

Two Sides of One Coin: Aligning Configuration System with Product Architecture for ETO Products

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Abstract: In Engineering-to-Order (ETO) industries, configuration system and product architecture must be closely aligned to support efficient customization, as both the digital model and the design model describe the same product. However, in practice, there may be misalignments between these two domains. Using the Multiple-Domain Matrix (MDM) framework, the study captures internal interfaces within product architecture and configuration system, as well as cross-domain relationships between them. The framework was applied in a modular construction company as a case study and demonstrates the practical value of MDM for diagnosing alignment issues and supporting more consistent development of product architecture and configuration system. While the findings are based on a single case, this study offers practical insights and sets a foundation for future research, particularly in ETO companies with complex configuration systems.

Keywords: Product Architecture, Configuration System, Alignment, ETO, MDM

1 Introduction

To address the growing challenge of delivering customized products without compromising on time, cost, or quality, many companies have adopted the mass customization strategy (Hvam et al., 2008; Pine, 1993). This strategy is often described as the ability to provide tailored products through flexible processes and organizational structures while maintaining the low costs associated with standardized mass production (Hart, 1995). One effective approach to achieving mass customization is the development of modular product architectures, which reduces internal complexity while preserving external variety to meet diverse market demands (Huang et al., 2005; Meyer and Lehnerd, 1997). Another critical factor is technology, such as configuration system, which serves as an important toolkit to realize the mass customization strategy (Da Silveira et al., 2001; Tseng et al., 2017).

In the Engineer-to-Order (ETO) industry, characterized by complex designs tailored to unique customer requirements, configuration systems are widely adopted (Hvam et al., 2008; Rudberg and Wikner, 2004). The literature documents several configuration systems implemented by ETO companies and highlights their potential to streamline sales and engineering processes and deliver various benefits (Haug et al., 2019, 2011; Hvam, 2006; Kristjansdottir et al., 2015). However, the technical realization of ETO configuration systems is both demanding and complex, and ETO products often consist of multiple sub-products that interact with each other, making it difficult to implement traditional single configurators (Blecker et al., 2004; Christensen and Ditlev Brunoe, 2017).

Multiple configurators in ETO configuration system, similar to the multiple modules in ETO product architecture, must be aligned because both the digital model and the design model are intended to describe the same product. This study aims to address this research gap by exploring how to analyze the alignment between configuration system and product architecture in ETO products. Just as modules in the product architecture must be structured and integrated into a coherent system, configurators in the configuration system must also be organized accordingly. With many modules and many configurators involved, understanding their alignment and analyzing their interactions presents a significant challenge. To support this analysis, we apply the MDM framework, which can capture both internal interfaces within product architecture and configuration system, and cross-domain relationships between them.

The paper is structured as follows: Section 2 reviews related literature. Section 3 describes the MDM framework. Section 4 states the research methodology. Section 5 presents a case study. Section 6 discusses the results and outlines future work. Section 7 concludes the study.

2 Literature Review

2.1 Product Architecture and Configuration System in ETO

ETO companies are responsible for designing, manufacturing, installing, and commissioning complex systems tailored to highly specialized customer requirements (Caron and Fiore, 1995). Unlike the automotive and electronics sectors, which are characterized as the high-volume sector, ETO products belong to the low-volume sector, with examples including oil platforms and power plants (Hicks et al., 2000). Based on the position of the customer order decoupling point in value-added material flow, ETO companies usually require a considerable amount of work in design and specification to fulfill customer requirements (Hvam et al., 2008; Rudberg and Wikner, 2004). In the ETO industry, increasing competitive pressure has pushed ETO companies to seek new ways to reduce costs and manage technical complexity (Large plant

manufacturers group (VDMA), 2014). One effective approach is the adoption of standardization, modularization, and platform concepts in ETO product development. Rather than relying on fully customized solutions for each project, companies are shifting toward solution approaches based on the reuse of predesigned and validated standard modules (Gepp et al., 2016). This strategy is closely related to the concept of product architecture, which defines the structure, functions, and interfaces of a product, essentially serving as a blueprint for product development (Ulrich and Eppinger, 2016). An ideal product architecture breaks down the product into practical and reusable modules. Well-designed modules can be easily updated, removed for maintenance, or replaced to add new functionality. Furthermore, modules can be designed across multiple levels to offer a wide range of product variations while managing complexity (Huang et al., 2005).

