



The challenges of developing sustainable products: adopting modular platforms in the context of high-variety complex products

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Abstract: In today's rapidly evolving market, which increasingly favours sustainable products, manufacturing companies must turn to the development of modular product platforms. However, the complexity arising from developing complex products and the increasing demand for mass personalization brings forth multiple challenges. This preliminary study identifies and ranks the challenges encountered in designing modular product platforms to meet a demand for high-variety sustainable products. A two-pronged methodology combines semi-structured and structured interviews with ten experts from three companies. This approach reveals seven categories of challenges. The results show that specific challenges become more critical depending on the company's context and maturity. Thus, addressing the seven groups of challenges requires consideration of the particular situation of each company. Identifying these groups of challenges will allow for developing diagnostic frameworks and product development strategies to address them in future research. Furthermore, integrating interventions more strongly focused on sustainable product design remains to be fully developed within the processes and tools present in current product development strategies.

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Keywords: Complex Products, New Product Development, Collaboration, Competitiveness, Challenge, Modular Product Design, Variety, Product Design, Sustainability

1. INTRODUCTION

In the context of globalization, manufacturing companies face a growing variety of consumer needs. Different regions' specific requirements drive this growth, multiple market segments for each product, and the rapid pace of technological advances (Algeddawy, 2014). To address these needs, companies employ mass customization strategies (Kumar, 2004). These strategies seek to increase the number of product configurations, resulting in growing complexity and diminished performance (Efthymiou et al., 2016; Mesa et al., 2020; Schuh et al., 2021). The emergence of mass personalization further intensifies the increase in variety, heightening complexity. Mass personalization requires companies to deliver unique products while maintaining costs similar to those of mass production (Wang et al., 2017). The rising degree of product customization can increase resource consumption and generate more emissions, underscoring the need to address environmental aspects beginning at the design phase (Mesa et al., 2020). However, current approaches to mass personalization strategies, however, are often superficial and incomplete (Bogner et al., 2017).

Many manufacturing firms have evolved to offer higher-value-added products, thus becoming suppliers of complex systems (Krebs and Ranze, 2015). Numerous companies are now adopting the product platform concept to meet the global market's increasingly diverse needs. A product platform is defined as a set of parts, interfaces, and subsystems shared among multiple products, serving as a common foundation for various configurations while reducing cost and lead time

(Magnusson and Pasche, 2014). To minimize environmental impact, employing modular design strategies helps reduce waste and integrate more sustainable processes—especially when developing complex products (Mesa et al., 2020; Tseng et al., 2004).

Therefore, companies must rethink how they design their complex products to remain competitive. Product development processes play a crucial role, given that 70% of a company's competitiveness is tied to the products themselves (Qiu et al., 2022). While the literature points to numerous unresolved and scattered challenges, no studies have prioritized these challenges. The present article addresses this gap by compiling and ranking the challenges encountered while developing high-variety complex products, ultimately aiming to propose a more comprehensive strategic framework.

The primary goal of this preliminary study is to identify and prioritize the groups of challenges encountered in the context described. This article details the development of brief questionnaires as well as the collection of data via semi-structured and structured interviews. This research is part of a broader program to create a strategic framework focusing on the main priority challenges. Adopting design strategies centred on sustainability is essential to meet future demand for sustainable products while maintaining customization flexibility (Mesa et al., 2020). The objective of this research program is to facilitate the development of sustainable products while controlling complexity. The remainder of this article comprises the following sections: 2. Literature review,

3. Methodology, 4. Results, 5. Discussion of the results, and 6. Conclusion.

2. LITERATURE REVIEW

This section first examines interventions associated with the development of complex products (2.1), then discusses those devoted explicitly to high-variety products (2.2), and finally, catalogues 16 challenges documented in the literature (2.3). These interventions refer to any method, technique, or mechanism implemented to handle the growing complexity of the product design process.

2.1 Interventions for Complex Product Development

Model-Based Systems Engineering (MBSE) centralizes information in standard models, facilitating design, validation, and traceability of requirements. These models can be structured following the RFLP framework (Requirements, Functions, Logic, Physical) (Biahmou, 2015). The Set-Based Design concept-development methodology, which enables the simultaneous exploration of multiple design alternatives, is thus more suitable for complex products (Shallcross et al., 2020). Lastly, composable design architecture and the reference architecture principle foster the reuse of concepts and components across different platforms, boosting product similarity while expediting the development of product lines (Oster et al., 2016).

