Product Variant Master in the Construction Industry

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Abstract

The architecture, engineering, and construction (AEC) industry is increasingly exploring the potential of mass customization and its impact on digitalization. However, developing digital tools can be challenging in terms of defining, delimiting, and structuring a construction product platform. To address this, a suitable information model is crucial to translate the information from the real world into a subset of data that a configurator can handle. This research aims to identify the common characteristics of construction product platforms to enhance their deployment into an information model, the so called product variant master (PVM) model. The study adopts a case methodology approach, typifying product platforms in three construction companies, and evaluates the applicability of the PVM model. Based on the findings, a systemic framework is proposed for depicting construction product platforms within the PVM model. he research concludes that by adopting this framework, the industry can streamline the modeling process, facilitate collaboration, and pave the way for effective digitalization in the AEC sector.

Keywords

AEC Industry, Configurator, Product Platform, Product Variant Master

1. Introduction

During the last decades, the architectural, engineering, and construction (AEC) industry has followed two main trends. In the 1950s and 1960s, it followed a mass production development, and later, in the early 1980s, it switched to an individual customization approach. Currently, the industry is embarking on a new strategy to exploit the best of both paradigms, uniqueness, and commonality in construction. However, there is still seldom research that can support the AEC industry in this new journey [1].

Adopting a mass customization strategy implies a major audition of a company's business model, and the critical activity revolves around a proper definition of a modularized product range [2]. An established tool in the manufacturing industry to describe a company's product range is the product variant master (PVM) model. The PVM model provides a rational and overall view of the product range's structure, including the product families and their variants [3].

Hence, adopting a mass customization approach could boost digitalization in the AEC sector, and the first step entails defining the product platform.

The topic of utilizing configurator methods in the AEC industry is not a novel concept. In fact, knowledge experts have employed the PVM model in limited construction projects and its application has also been documented [4, 5].

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However, the validity and suitability of the PVM model, originally designed for manufacturing products, in representing product platforms within the construction industry, have not been thoroughly examined. Therefore, our objective is to identify the shared characteristics specific to construction product platforms and establish a systematic framework for their representation using the PVM model. The adoption of this framework will facilitate collaboration between knowledge representation experts and domain experts in the construction industry, facilitating a deeper understanding of the rationale behind construction product platforms. Consequently, more robust, logical, and comprehensive representations of the models can be achieved, streamlining the modeling processes and enhancing insights into the product itself. This, in turn, enables the development of IT tools that were previously hindered by the challenge of representing the complex structures inherent in AEC products.

Based on this premise, we have formulated the following research questions:

RQ1- How can product platforms be generically portrayed in the AEC industry?

RQ2- How can the PVM model be used for systematic representation of AEC information?

RQ3- What are the key differences in the application of the PVM model between the construction industry and the manufacturing industry?

The remaining paper is structured as follows. Section 2 provides a comprehensive theoretical background on product platform development within IT systems, product modularity, and the product variant master model. In Section 3, the methodology used in the research is described. Section 4 presents the findings from the case studies, including the development of a generic systemic framework for construction product platforms, the ap-

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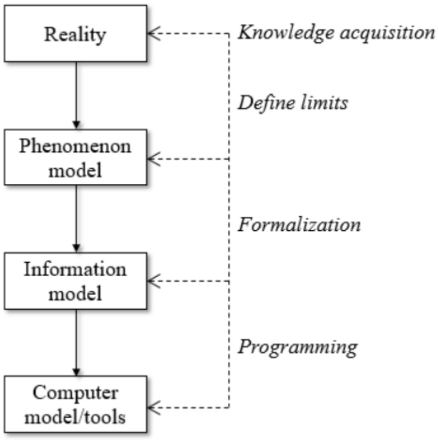

Figure 1: Process of translating the knowledge from the real word to an IT system. Adapted from Duffy et al. [6].

plication of the PVM model in the construction industry, and the differences in the application of the PVM in the construction industry compared to the manufacturing industry. Finally, Section 5 discusses the results and concludes the paper with implications for future research and practical applications.