To fully leverage the benefits of modular product architecture, companies often implement configuration systems, which are typically software-based expert systems that support users in creating product specifications (Haug, 2008). At the same time, a well-defined modular product architecture is also a prerequisite for the effective development and use of configuration system (Hvam et al., 2008). In the ETO industry, the benefits of using configuration systems are well documented (Haug et al., 2019, 2011; Hvam, 2006; Kristjansdottir et al., 2015). Configuration systems can include several configurators, for example, sales and technical configurators, as well as configurators operating at different levels of abstraction (Forza and Salvador, 2006; Petersen, 2007). Several examples of ETO configuration systems from the past ten years are presented in Table 1. These articles cover a range of application areas, including construction, energy, machinery and plant industries. They highlight some observed benefits, explain how configurators can be developed or structured, and discuss challenges encountered in practice. A common theme across these studies is that different configurators are often applied to particular project phases or specific product levels.

Table 1. Example of ETO companies using several configurators

Article	Application
(Cao et al., 2021)	Apartment buildings
(Ghosh et al., 2019)	Chemical process plants
(Christensen, 2019)	Wind turbines
(Kristjansdottir et al., 2017)	Catalyst plants
(Kristianto et al., 2015)	Ship engines

2.2 DSM and MDM

Design structure matrix (DSM) is a matrix-based tool used to represent and analyze the structure of complex systems by capturing the relationships between system elements, and it enables visualization of dependencies and supports system decomposition, modularization, and sequencing of tasks or components (Eppinger and Browning, 2016). DSM has been widely applied in product development, project planning, project management, systems engineering, and organization design (Browning, 2001). Over the years, DSM has been extended through clustering algorithms, iteration modeling, and integration with optimization methods (Browning, 2016). While DSM is effective for modelling within a single domain, it has limitations when analyzing systems that cross multiple domains. This led to the development of Multiple-Domain Matrix (MDM) (Lindemann and Maurer, 2007). MDM builds on the DSM concept by integrating several DSMs into a single framework, using Domain Mapping Matrices (DMMs) to represent relationships between different sets of items across domains. MDM provides a more holistic view of complex systems by showing how domains interact, rather than analyzing them in isolation.

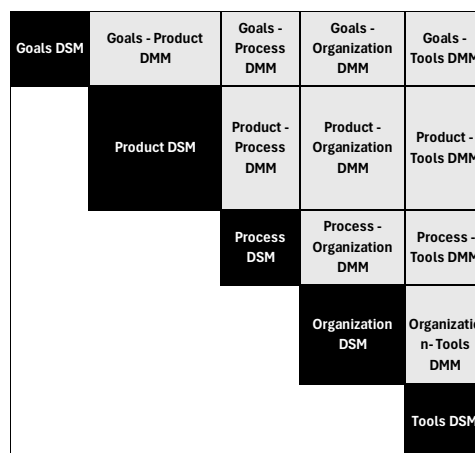


Figure 1. "Periodic table" of DSMs and DMMs, forming an MDM (adapted from (Danilovic and Browning, 2007)).

2.3 Research Gap

Although configuration system is closely linked to product architecture as it is a prerequisite for effective development and implementation, and many researchers have addressed the challenges of handling complex ETO product architectures to support configuration systems, there is still a lack of studies focusing on the alignment between ETO product architecture and configuration system and how to analyze and visualize the alignment.

Technically, misalignment should not occur. However, based on our observations across various configuration projects in the ETO industry, such misalignments are common. A recurring cause is the organizational separation between the teams responsible for product architecture development (typically engineering-driven) and those developing configuration models (typically IT-driven). These teams often operate with different languages, tools, and objectives. As a result, misalignments emerge not due to technical limitations, but due to a lack of coordination and shared understanding.

In reviewing the literature, we found numerous studies on using DSM for analyzing product architecture, but none on using MDM to analyze product architecture and configuration system together. Based on this gap, we chose to apply the MDM framework to provide a structured method for analyzing and visualizing both the internal interfaces within ETO product architectures and configuration systems, as well as the cross-domain relationships between them.

