Comparative Analysis of Variability Management in Product Line Engineering across Industries

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1 Introduction

As modern systems grow in complexity and variety, effective variability management becomes increasingly critical across industries such as automotive, aerospace, defense, and software. Product Line Engineering (PLE), particularly when combined with model-based approaches (MBPLE), offers a powerful framework for managing these variations. However, each industry has its unique challenges and specificities that influence how variability is modeled, managed, and implemented. This research presents a comparative study of PLE applications in automotive, aerospace, and defense sectors, focusing on identifying key variability management practices, processes, methods, and tools employed in each context.

2 Methods

A Systematic Literature Review (SLR) conducted as part of this research has identified several challenges of PLE methodologies when applied to Systems Engineering (SE) (Lameh et al., s. d.). The SLR was conducted following the PRISMA guidelines (Page et al., 2021) to synthesize scientific data relevant to PLE and SE. The method involved a structured, two-stage selection process, which included initial screening and a comprehensive full-text review, resulting in the final inclusion of 62 articles (out of 4866) that meet specific criteria related to PLE from an SE perspective. The results were organized along three main axes: PLE methodology, modeling variability and feature models, and lessons from PLE applications, allowing for a detailed analysis of the selected literature.

3 Results

The findings from the SLR highlight industry-specific practices, key variability management tools, and unique challenges each sector faces. This analysis emphasizes the importance of tailoring PLE approaches to meet the diverse needs of each domain. **In the automotive industry,** managing variability is crucial due to market demands' large variety. The concept of partial configuration (known as 120% configuration in the industries) becomes essential to manage this complexity. This approach allows manufacturers to define a comprehensive set of features and components that can be tailored and customized for individual customer needs, while still maintaining control over the product's core architecture. Given the wide range of vehicle types, such as sports cars, electric daily-use vehicles, and specialized trip vehicles like camping cars, the need for client personalization becomes more significant. Each vehicle type demands a unique set of functionalities and features. For instance, sports cars prioritize performance and aerodynamics, while electric cars focus on energy efficiency and sustainability. Camping cars, on the other hand, require interior flexibility and durable designs suitable for long trips. Additionally, the need for customization isn't limited to aesthetic choices but extends to functional elements like software integration, safety features, and compliance with regulations such as crash tests. As clients continue to demand vehicles tailored to their preferences and usage scenarios, the industry faces the challenge of scaling mass production while maintaining the flexibility to offer a personalized driving experience. Effective variability management across this landscape ensures that manufacturers can meet regulatory requirements, manage supplier complexities, and offer highly customized products to a diverse client base, all while ensuring production efficiency and quality. In contrast, **the aerospace industry** places a significant emphasis on the long lifecycle of its products, as well as the certification required by regulatory bodies such as the FAA and EASA. System integration, particularly the integration of avionics systems, poses a unique challenge in terms of variability management. Custom configurations are often necessary to meet specific customer and mission requirements, necessitating robust models that can handle the complexity of these interactions. **The defense industry** faces variability management challenges unique to its mission-critical nature. Security, confidentiality, and fault tolerance are paramount, and systems must ensure interoperability with both legacy systems and those used by allied forces. Military standards impose strict constraints on the development and configuration of systems, further complicating variability management. Product lines in the defense sector typically involve low-volume production with highly customized features. **Software products** (i.e. web and mobile applications, tools) industry represents the dominant sector for PLE, with nearly 70% of PLE applications focused on software systems. This is largely due to the unique characteristics of software development, such as the need for rapid development cycles driven by agile and iterative methodologies. Software products inherently possess high variability, with different platforms, configurations, and user requirements that need to be managed efficiently during continuous delivery and regular. Scalable software architectures play a crucial role in enabling PLE by allowing easy adaptation and evolution of systems without significant overhead. Moreover, software enjoys relatively low production costs, especially when compared to hardware, making it easier and more cost-effective to implement and manage variability at scale. This combination of factors makes software PLE the most prevalent, reflecting its flexibility, efficiency, and capacity for constant evolution.

Although methods such as modeling (e.g., Feature-Oriented Domain Analysis FODA, Feature Models) and tools (e.g., pure::variants, Gears) are widely shared across the sectors, their concrete implementation is influenced by the specific priorities of each sector. The specificities of the variability sources in each sector will influence PLE process and impact feature modelling. The main key specificities, along with their relevant references, are presented and summarized in the following table.

Table 1: Key Specificities of PLE per industry

Industry	Key Specificities	Key References
Automobile	- Extremely large product set and complex product. - Multistage configuration and partial (120%) configurations need. - High product variation for markets and product personalization and market (Business2Business and Business2Customers markets) - Mass production scalability for personal vehicles and customization for utility vehicle. - A mega-scale PLE, with several platforms (different types of vehicles). - Consistent variation management in artifacts across the full engineering lifecycle. - Complex system integration and diverging scopes and life cycles. - Supplier and partners network complexity and relationship with manufacturer, unlike the stability seen in the aeronautics industry. - Strict safety regulations. - Organizational structures complexity.	(Bilic et al., 2018; Hanselmann, 2008; Reiser, 2008; Shaker, 2010; Wozniak & Clements, 2015)
Aeronautic	- Complex, long certification process (FAA, EASA). - Long lifecycle of products. - Complex system integration (e.g., avionics) and less variability due to technical constraints (e.g. weight & fuel efficiency optimization.) - Custom configurations but limited number of clients (compared to automobile).	(Forlingieri, 2022; Gaeta & Czarnecki, 2015; Milford & Pena, 2014)
Defense	- High security & confidentiality. - Mission-critical systems, high fault tolerance. - Interoperability with allied forces & legacy systems. - Compliance with military standards (MIL-STD). - Low-volume, custom production.	(Clements & Northrop, 2002; Young et al., 2017; Young & Clements, 2017)
Software Products (Apps & Tools)	- Rapid development cycles (agile, iterative). - High variability (platforms, configurations). - Continuous delivery & updates. - Scalable software architectures and almost no hardware integration. - Low production costs, less regulations, and risks.	(Birk et al., 2003; Clements & Northrop, 2002; Marciniak, 2002; Metzger & Pohl, 2014; Yoshimura et al., 2008)

4 Discussion and Conclusion

The results suggest that while PLE can be universally applied across industries, it must be tailored to address the specific challenges of each domain. Future research should explore the development of more advanced tools for managing variability, especially as industries like automotive push the boundaries of PLE with features such as concurrent development and distributed engineering. Additionally, industrial practices could benefit from experience in each industry. Lessons learned from the defense industry's stringent security requirements, for instance, could inform the development of more secure automotive systems, while the aerospace sector's approaches to long-term lifecycle management could inspire more sustainable practices in other fields. This study contributes to a deeper understanding of how PLE can be effectively applied across industries, offering a roadmap for improving variability management and system scalability in each sector.

References

Due to space constraints, we have cited only one reference that encompasses all the relevant works on this topic and include the cited articles.

Lameh, J., Dubray, A., & Jankovic, M. (s. d.). A Systematic Literature Review on Product Line Engineering Approaches in Systems Engineering : From Models to Applications (in press). *submitted to INCOSE Systems Engineering Journal (October 2024)*.