2.2 Interventions for High-Variety Product Development

Interventions for designing products in a high-variety context primarily involve developing a modular product architecture that facilitates grouping functions and interfaces to manage complexity (Algeddawy, 2014; Rincon-Guevara et al., 2020). Modular partitioning breaks down the product into reusable modules, allowing multiple combinations to address the broad range of consumer requirements (Magnusson and Pasche, 2014). Incorporating sustainability-focused modular principles improves the reuse and recycling of components, thereby reducing the product's environmental impact (Hvam et al., 2017; Shaik et al., 2015). A product platform provides flexibility, effectiveness, and efficiency while accommodating a large product variety (Pakkanen et al., 2019). Other interventions—such as variety management, interface management, production strategy considerations, configuration, complexity management, and modularity metrics—must be integrated to effectively address mass personalization (Roy and Abdul-Nour, 2024).

2.3 Challenges of Developing Complex Products in High-Variety Contexts

A targeted review of significant publications on modular design and mass customization identified 16 challenges. The search was performed using the Scopus database, selecting articles on modular design in the manufacturing domain for mass customization or personalization. These challenges are as follows:

1. *Frequent changes in requirements:* Rapid market and technological shifts often render initial requirements obsolete, leading to costs and delays associated with redesigns (Vierlboeck and Nilchiani, 2021).

2. *Inadequate requirements management tools:* Current tools do not precisely meet the complex needs of modular design (Pakkanen et al., 2020).

3. *Difficulty balancing constraints:* Challenges arise in optimizing personalization, costs, performance, and technical constraints (Qiu et al., 2022; Vierlboeck and Nilchiani, 2021).

4. *Increased complexity due to advanced technologies:* Integrating advanced technologies requires specialized skills and tools (Qiu et al., 2022).

5. *Organizational challenges:* Internal difficulties intensify due to the growing complexity of products (Bouchard et al., 2023).

6. *Difficult integration into the process:* Complexity is complex to integrate effectively into development processes (Vierlboeck and Nilchiani, 2021).

7. *Restricted development times:* High complexity extends lead times and diminishes market responsiveness (Qiu et al., 2022).

8. *Delayed benefits of product platforms:* The benefits of modular platforms are often deferred and uncertain (Anggraeni et al., 2013; Magnusson and Pasche, 2014; Pakkanen et al., 2019).

9. *Lack of qualified personnel in modular design:* A limited number of specialists in modular design (Pakkanen et al., 2019).

10. *Difficulty achieving cross-functional alignment:* Complex design decisions arise from conflicting internal priorities (Magnusson and Pasche, 2014; Rincon-Guevara et al., 2020).

11. *Knowledge transfer challenges in modular design:* Documentation and dissemination of modular expertise are problematic (Lu et al., 2022; Pakkanen et al., 2019).

12. *Lack of maintaining processes for modular design:* There are no ongoing processes for preserving modular design (Pakkanen et al., 2019).

13. *Extensive information management:* The wide variety of products requires handling vast amounts of information (Peng et al., 2011).

14. *Lack of guidance in tool selection:* There is a lack of direction for choosing suitable tools (Pakkanen et al., 2019).

15. *Multitude of tools without a unified framework:* The literature identifies a lack of a unified framework and a precise sequence for implementing available tools (Bouchard et al., 2023; Roy and Abdul-Nour, 2024).

16. *Lack of leadership, vision, and governance:* Insufficient governance undermines strategic effectiveness and the consistent evolution of modular products (Anggraeni et al., 2013; Jiao and Tseng, 2000; Pakkanen et al., 2019).

Although the literature highlights several interventions, none prioritize or synthesize these 16 challenges. Each challenge was analyzed in this study, and their association with a group

of challenges is presented in the analysis. This mapping aligns theoretical and empirical findings on designing modular product platforms, which serve as a crucial lever for developing more sustainable products in a high-variety context.

3. METHODOLOGY

3.1 Overall methodological approach

To meet the main objective, semi-structured interviews were first conducted to assemble a broader list of challenges, which were grouped using thematic analysis. Then, structured interviews were held to prioritize these groups of challenges.