3 MDM Framework

Figure 2 illustrates the central idea of this paper: product architecture and configuration system are fundamentally interlinked in ETO products since the design model in product architecture and the digital model in configuration system are intended to describe the same product. They are two sides of the same coin, and the edge of the coin represents their alignment. The proposed framework is structured as an MDM below the coin, which consists of three matrices:

Product architecture (PA) DSM captures the interfaces between modules within the product architecture.

Configuration system (CS) DSM captures the relations between configurators, specifically the logical constraints that govern interactions between them.

PA-CS DMM links modules and configurators, identifying which configurators are responsible for which modules.

A key proposition is that the interfaces among modules defined in the PA DSM should be reflected in the relations among configurators in the CS DSM. Misalignment between these two can result in inconsistent and incompatible configuration processes.

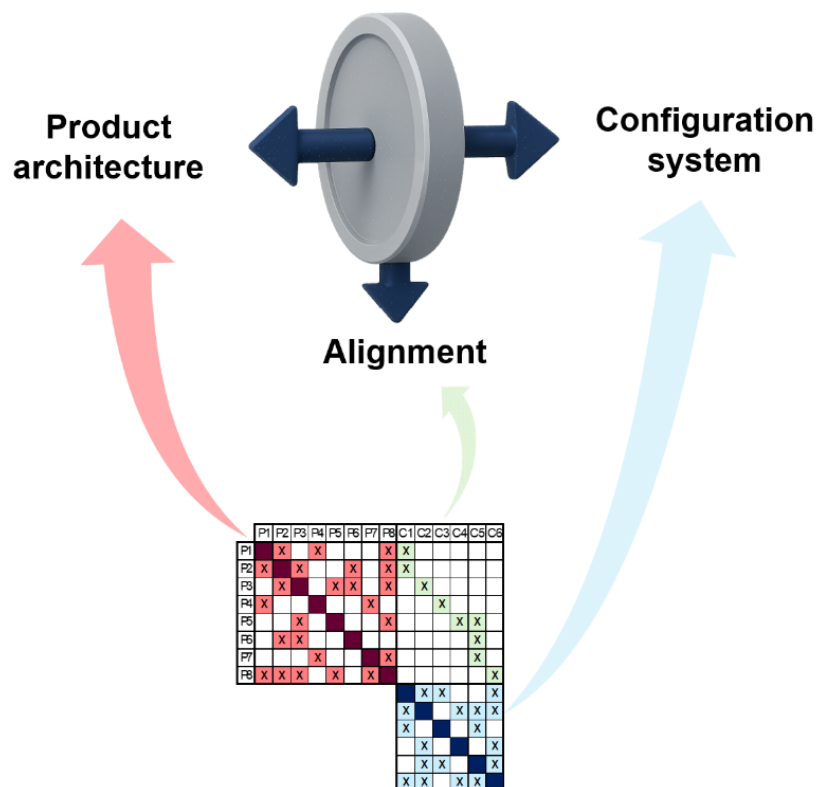


Figure 2. Two sides of one coin: the alignment between product architecture and configuration system by MDM.

This framework can be applied in different scenarios. One possible application is prior to the implementation of configuration system. In this context, ETO companies can first analyze their product architecture using the PA DSM to gain insights into potential configuration system structures. For instance, the analysis can support decisions such as whether to implement a single configurator or multiple configurators. If multiple configurators are required, CS DSM enables a structured analysis of the interfaces between configurators and how these can be effectively managed.

A hypothetical example could be an ETO company that designs and manufactures beverage filling lines, comprising multiple types of machines. Each machine is customizable to meet specific customer requirements, and these machines must operate together to complete the overall filling process. From a product architecture perspective, each machine can be viewed as a module within the overall system. These modules have interfaces; for example, all machines must operate at a synchronized transport speed to ensure an uninterrupted flow of bottles. Due to the complexity of the overall system, it may not be feasible to include all machines within a single configurator. As a result, the company may decide to develop separate configurators for different machines or functional groups. In this case, the MDM framework can be applied to support the alignment between the product architecture and the configuration system, helping to identify what information or constraints must be shared to ensure configuration consistency and system compatibility across the entire filling line.

