INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.266

Variability in complex product/system design: case study in automotive industry

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Abstract

The complexity of the products/systems requires an in-depth understanding of variability and its impact on all phases, from design to maintenance. This study explores Variability Management (VM) emphasizing its challenges. Conducting semi-structured interviews with experts at Renault Group, the research examines variability aspects, semantics, methods, challenges, and possible solutions. The findings offer practical insights into industrial-scale variability management, addressing the use case of the automotive industry.

Keywords: variability management, complex systems, automobile engineering, product line engineering, systems engineering (SE)

1. Introduction

When the American industrialist Henry Ford, declared that "any customer can have a car painted any color that he wants, so long as it is black", for the Model T (Alizon et al., 2009) a "zero variability" concept was created. Having diversity would have implied taking the risk of applying the wrong color. At that time, the concept of Variability Management (VM) and its importance were not realized. In fact, variability refers to the ability to configure, customize, and exchange an artifact – any entity of a product (Bachmann & Clements, 2005). VM is crucial to meeting diverse and changing customer demands while maintaining optimum efficiency and profitability. This means considering the specific needs and preferences of different market segments while ensuring consistency and overall product quality. It is noted that the more complex a product is, the greater the challenge of managing its variability, especially if it is a mass-market product. In this context, a series of challenges emerge regarding the representation and management of product variability. Variability raises several key questions, and the purpose of this study is to understand current sources of variability, current management techniques, and challenges of variability within a complex product. According to (INCOSE, 2015), the opposite of complexity is decomposability; a system is complex when multi-scale descriptions are needed to describe its structures, and a single level or with a single view is insufficient.

While there's a considerable amount of literature on the topic, there's a noticeable gap in studies examining variability in the industry and its current management. Existing research lacks descriptive insights into how variability is presently handled on an industrial scale, the tools used, and the challenges faced amid evolving customer demands for more personalization. Our study focuses on the specific case of a complex product. We intend to provide practical insights into how variability is managed in the industry, addressing the challenges posed by changing customer expectations and the increasing demand for personalized products. The automotive sector, with its complexity and diversity of products, highlights the need for an in-depth understanding of variability and its impact on vehicle design, production, and maintenance. Through this exploration, a comprehensive overview of the challenges

and opportunities associated with the variability of complex products is offered. The example of Renault and its expertise in VM in the automotive sector is particularly relevant. Semi-structured interviews with 21 experts from Renault's Technocentre provided essential insights into these complex questions.
The remainder of this paper is structured as follows. After the current introduction, and the brief literature review in section 2, section 3 presents the method of semi-structured interviews used. Section 4 shows the results collected. These are discussed in section 5. The paper is concluded in Section 6.

2. Literature review

A systematic literature review is currently undergoing addressing Product Line Engineering (PLE) methods, support, and tools in complex system design. Due to the page limitation, here we propose to address only some of the key papers tackling product variability in complex system design. VM represents the procedures and the activities that are applied to represent the variability of the several artifacts throughout their lifecycle (Schmid & John, 2004). Here, dependencies and instantiations of the variabilities are studied. Diversity is a key element in economics, especially in terms of product management. In fact, product differentiation is at the center of economist theories (Ranaivoson, 2005). In parallel, companies are under increasing pressure from their customers, who want a greater variety of products with the last technological options. This diversity and the existence of different variants increases the complexity of components configuration since current solutions struggle to support configuration across multiple domains, resulting in duplicate data, errors, and overwhelmed resources (Beuche, 2017). Therefore, mastering a diverse, customer-specific offer and providing focused product features to meet such demand is becoming a key competitive advantage for automotive companies. The variety of products found in this industry presents nowadays a complexity that is impossible to deal without the adapted tools. The key difficulty in that is managing such variability across various system engineering viewpoints and domains from vehicle design to components to even concepts of marketing. Variability is about making things different based on specific needs and resources. This applies not only to what customers want but also to how a product is designed and put together. Variability can happen at many levels, and it is important to look at variability from different angles and see how they relate to the overall system. For example, the choices made about suppliers can greatly affect the options for components. Choices are interconnected – picking one thing might mean you can't use another. One choice can impact different qualities, sometimes only showing up during testing (Sinnema & Deelstra, 2007). A study conducted by Evalueserve in 2010 found that around 40% of the global automotive market was served by just twenty vehicle platforms. Renault was a pioneer in sharing and reusing these platforms to cut costs in production and development (Wald, 2012). Some requirements might only apply to certain models or markets. Second, the combinations and variants that are defined at this level need to be managed on a larger scale for all the products in a company's range. Dealing with a wide range of markets, rules, and customer preferences makes designing products quite complex (Dumitrescu et al., 2013). Even though some in the industry want to avoid too much variability, it's important to create products that match what customers want.