3.2 Company selection

Companies selected for this study had to meet five criteria: (1) an internal product development and design process, (2) complex product design, (3) undergoing a transition toward mass personalization, (4) some level of maturity in interventions, and (5) a multi-platform product line. This choice ensures diversity in complexity, organizational maturity, and customization strategies.

Potential manufacturing companies were identified through the researchers' network. The websites of these companies were reviewed to confirm the initial selection criteria. Once confirmed, companies were recruited via telephone call or video conference. The criteria were subsequently verified with company experts prior to conducting interviews.

3.3 Overview of selected companies

The three participating Quebec manufacturing firms are mid to large-sized (>175 employees, >50 M CAD), and each has a unique internal collaboration structure. Two of them operate multiple facilities worldwide and offer various product lines. All of the companies export a portion of their production internationally.

3.4 Participant selection

Ten experts were chosen based on four criteria: (1) a minimum of three years of service within the company, (2) an operational role without strategic responsibilities, (3) active involvement in product development, and (4) knowledge of modular product design. Special attention was paid to ensuring diversity in roles, experience, and educational backgrounds to capture various perspectives in the development process.

3.5 Identification and clarification of challenges

A short questionnaire was developed from the literature to clarify issues related to product development strategies tailored to flexible, sustainable modular product platform design. Two experts validated the questionnaire and then tested it in a pilot interview to refine the wording of the questions. The first two questions addressed specific documented challenges, while the third sought to uncover potential difficulties. Interviews took place either in person or by videoconference. In total, 94 challenges were identified. All 16 challenges initially identified in the literature were detected within these 94 expert-reported challenges.

Using a four-step inductive approach (preparation, close reading, categorization, refinement), these challenges were consolidated into 27 subcategories based on conceptual similarities. A second grouping was performed in keeping with thematic analysis guidelines, which recommend identifying between 3 and 9 themes (Blais and Martineau, 2006). Seven categories emerged from this process and were validated with the respondents. The analysis of results presents how the 16 literature-documented challenges correspond to each group. This alignment connects theoretical and empirical challenges related to modular platform design, regarded as an essential lever in developing more sustainable products in a high-variety context.

3.6 Structured interviews for challenge prioritization

A new structured questionnaire was derived from the results of the first questionnaire analysis to rank the main categories. The procedures from the first questionnaire were repeated regarding the validation process, the interview approach with the same 10 participants, and the documentation of responses. The structured interviews contained a single question to rank the seven categories of challenges from 1 (highest priority) to 7 (lowest priority) based on their importance within each participant's company. The rankings were compiled, and each company's average was calculated to determine the main categories' relative importance. The average category rankings yielded an overall mean ranking.

4. RESULTS

This section presents the outcomes of the seven main categories and the prioritization results for the three companies.

4.1 Identification and Clarification of Challenges

1. Difficult project management: The variety of products spread across multiple platforms significantly increases complexity and the volume of information to manage. The large amount of information complicates team coordination and project planning. Multiple platforms with frequent deliverables further intensify management complexity.

2. Organizational structure: Sometimes, the company focuses on optimizing individual projects rather than adopting a unified approach across the entire range of product platforms. A siloed organization complicates the management of complexity tied to information and modular design, limits cross-functional knowledge sharing, and hinders the development of a shared vision.

3. Leadership, vision, and strategy: Reducing a company's overall complexity without clear leadership, vision, and strategies remains challenging. Divergent cross-functional visions make it even more difficult. A lack of long-term planning leads to uneven and scattered complexity-reduction efforts.

4. Stakeholders and skills: A large number of stakeholders slows and complicates decision-making processes. Sophisticated tools require highly qualified personnel, notably for their successful implementation. Knowledge transfer in

modular design among the various actors involved remains complicated.

5. Tools and integration into the process: Companies struggle to handle the complexity of modular products and wide variety without suitable tools. Integrating new tools and methods into an iterative and sometimes vague development pipeline is complex. Ensuring enterprise-wide adherence to modular design also poses difficulties, which become even more pronounced when the benefits of each function are not clearly demonstrated.