The framework is also applicable in situations where a configuration system is already in use. Here, companies can apply the MDM to assess the alignment between the existing product architecture and the configuration system. Specifically, the framework allows for verification that the interfaces between modules in the architecture are correctly mirrored by the relations between configurators.

Returning to the previous example, suppose the company introduces an upgraded module that increases the number of interfaces with other modules. By using this framework, the company can systematically analyze which relations between configurators need to be revised and identify which configurators are affected. This ensures that the configuration system remains aligned with the evolving product architecture.

4 Research Methodology

The framework was initially inspired by DSM literature on product architecture, as DSM has been widely used to study interfaces and has been successfully applied in various cases (Eppinger and Browning, 2016). Additionally, research on DSM applications in software and IT systems (Lagerström et al., 2014) inspired the use of DSM to model configurators. By combining these two, we decided to use the MDM framework to analyze the alignment between product architecture and configuration system.

This study adopts a case study methodology as it allows for the study of a phenomenon in its natural setting and a fuller understanding of the nature and complexity of the phenomenon (Voss et al., 2002). A single case study was used because it enables in-depth observation of phenomena in exploratory investigations and provides an opportunity to access multiple contexts within the case (Barratt et al., 2011). The selected case company has implemented a building system concept composed of different modules, where each module includes several customizable submodules. A building system is a coordinated set of prefabricated components or modules designed to work together structurally and functionally as part of a larger construction framework. It standardizes elements to improve design efficiency, production, and on-site assembly (Gibb, 1999). To support the design process, the company utilizes a set of configurators that enable the configuration of individual modules or submodules based on specific project requirements. The company designs and develops buildings on a project-by-project basis, and the construction sector aligns well with the characteristics of the ETO industry. With a mature product architecture and a well-established configuration system, this case company serves as a strong case for this study.

Data for this study was collected from multiple sources, including internal documentation and previous knowledge gained by one of the authors through several previous projects conducted with the company. In addition, we conducted in-depth semi-structured meetings with the CEO and engineers to understand the product architecture, and with the system manager to gain insights into the configuration system used in the company. This data and information were used to build the final MDM model, and it was reviewed by the case company. Results, feedback and discussions of interviews are documented in the following sections.

5 Case Study

5.1 Case Content

The case company is a construction company from Sweden, and this company is able to fully integrate automation and modularization into its design and construction processes. This helped them control product quality, reduce variation, and improve efficiency. A key strength of the company is its early focus on digital tools, including configuration system. Unlike most traditional construction companies, it brings together many areas of expertise under one roof, which includes

architecture, engineering, electrical, ventilation, and plumbing. This allows for better coordination and standardization. The company is part of a larger group that manages most of the construction value chain, from choosing building sites to producing modules off-site and assembling them on-site. Most work is done in-house, with only a few services like acoustics and fire safety outsourced.

5.2 Product Architecture

The case company’s building system concept can be considered as modular product architecture, which divides buildings into distinct modules that can be customized for individual projects. Key modules include the roof, balcony, foundation, façade, and building volume, each made up of several submodules. For instance, the foundation module includes submodules such as the base wall, foundation assembly, foundation frame, and hammock. Figure 3 shows the product architecture using both 2D and 3D visualizations. The building volume is the most complex module in the product architecture, consisting of up to twelve submodules, some of which are optional while others are required. Different combinations of the optional submodules result in six distinct volume types. In the product architecture, the building volume is represented as a single module rather than being split into six separate volume types. This approach avoids duplication in the representation of shared submodules. As a result, the building volume module includes all submodules necessary to configure any of the six volume types. Merging the six types into one module provides a clearer and more consolidated view of the building volume within the product architecture. There are 21 submodules in total and each submodule has defined interfaces with other submodules, such as mechanical, electrical, heating, water, etc.