2. Theoretical Background

2.1. Product Platforms in IT System Development

Defining product platforms is crucial in fostering mass customization and digitization in the AEC industry. In order to develop configurators that enable this level of customization, it is necessary to transform the knowledge of industry experts into a manageable subset of information [6]. The first step is the construction of a descriptive model that captures both explicit and tacit knowledge of the product. This knowledge is often dispersed across various departments within the organization. Such phenomenon model is collaboratively built with inputs from different domain experts and holds significant importance as it sets the foundation of the product platform architecture since it comprehensively defines the structure, functions, and properties of the product, encompassing its entire lifecycle. The next step involves formalizing the model to enable integration and modeling within an IT tool, such as a configurator. Formalization ensures that the knowledge represented in the phenomenon model can be effectively utilized in the development of a computer model tool. *Figure 1* illustrates this process.

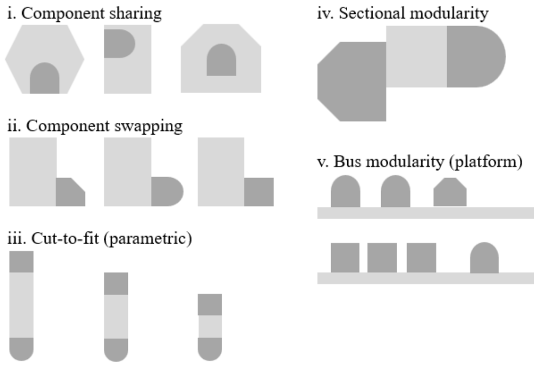

Figure 2: Modularity types based on [9, 10].

2.2. Product Modularity

One of the mass customization principles is modularization, which relates to using and arranging modules in a product architecture. There are many definitions of modularity and modules. However, one can describe a module as a definite object of a product with a distinct function and a defined interface to the other modules [2, 7]. The interface function is a crucial part of a modular product, and it should remain unchangeable as much as possible to grant the upgrade of modules over time [8].

The main types of modularity are depicted in *Figure 2* [9, 10].

1. *Component-sharing* modularity entails sharing modules across the product platform: E.g., the same engine used in different tools.
2. *Component swapping* modularity implies exchanging parts in a product: E.g., a phone with different case color options.
3. *Cut-to-fit* modularity concerns objects with parametric designs. E.g., a curtain cut with different lengths.
4. *Sectional* modularity involves the association without the restriction of modules: E.g., LEGO brick games.
5. *Bus* modularity (platform) means having the same interfaces for a base element. E.g., an Arduino board is a platform for electronic components.

2.3. Product Variant Master

A well-established modeling technique for developing product platforms is the PVM model. The PVM model provides a holistic view of a company's product platform.[2].

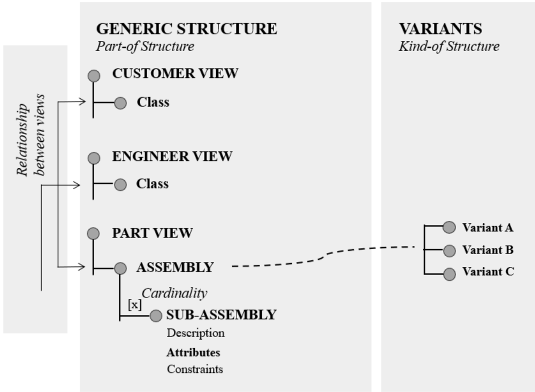

Figure 3: Basic notation of the PVM model.

The tool relies on three theoretical domains [3]. First, object-oriented modeling [11] makes it suitable for further developing digital tools. Second, the systems theory [12] provides the structure of the PVM. Third, modeling mechanical products [13], which is one of the reasons for this research to investigate the validity of using the PVM in the AEC industry.

The PVM technique, also named by some researchers as Product Family Master Plan (PFMP) [14, 15], provides a holistic, systemic representation of the information from three dimensions: the customer, the engineering, and the part view. First, the customer view reflects the customer's desire to buy the product. Second, the Engineering view contains the functions and principles to configure a solution. Third, the part view presents all the physical objects that can integrate the final product.