3. Method

The research methodology adopted for this study is based on semi-structured interviews (Ruslin et al., 2022), conducted with a cohort of leading professionals operating within Renault's Technocentre at Guyancourt. Choosing semi-structured interviews over other approaches was motivated by their qualitative nature, providing a flexible and focused approach to delve deeply into the perspectives of professionals, allowing dynamic exploration of emerging themes and individual experiences. The research methodology is an exploratory interview (Magaldi & Berler, 2020), based on semi-structured interviews which strikes a balance between pre-established structure and inherent flexibility. As a qualitative research method, they stand out for their ability to offer a flexible, focused approach to exploring in depth themes and perspectives of interest within a specific context (DiCicco-Bloom & Crabtree, 2006). Interviews are guided by a set of pre-defined questions, which ensure conceptual and methodological consistency. This structure is adaptable, allowing interviewers to add additional questions to explore emerging themes and draw on the specific experiences of each participant. Semi-structured interviews offer significant advantages in gathering rich, nuanced information (Nair, 2023). The interviews context was defined according to (Eckert & Summers, 2013). The selection of 21 Renault engineers at the Guyancourt Technocentre for interviews was based on representative purposive and convenience sampling (Bhardwaj, 2019). The interviewees are experts in different domains managing variability in complex system design from different perspectives and at different points of the process: configuration management, competitive analysis, marketing, and systems, product, requirements, project, and software engineering. The expertise of these professionals was judged through their roles and experiences within Renault, aligning with the research's focus on gaining insight into strategies, challenges, and opportunities for variability management.

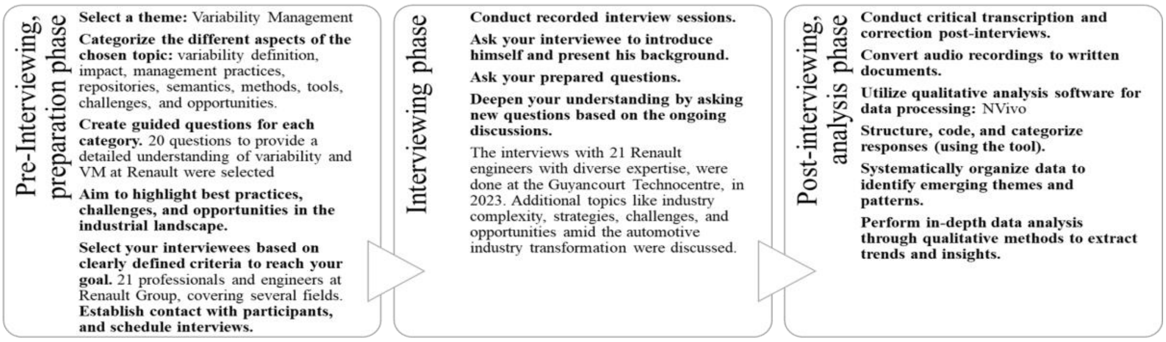

Figure 1. Method steps

Each step converges to offer an in-depth, contextualized perspective on managing variability within the dynamic environment of Renault. This methodological approach offers a balance between an organized structure and the flexibility needed to explore the nuances and subtleties of the challenges and solutions encountered. It thus become an effective vehicle for gathering meaningful qualitative data, contributing to a better appreciation of the professional environment and the issues addressed.

4. Results

Result analysis has been done using the grounded theory (Chun Tie et al., 2019) and is consequently organised by different themes (challenges that have been identified by interviews but also cross referenced with the literature review pertaining to these issues). Each interview was transcribed, and coding was done by authors. Aggregation of codes has been discussed in order to highlight different overall themes. The coding and aggregation of codes has been verified by a second researcher to discuss possible biases. To illustrate the challenges discussed by experts, we propose to introduce a quote *in italic* that highlight the main and frequent ideas for a given issue. These quotes have been translated from French in the most authentic way. The saturation of answers was examined to gauge consensus among experts on the identified themes. At this stage, our focus encompasses both established knowledge within the research community and novel findings derived from the conducted interviews.