6. Collaboration in the context of massive information flows: Large volumes of data create hurdles for collaboration, transfer, and sharing. These large information flows raise the risk of information overload. Manual analysis becomes increasingly ill-suited for these expanding data sets. Adjusting the amount and frequency of data exchange is a significant challenge. Differing understandings among stakeholders further complicate alignment and collaboration, amplifying the existing workload.

7. Development time and responsiveness in a rapidly evolving market: Effectively responding to global demand is complex. Growing complexity and variety lengthen development lead times while competition demands faster cycles. A more responsive market drives further changes in requirements during projects. Companies find it challenging to design product platforms that can quickly adapt while simultaneously managing cost increases associated with complexity.

4.2 Literature-based identification of challenges

Table 1 below provides a matrix linking the 16 challenges identified in the literature to the seven categories of challenges. It illustrates the overlaps among categories.

4.3 Prioritization of Challenges

Table 2 presents how the three companies (A, B, C) prioritized the main categories.

5. ANALYSIS

This section analyzes the results regarding the challenges discussed in the literature and examines their practical and theoretical implications.

5.1 Analysis of the prioritization

The associations show that Category (5), Tools and Integration into the Process, encompasses the most considerable literature-documented challenges, which could explain why it ranks essential. The interviewed companies acknowledge that product development complexity cannot be reduced without appropriate tools and methodologies. However, tools and processes alone are insufficient. Without suitable vision, leadership, and strategy, the benefits of a

The associations show that Category (5), Tools and integration into the process, encompasses the largest number of literature-documented challenges, which could explain why it ranks high in importance. The interviewed companies acknowledge that product development complexity cannot be reduced without appropriate tools and methodologies. However, tools and

processes alone are insufficient. Without suitable vision, leadership, and strategy, the benefits of a modular platform design strategy remain limited. Several respondents also pointed out that organizational improvements (2) need to coevolve with establishing a unified vision (3) to avoid limiting initiatives to a single department. Without a commitment to simultaneously addressing challenge groups 2,

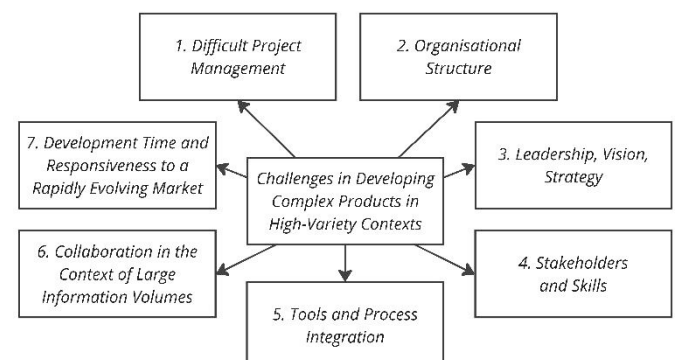
Table 1. Summary of how the 16 literature-documented challenges map onto the seven main categories of challenges

	1. Difficult Project Management	2. Organisational Structure	3. Leadership, Vision, Strategy	4. Stakeholders and Skills	5. Tools and Process Integration	6. Collaboration in the Context of Large Information Volumes	7. Development Time and Responsiveness to a Rapidly Evolving Market
1. Frequent changes in requirements							☑
2. Inadequate requirement management tools					☑		
3. Difficulty balancing constraints						☑	
4. Increased complexity (advanced technologies)							☑
5. Organizational challenges	☑	☑	☑				
6. Difficulty integrating into the process					☑		
7. Restricted development timelines							☑
8. Delayed benefits from platforms					☑		
9. Lack of qualified personnel				☑			
10. Difficulty achieving interfunctional alignment			☑				
11. Knowledge transfer difficulties				☑			
12. Lack of processes for design maintenance					☑		
13. Large amounts of information to manage						☑	
14. Absence of guidelines for tool selection					☑		
15. Multiplicity of tools without a unified framework					☑		
16. Lack of leadership, vision, and governance			☑				

Table 2. Summary of Prioritized Challenge Categories

Main Categories	A	B	C	Mean Rank
1. Difficult Project Management	6	5	4	5.0
2. Organizational Structure	4	2	6	4.0
3. Leadership, Vision, Strategy	1	1	7	3.0
4. Stakeholders and Skills	7	3	5	5.0
5. Tools and Process Integration	2	4	2	2.7
6. Collaboration in the Context of Large Information Volumes	3	6	3	4.0
7. Development Time and Responsiveness to a Rapidly Evolving Market	5	7	1	4.3

Figure 1 provides a summary of the seven groups of challenges.