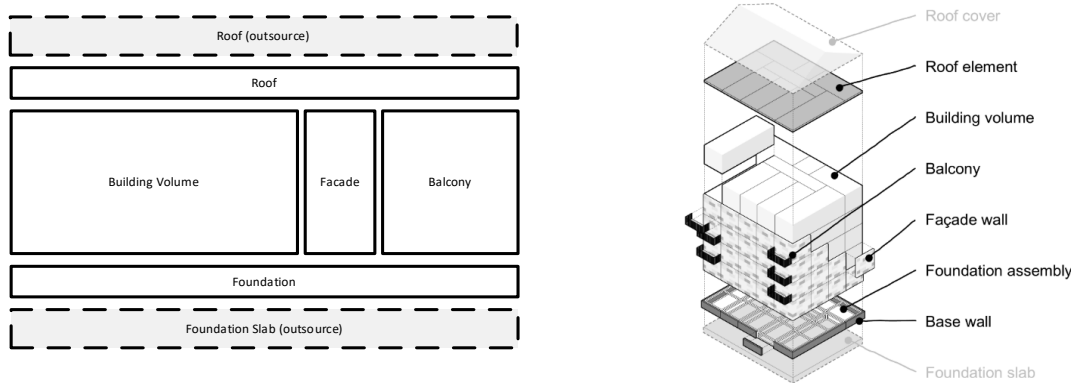


Figure 3. 2D and 3D visualizations of product architecture from the case company (Adapted from internal documents)

5.3 Configuration System

The company's design process is divided into three stages. Stage 1 involves concept design, where architects use 3D tools to create early designs and visualizations while working within the scope of the product architecture. Stage 2 begins with design validation to ensure compliance with the defined product architecture. This is followed by the detailed design of electrical, ventilation, and plumbing systems. The final step in this stage is exporting design data into spreadsheets that serve as inputs for the configuration system. Stage 3 involves the use of the configuration system, which automatically generates detailed 2D drawings, 3D CAD models, bills of materials, and other production documents. These outputs support off-site manufacturing.

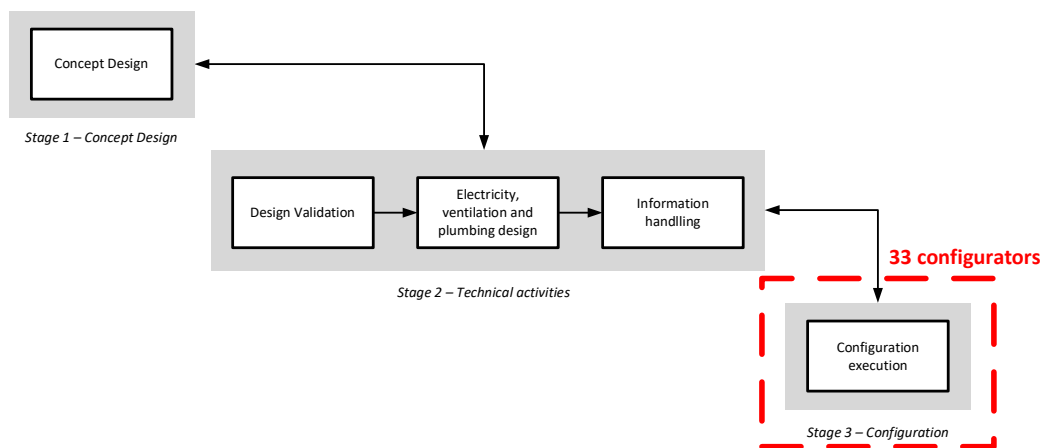


Figure 4. The company’s design process (Adapted from (Gay, 2024))

The configuration system comprises 33 configurators, and each module or submodule of the product architecture is configured individually in one configurator. Furthermore, complex modules will have multiple specialized configurators. For instance, five configurators are dedicated to handling the roof, balcony assembly, assembly tension, terrace, and foundation. These configurators operate independently and do not directly interact with one another. Constraints within each configurator are managed internally, while constraints between configurators are addressed in earlier steps. At the end of the configuration stage, the system generates detailed 3D and 2D CAD drawings, which are then delivered to the off-site manufacturing company to support production.

5.4 MDM Result

After collecting information from the case company, it became clear that the MDM could help analyze the company's product architecture and map relationships between product architecture and configuration system. Although there are no direct interactions between configurators, the digital model within the configuration system still mirrors the product architecture. Therefore, the company could still use MDM to analyze potential constraints that should exist between configurators based on the relationships identified in the product architecture. In conclusion, the MDM framework addresses three objectives:

- Visualization of constraints between modules and submodules using PA DSM.
- Mapping configurators to corresponding modules and submodules via PA-CS DMM.
- Identifying potential constraints between configurators, even though actual configurator interactions do not occur in practice. CS DSM can still be derived from the PA DSM and PA-CS DMM. This DSM helps visualize constraints that should be considered and managed by engineers during the configuration stage.