Moreover, the PVM is divided into two general sections. On the one hand, the left side of the PVM illustrates the generic structure or part-of structure with the different objects organized in a hierarchical structure. On the other hand, the right side of the PVM represents the variants or kind of structure, which describes the alternatives of the objects to the left.

Additionally, the generic structure is organized into classes further described by a cardinality property and a set of attributes and constraints. Finally, classes relate to instance connections on the left side of the PVM to represent when a class needs another class to fulfill its responsibility.

The PVM model is primarily used as a data collection method to retrieve information from the real world. Besides, it has a significant role as a communication tool to exchange and validate data with different knowledge experts. Building the PVM consists of multiple iterations that refine the model. *Figure 3* presents the basic notation of the PVM model.

3. Methodology

The case study methodology is a very suitable process in an exploratory investigation where research has yet not developed a theory. In this case, we opt for a multiple-case study approach to augment external validity. Nevertheless, we keep the number of cases to three to allow an in-depth analysis suitable for theory-building studies. Hence, we seek to achieve the generality of the conclusions while conceiving robust knowledge for the academic world [16, 17].

We developed and analyzed three different product platforms in three different companies. Our primary collection methods were semi-structured interviews, interaction with the various domain experts, and observations. On the other hand, we conducted data representation and documentation tasks mainly employing the PVM. Finally, we analyzed the information models under an iterative observation process of the PVM.

3.1. Case description

Companies 1 and *3* are medium enterprises with over 350 and 450 employees, respectively, while *Company 2* is a micro-enterprise with less than five employees. All companies operate in Scandinavian countries, Sweden and Denmark, and have embedded digital tools in their routine tasks to a certain extent, but only the third company has experience employing configurators. Moreover, each company performs in a different stage of the construction value chain and experiences a particular obstacle regarding a fragmented specification process. Table 1 provides an overview of the main distinctive features of the companies.

Company 1 pursues delivering more sustainable solutions to private investors to fulfill new governmental regulations. However, no digital tools can support them in developing environmental declarations, and they must resort to technical consultants to generate certified environmental declarations.

Company 2 seeks to speed the generation of quotes and bills of material to provide a faster response to private investors and agilely decide on the contractor by benchmarking.

Company 3 aims to speed up the design generation process. Even if they use digital tools to support different tasks during the process, no one can co-generate this design with the designers and potential customers and additionally include environmental assessment currently done in a separate operation.

All three companies have a shared approach when it comes to the configurator tool, which is seen as a decision support tool utilized by designers to adopt a proactive approach to design rather than a reactive one. This proactive approach helps prevent potentially high costs in sub-

Table 1
Features of the three analyzed company cases.

Features	Company 1	Company 2	Company 3
Employees	~ 350	~ 5	~ 450
Stage on the construction value chain	Construction materials	Main contractor	Construction materials
Product	Concrete products	Single-family houses	Façade Systems
Main collaborations with other parts of the construction value chain	Private investors (institutional) Architects Technical consultants on environmental declarations	Private investors (individual) Architects Technical consultants on energy assessment Technical consultants on structural assessment Contractors	Private investors (institutional) Architects Technical consultants on environmental assessment
Location	Sweden	Sweden	Denmark
Configurators experience	No	No	Yes
Organizational main problem	Boost more sustainable products	Reduce proposal lead times	Reduce design lead times
Main Construction Type	On-site and prefabricated	On-site	Prefabricated

sequent project phases. Additionally, in all cases, the configurator is integrated without the need for connecting external data or undergoing extensive reengineering processes. Therefore, the configurator successfully fulfills its primary objective of automating processes, relieving the workload on human resources, and speeding up lead times.

3.2. Data collection, representation, and analysis

We developed case studies related to *Companies 1* and *2* in parallel for 30 months until we produced functional and testable configuration system prototypes. On the other hand, we developed the case study in *Company 3* separately over seven months. In all cases, we gather the product information through modeling sessions with the relevant domain experts in each case. The sessions were an hour long, and we held them mostly individually.

In *Company 1*, we had 35 sessions with the project leader, 24 sessions with an environmental assessor, and three sessions with the domain expert. Additionally, we held a testing workshop with the external project committee.