4.1. Several aspects of variability

4.1.1. Variability and its sources

Variability can be defined as the ability of a product, (system or artifact) to present different options, variants, and versions. In general, the literature addresses variability in majority regarding customer needs, constraints, and preferences. However, here we adopt the broader definition also integrating the diversity and flexibility offered in product design, manufacture, and customization to satisfy these needs. The results underline that the variability manifests at several levels and in different aspects of a product. Some of the categories inducing variability in complex system design are given in Table 1. It can be reflected in product parts, hardware, software, technical choices, configurations, equipment levels, functionalities, materials, finishes, styles, as well as in the services and options available. It can also translate into variations in performance, aesthetics, price, size, or functionality.

https://doi.org/10.1017/pds.2024.266 Published online by Cambridge University Press

Table 1. Main variability sources

Sources	Example
Mission and function variability	Different use: goods vs. passengers' transport
Market needs, geographical and cultural specificities	Metric vs. imperial systems
Individualized customer demand and taste	Interior personalization leather and fabric seats
Economic and variants differentiated by cost	Luxury versus economic finishing
Regulatory constraints and requirements	Mandatory safety systems such as airbags and TPMS
Technical solutions available at engineering level	Different types of engines for the same car model
Parts diversity and performance variations	Different suppliers for braking system
Product on the assembly process	Color tint
Design and aesthetic variability	Differences in body style and design elements
Software diversity	Different versions of an operating system

4.1.2. Good versus bad variability

"We should consider that there is good diversity and there is bad diversity. It's like cholesterol..." The notion of variability in different contexts can be classified into two distinct categories: anticipated and planned variability, which is associated with good diversity, and involuntary and incurred variability, which is linked to poor diversity. Good and relevant variability brings added value to customers and meets their expectations. Bad and superfluous variability can increase complexity and costs without any real benefit. In the first case, anticipated variability manifests itself in conscious, proactive planning. On the other hand, variability often results from a lack of control over diversity factors, which can lead to results that are valueless. Ultimately, effective management of variability aligns with the company's strategic goals, ensuring that the right balance is struck between customization and standardization to maximize value creation and maintain competitive advantage. The underlying question is related to the degree of variability that is integrated into complex system design. Proactive management with the definition of appropriate processes are important as they help identifying, declaring, and properly managing variability in a product's project.

4.1.3. Variants versus versions

"Configuration management tackling versions and temporal evolutions has been much confusing with the instantiation or the variability configuration of our vehicles variants…" It's crucial to distinguish between variants and versions. Variants express a difference in terms of choice, diversity, and personalization. Variant selection focuses on customizing and configuring the product to meet individual customer preferences. Product personalization has become a major factor in the way companies interact with their customers. Today's consumers are looking for products that meet their specific needs and reflect their individuality. Companies are responding to this demand by offering customization and configuration options that enable customers to create unique products. Versions express a temporal evolution, and changes and updates of a product over time. Configuration management has become an essential aspect of the successful development of complex products such as software, electronic systems and even manufactured goods. It encompasses the way in which versions and variants of a product evolve over time, while maintaining traceability of changes and choices made. Configuration management makes it possible to systematically track changes, guarantee consistency and avoid potential errors.

4.1.4. Variability and Systems Engineering viewpoints

"Variability includes 3 aspects, one is what is the need for the client. The 2nd aspect concerns the technical solutions to meet the needs. The 3rd type is about transcribing the second aspect in an architecture in hardware or software terms…" From a Systems Engineering perspective, we can have three types of diversity at three different viewpoints: operational, functional, and organic. Each of these viewpoints of diversity has its own drivers. At the operational viewpoint, diversity takes the form of the variety of conditions and environments. This drives systems' adaptability and robustness to cope with a

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range of changing circumstances. At the functional viewpoint, diversity takes shape through the variety of technical solutions available to answer the tasks and missions the system is designed to accomplish. This form of diversity stimulates innovation, encouraging the integration of new and varied functionalities to meet specific user needs. Finally, at the organic viewpoint, diversity takes the form of the variety of parts, components and teams involved in system development and implementation. This encourages interdisciplinary collaboration and the combination of diverse expertise to create complete, balanced solutions. Each of these levels of diversity is driven by distinct factors, but together they form a complex web that helps shape resilient, adaptable, and high-performance engineering systems.