	Facade	Roof	Balcony	Foundation	Building volume	Accessories configurators	Stair case volumes configurators	Walls configurators	No shaft volume configurators	Grey water room configurator	Dry volume configurators	Water and heater volume configurator	Standard shaft configurator	Walls configurators	Foundation configurators	Balcony configurators	General roof configurators	Facade configurator	
Facade	Facade Wall Module																		
Roof	Roof Element Module																		
Balcony	Balcony Roof Module																		
	Balcony Assembly Module																		
	Balcony Foundation Module																		
Foundation	Base Wall Module																		
	Foundation Assembly Module																		
	Foundation Frame Module																		
	Hammock																		
Building volume	Outer Walls + Electric Module																		
	Triner Wall + Electric Module																		
	Water + Heater Shaft Module																		
	Ceiling Module																		
	Top Frame Module																		
	Grey Water + Dry Shaft Module																		
	Wet Room Module																		
	Connector Module																		
	Mechanical Module																		
	Interior Module																		
	Elevation Module																		
	Floor Module																		
	FW - Facade Wall (201000)																		
	RE - Roof Element (303001)																		
	BR - Balcony Roof (401001)																		
	BA - Balcony Assembly (401000)																		
	BA - Balcony Assembly Extension (401000)																		
	TR - Terrace Part (404000)																		
	BS - Foundation Balcony (406001)																		
	BW - Base Wall (103001)																		
	FA - Foundation Assembly (101001)																		
	FF - Foundation Frame (102001)																		
	HA - Hammock (105001)																		
	OWEL - Outer Wall + Electric (20300)																		
	IWEL - Inner Wall + Electric (204000)																		
	SW - Shaft Wall (205000)																		
	Ceiling_WH (206000 Water Heater)																		
	VA_WH (201000 Water heater)																		
	Ceiling_DV (206000 Dry Volume)																		
	VA_DV (201000 Dry Volume)																		
	Ceiling_SW (206000 Greywater)																		
	VA_GW (201000 Greywater)																		
	Ceiling_NS (206000 No Shafts)																		
	VA_NS (201000 No Shafts)																		
	Ceiling_UCA (206000 UCA)																		
	VA_UCP (201000 Undercentral A)																		
	Ceiling_SCA (206000 Staircase A)																		
	RE - Root Element Staircase A (30300)																		
	VA - SCA (201000+202001)																		
	Ceiling_StairCase B																		
	RE - Root Element Staircase B (30300)																		
	VA - Staircase B (201000+202001)																		
	PF - Passage Frame																		
	PW - Parapet Wall																		

Figure 5. The MDM result from the case company

Based on information from the product architecture, the PA DSM was constructed. In this DSM, only mechanical or physical interfaces between submodules are represented. The elements of the PA DSM are the submodules, grouped according to their respective module types, clearly showing the physical constraints within the product architecture. Next, information from the configuration system was used to create the PA-CS DMM. In the PA-CS DMM, columns represent individual configurators, while rows represent the submodules from the product architecture. This matrix illustrates the relationships between configurators and their associated submodules. Finally, the CS DSM was derived from the PA DSM and the PA-CS DMM. If physical constraints exist between submodules in the product architecture, these constraints are mirrored in the CS DSM, indicating constraints that engineers should consider during the configuration stage. The complete MDM is illustrated in Figure 5.

5.5 Findings

A key insight from the MDM analysis is that the company's product architecture and configuration system are not fully aligned. Firstly, certain modules or submodules in the product architecture correspond to multiple configurators. For instance, the building volume module is represented as a single generic module in the product architecture, whereas the configuration system includes multiple configurators for different variants of the building volume. Similarly, there are two distinct roof elements handled by two different configurators, but the product architecture only recognizes a single roof type.

Additionally, some configurators do not have clear counterparts in the product architecture. For example, passage frames are essential connections between building volumes, and they are explicitly configured but not clearly represented in the product architecture. Conversely, certain submodules identified in the product architecture lack corresponding configurators. Interior elements, for instance, are represented in the architecture but are intentionally excluded from the configuration system. This is because the case company prefers to manage interiors separately from the off-site manufacturing process.

