms is needed.

6.2. Decision-Making Practices

Software Changes Decision-Making Processes. We gathered various insights into to decision-making practices for managing automotive electrics/electronics platforms, which confirmed findings from our previous interview survey. Specifically, our results highlight that decision-making is key, while it is also increasingly influenced by the growing share of software and new requirements in the automotive industry (DQ1, DQ2). Experts in the workshop discussions emphasized that decision-making process must become more agile and flexible to cope with these changes. Otherwise, they will not be able to accommodate new requirements, such as the increasing frequency of changes, shorter development cycles, the growing share of software, or updates of functions and features throughout a vehicle's life cycle. This reflects the broader shift towards software-defined vehicles and emphasizes the need for responsive and life-cycle-aware decision-making frameworks. Similarly, in our previous interviews, we identified electrics/electronics platform compatibility and backwards compatibility as critical for delivering customer benefits and enabling seamless vehicle maintenance. Without careful consideration, platform and vehicle variants may evolve separately, potentially leading to incompatibilities over time.

Hardware–Software Dependencies Challenge Decision Making. Interdependencies of and between distributed hardware, software, and electrics/electronics components introduce significant complexity to decision making. This finding aligns with our previous interview study, in which "dependencies of distributed software-based functions" emerged as one of the most frequently reported challenges in decision-making for electrics/electronics platforms. In turn, it becomes difficult to effectively divide and prioritize electrics/electronics platforms for specific releases. Our questionnaire confirmed that such dependencies impact decision making, too (DQ3). However, opinions on the role of hardware and software in decision-making varied (DQ4), likely due to differences in participants' work areas and priorities at varying development stages. Moreover, decision-making priorities may evolve throughout different development stages, potentially contributing to the observed discrepancies. These findings underpin a need for more transparency in decision making to guide the development and maintenance of increasingly complex automotive platforms.

Tool Support for Decision Making is Lacking. In our previous interview survey, interviewees reported that only a few methods support decision making for software-intensive platforms. This emphasizes the importance of either adopting or redesigning existing processes and tools to effectively address software-focused challenges in decision-making. This finding was confirmed in our questionnaire (DQ5, DQ6), with the majority of participants agreeing to our respective statement. Additionally, the participants emphasized that limited transparency and decentralized inputs negatively impact the workload and quality of decisions. Interestingly, we gathered somewhat different results in our workshop discussions. The experts emphasized that sufficient tools and methods are present, but lack integration and transparency to support decision-making. As software becomes the dominant factor in decision making, some experts noted the limited availability of suitable tools, which adds complexity to decision-making processes. In particular, certain software properties, such as flexible (i.e., regarding time and location) deployments or updates, contribute to increasing software variance that must be accounted for.

New Criteria are Needed for Transparent Decision Making. Our previous interview survey contributed insights into current and requested criteria for decision making. Not surprisingly, we found that current criteria still focus on the mechanical background, so decision making does not appropriately account for software. For this reason, all results in our questionnaire underpinned the importance of expanding the existing criteria. These new criteria must cover various aspects to fit modern vehicle platforms, including costs and revenues of platform variants over their entire life cycle (e.g., for OTA updates), attributes of electric vehicles (e.g., charging time, range, efficiency), and market comparisons (e.g., demanded software features). Still, DQ7 received the highest number of abstentions in our questionnaire, indicating that our participants may struggle with defining clear criteria. In turn, we argue that there is a lack of transparency in decision-making processes, which asks further research on a comprehensive framework to support decision-making for electrics/electronics platforms.

6.3. Future Decision Making

As we have highlighted, new criteria are needed to implement a transparent decision-making framework for modem electrics/electronics platforms, particularly in the automotive industry. These criteria must address the increasing importance of software and the interdependencies with hardware as well as electrics/electronics components in particular. With our study, we elicited and confirmed several such requirements, notably to consider variant management across the entire platform life cycle, to integrate meaningful KPIs, and to incorporate external factors like competition and customer satisfaction. Despite the generally high agreement across the criteria, variations in the proportions of "strongly agree" and "agree" offer insights into implicit priorities of our participants. Criteria with a notably higher ratio of strong agreement are likely more critical from practitioners' viewpoint. Additionally, financial metrics, software integration, as well as security and compliance criteria were emphasized as crucial during the expert workshops. Building on the insights from our previous interview survey and this study, we discussed, evaluated, and prioritized what automotive experts perceived as the most relevant criteria for improving decision-making in Table 3. Thus, we contribute an overview of relevant criteria that decision-making frameworks should incorporate. We envision that this provides the foundation for new research not only for the automotive domain, but also for other domains that build on electrics/electronics platforms.

7. Threats To Validity

Internal Validity. The internal validity of our study is threatened by what questions we asked with what wording and our interpretation of the collected data. Our questions may have confused participants or may not be the most relevant. To mitigate these threats, we built on our previous, exploratory interview survey and discussions among all authors to define a feasible set of questions. Since we relied on closed 4-point Likert scales without free-text fields, we did not capture participants' individual reasoning. In addition, some phrases may have been more suggestive than would be ideal due to building on our previous work. This may partly explain the high level of agreement we observed for some questions, particularly those related to criteria for future decision making. We argue that the agreement may rather be caused by these criteria being based on our studies with practitioners; but even if not, the ratio of agreement and expert validations provide a useful judgment of importance. Moreover, the expert validations served as a cross-check on whether we missed important questions. Since, in the end, we interpreted the data, our findings may be threatened by subjectivity bias and personal interpretation. To minimize this risk, all authors with their different views and experiences have been involved. Again, the expert validations served also as a check for any misinterpretations on our side.