4.1.5. The impact of variability on a product’s life cycle

"Variability management has a huge impact on life cycle steps. Good VM speeds up the design process." The impact of variability on the life cycle of a product is mentioned in interviewee responses. Introducing new variants or options into the development process can have a significant impact on the product life cycle. When a new variant is introduced during development, it may require adjustments in the workflow and product architecture. This can lead to changes in development activities, testing and validation. Effective VM can speed up the design process, save money by adding or removing variants, but it also requires proper planning and coordination between the stakeholders to avoid delays and validation issues.

4.1.6. Variability in numbers

One of the questions that was asked to the interviewees was to give an estimate of the shared features and functionalities between the products. Interviewees' responses varied in terms of the granularity they work on, however all agreed that it is desirable to have a majority of standardized and reusable elements with a smaller specific share. Responses varied from 2/3 1/3, 70% 30%, to 80% 20%... Despite setting these objectives, achieving this ideal proportion remains a challenge.

4.2. Variability in the automotive industry: The Renault's use case

"The automobile is a product with a very stable architecture. We can consider that the structural framework of any car is more or less the same… However, the car is not only a complex product, but also a general public product. The scale of use of diversity is much greater than that found on very complex successful products like airplanes or radars..." From an automotive point of view, variability has some important specificities. Firstly, motor vehicle architecture is relatively stable, meaning that the structural framework of a car generally remains the same. However, the growing complexity of vehicles and the demand for customization have led to an increase in the diversity and flexibility required in design and production. The main difference lies in the scale of use of diversity in the consumer automotive industry. Unlike complex products such as aircraft or radar, automobiles are both complex and aimed at a wide audience. This means that the demand for diversity is much greater, as customers have individual preferences and specific needs. However, diversity remains limited compared to other industries, as there is still a certain standardization of vehicles for production and cost reasons.

"Variability has been a constant at Renault since the first cars were produced. Each model carries with it changing elements, testifying to the brand's continuous evolution over time." At Renault, the culture of variability has existed for a long time and is deeply rooted in the company. From the outset, vehicles have been broken down into their component parts, allowing variability to be managed at part level. This approach has existed for many years in terms of parts management, and has evolved over time, from artisanal to industrial engineering, to better manage the increasing diversity and flexibility of vehicles. Moreover, variability at Renault is characterized by the diversity of the brands and models it offers. Renault has four distinct brands - Renault, Alpine, Mobilize and Dacia - and seeks to differentiate these brands while seeking to maximize commonality between products to streamline production.

"We are now moving towards a more global approach to managing this diversity, adopting a systems' engineering perspective." "A strong interaction persists between the different professions and diversity." Interviewees answers show that within the complex context of engineering, a crucial interdependence between the various professional disciplines and the inherent variety finds its place. ISO standards, MBSE techniques, versioning and traceability are used to check that each solution chosen by an

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engineering profession is compatible with the solutions of the other professions. This interaction extends to several levels of the process, from the initial design, where the creative perspectives converge, to the analytical phases, where the technical skills come together. Engineering various fields, commercial diversity and purchasing management, and other players are responsible for reducing product diversity by identifying and optimizing variation points, collaborating with businesses and projects, and proposing appropriate solutions to manage diversity accurately.

4.3. Variability Management: Challenges and methods

"In the ever-changing landscape of challenges, mastering variability management becomes the secret sauce that empowers businesses to nurture stability amid ongoing evolution."