Due to the independent operation of configurators within the configuration system, errors sometimes occur in projects. For example, 3D models generated by configurators could not match in dimensions for final assembly, and employees often need to manually correct errors by revisiting earlier steps, such as modifying CAD models or updating spreadsheets. In this context, the CS DSM derived from the MDM analysis could be valuable in the future if the company considers transitioning to a centralized configuration system where configurators actively communicate and coordinate with one another. Additionally, it is recommended that the current product architecture be refined into a more detailed version that explicitly represents different building volume types, thus improving alignment with the configuration system.

6 Discussion

The implementation of the MDM framework was relatively straightforward in this case, as the interfaces between modules and submodules were already well documented. The use of the MDM framework provided several benefits for the company. First, it allowed the company to easily visualize all interfaces in a structured way. Second, it helped to clearly show whether configurators were correctly linked to the appropriate modules or submodules. Third, it inspired the company to consider what needs to be addressed in the future, particularly when aiming to integrate configurators into a more connected system.

Although we could not fully validate the CS DSM because all configurators currently operate independently, this case study still highlights that there could be misalignments, despite the company's mature product architecture and well-developed configuration system. Misalignments were identified in several forms: when modules in the product architecture were overly general, when modules existed in either the architecture or the configuration system but not in both, or when physical interfaces in the product architecture were not properly reflected in the configuration system. These misalignments could negatively impact the efficiency and effectiveness of the company's overall business processes. By applying the MDM framework, the case company was able to clearly identify where these misalignments occur and gain insights into how they can be addressed and improved in the future.

Previous research emphasizes that a well-defined modular product architecture is crucial for effectively developing and utilizing configuration systems (Hvam et al., 2008), especially for ETO products. Therefore, ensuring alignment between product architecture (design model) and configuration system (digital model) is essential. While certain misalignments can be intentional and justified, unexplained discrepancies are problematic. This study contributes by employing the MDM framework, known for effectively analyzing relationships between items across multiple domains (Eppinger and Browning, 2016), to explicitly address and visualize these alignment issues. The presented MDM framework in this study allows companies to visualize and systematically analyze the alignment between product architectures and configuration systems. Applying this approach can offer practical insights into managing and maintaining consistency and integration across both domains. Furthermore, as many ETO companies begin transitioning toward Configure-to-Order (CTO)

strategies (Gepp et al., 2016), this framework can assist in planning and organizing a coherent configurator portfolio that aligns with modular product architecture, supporting modularization and reuse while maintaining configurator efficiency.

The study has limitations due to its reliance on a single case company, which might affect the generalizability of the findings. Additionally, the case company currently does not implement real-time interactions between configurators. Therefore, the CS DSM here only serves primarily as an illustrative inspiration rather than representing actual configurator interactions. Future research should consider investigating ETO companies with mature product architectures and fully integrated configurators that actively communicate with one another. Such studies could offer a richer and more comprehensive understanding of how alignment impacts the organization. Additionally, exploring and defining metrics to assess the degree of alignment presents an interesting research opportunity. For example, Key Performance Indicators (KPI) could be developed to quantify the coverage or redundancy between domains. These kinds of indicators could help assess not only whether the configuration system is well-structured, but also whether it is efficiently and coherently aligned with the product definition. Moreover, further research could focus on how the MDM framework can be used to actively support and optimize the development of both product architecture and configuration system. Finally, since the current MDM framework is built in a simple Excel environment, future work could explore how to digitize the framework or integrate it directly into configuration system to enhance usability.

7 Conclusion

This study aimed to explore the alignment between product architecture and configuration systems in the ETO industry using the MDM framework. The case study showed that several misalignments could exist despite the company's mature modular product architecture and well-developed configuration system. By applying the MDM framework, the study provided a structured way to visualize and analyze these misalignments. The study demonstrates the practical value of using MDM to support alignment between the design model in product architecture and the digital model in configuration system. While the findings are based on a single case, they offer insights that may be relevant for other companies working with ETO configuration systems. Future research could explore similar alignment challenges in organizations with interacting configurators or investigate time-based design processes using dynamic MDM models.

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