3, and 5, tools and processes risk becoming confined to only one company function. modular platform design strategy remains limited. Several respondents also pointed out that organizational improvements (2) must involve establishing a unified vision (3) to avoid limiting initiatives to a single department. Tools and processes risk becoming confined to only one company function without a commitment to simultaneously addressing challenge groups 2, 3, and 5. Once the tools (5), vision (2), and organizational structure (3) are in place, prompt information sharing to align the various functions' visions becomes essential. Collaboration in massive information flows (6) is crucial for implementing the established vision and strategy. Development times increase without rapid and effective information exchange, undermining a company's responsiveness.

The categories of complex project management (1) and stakeholders and skills (4), which the companies ranked relatively low, gain prominence once a modular platform design process has been successfully implemented. These two groups of challenges are less pressing initially and focus more on the long-term maintenance phase.

5.2 Differences among companies

The results show that Companies B and C—more mature in modular design—prioritize stakeholders and skills more (4). These firms thus aim to maintain and evolve their existing platforms. Company C distinguishes itself through a dedicated internal team that identifies platform opportunities and reflects a proactive vision at the management level. In contrast, being smaller and less segmented, Company B deems collaboration challenges (6) less critical, likely owing to more straightforward internal communication. Regarding market responsiveness (7), Company B, facing fewer competitive pressures, views this as less urgent, whereas Company C, competing in a very intense market, considers it a top priority. Lastly, project management (1) garners little emphasis across all companies, suggesting that these firms believe they are sufficiently managing this aspect or see it as less urgent than other listed challenges.

Discrepancies in challenge prioritization among the three companies may reflect several factors, including organizational size. Larger firms may be compartmentalized, creating separate departments and potential communication gaps or a misaligned shared vision resulting from an inadequate organizational structure. In some companies, limited resources available for improving design methods can give higher priority to tools and processes. A company focusing on maintaining its modular product platforms would naturally place greater emphasis on challenges related to the upkeep of these product platforms.

Finally, Category 7 (Development time and responsiveness) mainly reflects the market's external pressures. Some participants believe internal issues (categories 1–6) must be stabilized first to address market forces effectively. Others see external constraints as the initial priority, necessitating an early alignment of company strategy. Some companies prioritize external concerns, while others first focus on internal aspects.

5.3 Development of sustainable modular platforms

Transitioning toward sustainable modular platforms requires profound strategic and operational transformations that enable mass personalization while minimizing ecological impact. Without adequate support, companies risk missed economic opportunities, technical inconsistencies, and minimal improvement in products' environmental effects. Hence, fully leveraging the modular platform concept entails orchestrating leadership and organizational aspects, tools, skills, and close collaboration. Given these findings, managing sustainable modular product platforms demands substantial, simultaneous changes at multiple organizational levels.

5.4 Discussion

In conclusion, companies must recognize that investing in solutions for only one group of challenges will not yield a competitive product development strategy. While tools and processes are necessary, they will not suffice without transforming leadership, strategic vision, and organizational structure. A holistic, systemic approach is essential to surmount the challenges of developing high-variety complex products and to remain competitive in the market. These observations align with other studies (Bouchard et al., 2023; Pakkanen et al., 2019).

By framing these challenges from a broad perspective, the seven groups can serve as a practical diagnostic framework to guide managers in prioritizing efforts according to their company's strengths and maturity level. This exploratory study has limitations concerning generalizing the results. A larger-scale investigation involving more companies and participants could outline specific paths for certain challenge categories, depending on company-specific factors. Such prioritization, reflecting a company's current situation, might be used to develop an implementation sequence in future research.

6. CONCLUSIONS

This article outlines seven key challenge categories that must be addressed concurrently when implementing modular platform strategies. Future research could propose an integrated approach to solutions for these seven categories of challenges and for existing interventions in the literature. Additional studies could also identify, integrate, or develop interventions tailored to sustainable development in complex modular product platform design.

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