Table 2. VM challenges

Governance and Organization	Variability Management	Systems Eng. Culture	Tools	Quality and Testing
(i) Project organization dedicated to configuration management, (ii) Early integration of diversity management, (iii) Management awareness of the importance of reducing diversity, (iv) Study and analysis of the impact of variability, (v) No neglection of the legacy, (vi) Establishment of overall governance to avoid proliferation and overlap, (vii) Improved communication and collaboration between different departments and businesses, (viii) Management's awareness raise of the importance of reducing diversity, (ix) Training of employees on managing diversity, and (x) Identification of the actors involved in leading change.	(i) Definition of variability lexicon, grammar rules and vocabulary to ensure consistent and understandable communication, (ii) Development of tools and approaches that consider both technical and product diversity, (iii) Definition of management rules and a description of possible variations, (iv) Optimization of variability to meet customer needs while reducing costs, (v) Consideration of organizational aspects and transitions in managing variability, (vi) Consideration of organizational aspects in managing variability (repositioning variability actors in organizational chart of the enterprise), (vii) Reduction of complexity of information manipulation, and (viii) Ensure of data continuity.	(i) Consideration of the SE perspective for VM, refined on the 3 viewpoints (operational, functional, organic), (ii) Building on a shared engineering culture, (iii) The set up of a coherent system engineering variability model and stabilize it with experience, (iv) Assurance of continuity between different diversity systems, (v) Management of technical and product diversity in a complementary way, (vi) Infusion of configuration management and variability early in the process, and (vii) Synchronization of a lifecycle approach for software and hardware development to ensure connection.	(i) Use of suitable tools and necessary methodological flexibility, (ii) Establishment of digital continuity, (iii) integration of PLM and ALM, (iv) Resource allocation for new processes and tools, (v) Strike a balance between in-house development for customization and control, and the use of third-party solutions for standardized functionality and time optimization, and (vi) the setup of a generic platform to test all variability configurations (partial and total) for a given system and defined design perimeter.	(i) The Set up of a generic platform with functionalities that can be activated at the request of customers, (ii) Assurance of upstream data quality and product governance, (iii) Implementation of a generic platform to test all configurations, and (iv) Assurance of data continuity and digital continuity.

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Participants highlighted various areas for improvement within the realm of VM. These areas primarily revolve around challenges that offer opportunities for growth and development rather than portraying them as insurmountable obstacles. Key areas identified include: (i) Addressing decision complexity amidst evolving contexts, (ii) Enhancing investment in VM initiatives, (iii) Encouraging stakeholder engagement and overcoming resistance to change, (iv) Resolving conflicts stemming from diverging directions and power dynamics, (v) Achieving a balanced workload distribution, (vi) Mitigating staffing and resource limitations. These challenges, outlined in Table 2., present avenues for enhancing VM practices. They underscore the need for a comprehensive holistic approach that integrates technical, organizational, and cultural solutions. By doing so, organizations can effectively harness the benefits of diversity while minimizing constraints and maximizing economic advantages.

4.3.1. Variability repositories, semantics, and vocabulary challenges

"The universe of variability repositories is rich in diversity and number. It is not imperative that all adopt the same granularity and mesh. Nevertheless, it is crucial that despite these differences, coherence is preserved to allow mutual understanding and effective harmonization." Repositories play a fundamental role in the complex engineering environment, bringing a multitude of benefits for process management and standardization. They serve as structured frameworks for defining vehicle characteristics and variants, facilitating the management of the diversity inherent in each project. In addition, they promote the unification of language and terminology within the company, stimulating fluid communication and collaboration between multidisciplinary teams. However, despite these advantages, repositories are not without challenges. The lack of deployment and global implementation can lead to inconsistencies and misunderstandings between different entities within the company. Coordination and alignment between different repositories can be complex, requiring careful management to avoid conflict. Adoption by users and businesses can take time, which can hinder the effectiveness of repositories in the initial phases. Some repositories may require additional efforts to reach full maturity, while the quality of incoming data may influence their usefulness. The possibility of overlap between repositories or unclear definitions of their perimeters can cause confusion and duplication. Interviewees also mentioned several challenges: (i) need for regular updating, versioning, (ii) impact on processes and tools, (iii) cross-functional collaboration, and (iv) impact on quality.

"Even in the word variability, there is a meaning that you needed to clarify at the beginning!" Semantics, lexicon, and vocabulary play an essential role in managing variability. It is important to clarify and clearly define the vocabulary used to ensure common understanding and avoid confusion. Lexicon, grammar rules and vocabulary are important to ensure consistent and understandable communication. They make it possible to establish a common language within the company. A well-defined lexicon and clear grammar rules promote mutual understanding and avoid misunderstandings. It also makes it possible to standardize the terminology used and to facilitate collaboration between the different teams and sectors of the company.