Another potential threat to internal validity arises from the fact that the first authors is employed at the company in which we conducted our study. Also, he was directly involved in key activities, including preparing the questionnaire and conducting the workshops. This dual role may have affected participants' willingness to participate and may have introduced social desirability bias in their responses. To mitigate this risk, we anonymized all questionnaire responses, used standardized procedures for data collection, and analyzed the data collaboratively including authors with no affiliation to the company.

External Validity and Transferability. The external validity of our study may be threatened by the participants of our questionnaire and workshops.Although the participants were employed by different companies, they all belong to Volkswagen AG, and thus may not be representative for the broader automotive industry. This means that our findings primarily reflect the perspective on one large, traditional automotive manufacturer and may not generalize to newer, more agile companies or suppliers. Still, Volkswagen AG is one of the largest automotive manufacturers and we involved experts from three independently operating brands in our study. We further employed multiple recruitment channels like personal emails, mailing lists, and personal contacts to gather a diverse set of experts regarding their roles and experiences. Through these means, we aimed to mitigate threats to the external validity, but we also acknowledge that these still exist. Still, we argue that our findings should be transferable to other organizations in adjusted form and that they contribute to informing practitioners and researchers.

While our results provide valuable insights into decision making for automotive electrics/electronics platforms, their transferability to other organizations and domains is subject to certain limitations. We identified several barriers that may hinder the transfer of our findings:

- Our participants operate within a large, structured multi-brand company with formal committees and processes for decision making. Smaller and agile organizations may not have the same governance overhead. Thus, our findings may require adaptations to organizational cultures and governance structures.

- Our participants frequently emphasized compliance concerns, such as UNECE 155 (FQ7). Such concerns are more relevant in regions where such regulations apply, and only for respective domains. Transferring our findings to domains with less or different regulations may require adjustments of our findings.

- Some of our insights (e.g., the need for hardware–software lifecycle harmonization) are shaped by Volkswagen's existing legacy platform architectures. Other OEMs that build greenfield platforms may not experience the same integration challenges, and their decision making may focus more on initial architecture trade-offs rather than variant reduction.

Further research is needed to analyze whether such factors impact our findings, extending and refining our study. However, we argue that our findings are transferable in the context of large and long-standing automotive manufacturers facing challenges in integrating software and electrics/electronics components into historical hardware platforms.

Construct Validity. The construct validity could be compromised by ambiguities in our questions or answering options of the questionnaire. These may be ambiguous or open to different interpretations. To reduce this risk, we worked closely with experts from the automotive domain to develop the questionnaire. We performed pilot runs to avoid misunderstandings and ensure that we captured the constructs we were interested in. Lastly, the first author could be contacted at any point by participants to clarify any potential confusions, while the expert validations served as a general confirmation of our findings.

8. Conclusion

In this article, we reported the results of a mixed-method study on the state-of-practice on decision-making for managing automotive electrics/electronics platforms. Through this study, we contribute a comprehensive overview of requirements and criteria for (re-)designing decision-making processes in the automotive domain. Our study included a questionnaire with 76 participants and workshop discussions with seven experts, validating and extending findings of our previous interview survey with 26 experts. Based on these sources, we analyzed temporary challenges in automotive decision-making. In brief, we found:

RQ_1 (Current Challenges and Requirements)

- Software has become the dominant factor for organizing automotive platforms and variant management, but incorporating a software perspective in decision-making processes is a challenge.
- Experts recognize decision making as key for managing modern electrics/electronics platforms, but the increasing relevance of software is not sufficiently accounted for in existing tools.
- Future research should compare legacy OEMs and software-native newcomers to identify to what extent their challenges and best practices regarding platform strategies vary.

RQ_2 (Future Criteria and Requirements)

- Modern electrics/electronics platforms in the automotive domain require criteria that account for software and the complexity it imposes, providing a holistic picture of hardware, software, and electrics/electronics components.
- Among the new requirements and criteria that have become relevant for decision making are the costs, risks, dependencies, and compatibility of the various different components in electrics/electronics platforms.
- Future research could help analyze trade-offs among decision criteria to better understand their relative importance and practical relevance.

We hope that these confirmed and extended insights help practitioners in the automotive domain and provide guidance for future research.

As a next step, we aim to leverage our findings to develop a comprehensive decision-making framework for managing electrics/electronics platforms. Our focus in this regard will be on how to integrate this framework into existing processes to integrate a software perspective without major disruptions. Due to our results, we argue that a standardized and well-structured framework is instrumental to improve the transparency of and accelerate decisions. Thus, this research direction holds significant potential, offering direct benefits for practitioners. Lastly, since modern vehicles resemble cyber-physical systems, we hope that our findings are transferable to other domains, but this must be explored.

Acknowledgments

We thank all experts who participated in and supported our research with their invaluable feedback, either through interviews, informal discussions, reviews, the questionnaire, or the validation workshops.

Disclaimer. *The results, opinions, and conclusions of this paper are not necessarily those of Volkswagen AG.*

CRediT authorship contribution statement

Philipp Zellmer: Conceptualization, Methodology, Validation, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Jacob Krüger:** Methodology, Validation, Writing - Review & Editing, Supervision. **Thomas Leich:** Conceptualization, Supervision.

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