"We sometimes have mnemonics that are extremely close, or even similar, between different lexicons." Vocabulary problems can lead to confusion and misinterpretation. Using similar or identical terms in different contexts can lead to ambiguities, misunderstandings, and communication difficulties. It is therefore necessary to establish rules and standards for the application of the terms and to ensure a common understanding. The main challenge lies in the appropriation of technical vocabulary by the members of the company. It is necessary to put in place means of support and training to allow a better appropriation of the technical vocabulary and thus promote a coherent and unified use. Dictionaries of variability are not always well established and used adequately. There may be gaps in the definition and understanding of terms related to variability, making their consistent use difficult. Managing and maintaining variability dictionaries requires ongoing efforts to ensure their relevance and effective use in the enterprise. Sometimes in complex projects, each project can have its own lexicon, which can lead to differences in understanding and communication. In addition, the use of similar terms to refer to different concepts has been observed, which creates confusion and comprehension problems. To clarify and standardize vocabulary, it is necessary to set up initiatives such as configuration management and codification to remove ambiguities. It is also important to define rules and standards for the application

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of the terms, particularly as regards points of variation. Collaboration between different teams and sectors of the company is essential to establish a dictionary of transversal variability that is adopted.

4.3.2. Variability Management (VM) methods

Good VM aims to balance the complexity and costs associated with diversity, while maximizing added value for customers. Effective VM aims to optimize choices, minimize unnecessary complexity, and maximize added value for customers. *"In the broad field of VM, a wide range of methods emerge, each with its own history and specific relevance. Some of these approaches have proven themselves over the years, while others are emerging and being implemented now."* Several techniques have been identified in the company, their maturity and deployment levels are not the same: Boolean logics and product structuring and configuration are historically used. Recently MBSE has been identified as potentially interesting for variability definition due to the increase in company's maturity in using these tools and capturing design data. Moreover, there is a consideration of integrating PLE in company, to organize different sources of variability and to support design teams to better manage them. This section presents only the methods mentioned by the interviewees, it transcribes also the concepts evoked during the interviews. Presenting each method in detail with scientific referencing is out of our scope.

Boolean logic and exclusion logic: Boolean logic is a branch of mathematical logic that uses logical operations (AND, OR, and NOT…) to evaluate Boolean expressions. In the context of diversity and VM, it is used to define rules and variation conditions. For example, a rule can specify that if a characteristic A is selected, then characteristic B cannot be selected simultaneously. This allows to manage the constraints and dependencies between different variants of a product or system. Exclusion and forcing the selection of only one variant reduces variability and simplifies the configuration process by reducing the number of combinations.

Product structuring (modules): It involves setting up methods and processes to organize and configure products according to the desired variations. This involves defining a modular architecture where the different components can be flexibly combined. Product structuring allows the system to be broken down into subsystems, modules, and components, thus facilitating the management of diversity and variability. Selecting the appropriate options for each component to create a specific configuration that meets the customer's needs is the next step.

Model-Based Systems Engineering (MBSE): MBSE consist of using models to represent the systems, architecture, and data flows of a project. These models make it possible to visualize and understand the structure, behavior, and interactions of the different components of a system. Common modeling languages are SysML (System Modeling Language) and UML (Unified Modeling Language). These languages offer graphical notations to represent the different aspects of the system, such as blocks, flows, requirements, relationships, etc. Systematic modeling makes it possible to capture system requirements, perform feasibility analyses, facilitate communication between stakeholders and perform.

Product Line Engineering (PLE): PLE appears as a promising strategy, offering the ability to manage change on a large scale and systematically. The component-oriented variability approach provides increased modularity by creating products from interchangeable components, making it easier to create custom variations. Respondents stressed the importance of considering change management and SE methods when working with a product line that embraces diversity.

5. Discussion

The approach of semi-structures interviews was particularly well suited to capturing insights from the professionals interviewed at Renault's Technocentre. Due to the complexity of fields such as systems and software innovation for tomorrow's mobility, participants could bring varied expertise and unique perspectives, often difficult to capture with more rigid methods. Semi-structured interviews allowed for more natural interaction and fluid communication, enabling participants to express themselves authentically and provide specific details of their experiences and viewpoints. The interviews realized were a window onto the expertise of these professionals, who play a fundamental role in the evolution of vehicles and mobility solutions for years to come. Their rich experience and unique perspectives were helpful to understanding VM in such a context.

The results of our variability study highlighted several interesting aspects. Firstly, although the experts have almost similar definitions of variability, there is still diversity in the nuances. Each expert, depending on his or her area of expertise and work experience, approaches variability from different angles, evoking both positive and negative aspects, as well as notions of versions and variants specific to his or her sector. In parallel, variability is influential throughout a product's lifecycle, underlining the need to control it. In this respect, it is important to recognize the plethora of frameworks, tools, and methods available to address variability. Each of these elements is adapted to a specific context, but it is essential to develop a global vision of diversity and its management. A major challenge is emerging concerning the semantics and lexicon of variability. This issue reflects the difficulty of describing diversity consistently across different departments, divisions, and scales within the same organization. The issues raised by this study are varied. However, the key issue is how to prioritize solutions to these challenges. It is suggested that integrating the notion of diversity and its management at all levels, right up to the company's overall strategy, remains the best approach to responding effectively.

It is important to note that Renault is currently implementing Model-Based Systems Engineering (MBSE) and Product Line Engineering (PLE). At the heart of this initiative lies a major focus on VM. The most important aspect of this approach is to develop a comprehensive diversity model at all levels, encompassing the various points of view of systems engineering. Of paramount importance, however, is the preservation of Renault's unique heritage, since unlike other companies that are creating complex products from scratch, Renault capitalizes on decades of experience in automobile industry.

An important observation lies in the impact of the specificities of the automotive industry on perceptions and responses concerning variability. Individuals with experience in other fields tend to adopt a broader perspective, comparing complex products. It is worth noting a few limitations of our study; Although we interviewed 21 different profiles, the number remains relatively small to cover all the variability within the industry. In addition, the sample of 21 interviewees came from the same company (Renault), which raises the possibility of extending this study to other companies and fields to gain a broader and more comprehensive perspective on the issue of variability. However, we believe that many variability management challenges evoked are globally the same in different industries. Some of them would be specific to the automotive context. The study is replicable and hence other researchers could repeat it to validate this hypothesis. We also believe that implementation challenges, the constraints in adapting to the specific needs of each company and the constant evolution of technology can create gaps between theory and practice.

6. Conclusion

In conclusion, in the light of this context and these issues, managing variability in complex products is a crucial challenge. This study has sought to delve into the many facets of variability, looking at its characteristics, advantages, and disadvantages, as well as methods for managing it effectively. The example of Renault, with its expertise in VM in the automotive sector, was particularly illuminating. Semi-structured interviews with experts provided essential insights into these complex issues. In summary, this research offers a comprehensive and nuanced view of the challenges and opportunities associated with variability in complex products such as cars. The knowledge gained from interviews with Renault experts provides valuable insights for the development of more effective VM strategies, better adapted to a constantly evolving market. This study thus marks a significant advance in the understanding and management of variability, while laying the foundations for future research in this ever-changing field. It is essential to develop a global vision of diversity and its management. It is suggested that integrating the notion of diversity and its management at all levels. Current results suggest integrating Systems Engineering and Configuration Management principles. In parallel of this study, it is important to highlight related work in the fields of PLE and VM in Systems Engineering. The authors have deepened their exploration by considering advances in these fields. This study is crucial for an in-depth understanding of the context. By combining aspects of variability with PLE methods, this research is positioned at the crossroads of two fields essential to the development of complex products.

Several avenues for further research have been identified. Firstly, it would be relevant to further investigate the practical integration of PLE methods in an automotive context and assess how they contribute to more effective VM. This could involve exploring advanced techniques such as automating

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the generation of product variants from a common base. In addition, it would be interesting to extend investigations to other industries and sectors to see how the principles of VM and PLE can be successfully adapted and applied. This cross-industry comparison could reveal innovative and transferable approaches. Finally, given the rapid evolution of technologies and methodologies in systems engineering and product design, it is essential to keep abreast of new trends and developments. Areas such as artificial intelligence, advanced modeling and data management could have a significant impact on the way variability is managed and exploited in the future.
In sum, this study not only sheds light on the current challenges of variability in complex products, but also opens new perspectives for future research in the field of complex product VM.

Acknowledgment

We thank the 21 esteemed experts at Renault whose invaluable insights and contributions proved to be instrumental during the interviews. Their expertise has greatly enriched this research endeavor.

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