In *Company 2*, we held 115 sessions with the project leader and 36 sessions with technicians. Additionally, we evaluated the prototype with the potential users through a testing session followed by a semi-structured interview.

In *Company 3*, we held 20 sessions with the project leader and 20 sessions with the architectural firm in charge of developing the product platform design. We used open-ended questions to gather the data, and later, we reflected it in an ontology model, the PVM, which at the same time served as a communication tool with the domain experts.

Finally, we correlated the three PVM models through an observation analysis. Based on the discussions held in the research group, we developed the study findings under an iterative process to refine the results.

3.3. Research maturity

The results and findings presented in this paper are derived from an advanced stage of research. Due to confidentiality reasons, the specific PVM models utilized by each company cannot be disclosed. However, the subsequent sections describe the outcomes based on the aforementioned research.

Currently, both Company 1 and Company 2 have successfully adopted the PVM model, leading them to incorporate configuration systems into their work environments. These companies have integrated configurator tools using standard configuration systems as supplementary resources to alleviate the burden on human resources. In Company 1, the configurator tool is undergoing final validation, where engineers employ it to make more informed design choices. Similarly, Company 2 has reached a comparable stage, where the configurator replaces previously manual tasks, reducing lead time from weeks to hours. Importantly, these configurators do not interfere with additional software, such as CAD systems, as they are employed at different stages and outputs of the construction value chain. Additionally, Company 3 has also achieved success in developing a configurator tool, which has been operational for the past three years. This tool serves as a decision support resource for architects, providing assistance during early design phases of projects. In this case, the tool enhances early design phases of the project. It is worth highlighting that the PVM model played a strong role, drawing attention to various modular design components and assemblies on the platform that required redesign to facilitate the subsequent development of the configurator.

4. Findings

We propose a generic framework to be used by AEC companies despite their stage in the construction value chain. For this purpose, we analyzed three product platforms in three companies with entirely different characteristics: company size, construction stage, product, digitalization aim, and on-site or prefabrication construction.

The main findings of the research are presented in the following three subsections. First, we describe the suggested systemic approach for developing product platforms in the AEC industries. Second, we illustrate how to use the PVM model in AEC projects to depict construction information. Finally, we highlight the main differences between the application of the PVM in the manufacturing industry compared to the AEC industry.

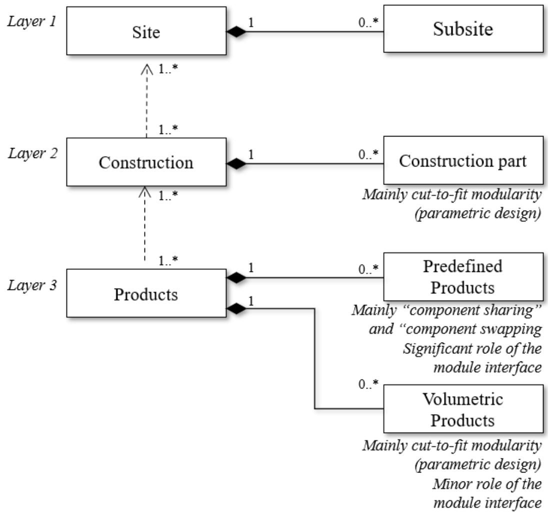

Figure 4: Systemic framework depicted using a UML diagram.

4.1. Systemic framework

Based on the analysis and observation from the three PVM models, we have identified a generic model applicable to any modular construction product platform embracing mass customization. The systemic framework comprises three layers: site, construction, and product.

1. This *site* depicts the place in which the construction is located. These can have relevance, for example, in terms of the transportation distance of the products from the factory to the working site, calculating the maximum structural load in the roof based on the average snowfall level, or knowing the accommodation capacity of construction machinery such as trucks or cranes, among other features. Moreover, the site layer can have more than one level, for instance, in renovation projects where both location and previous construction need to be considered.
2. The *construction* represents the volumetric shell in which the company's products are installed. In most cases, the *construction* might be broken up into *construction parts.* For example, the roof can be one of the *construction parts* of a building *construction.*
   The predominant modularity type in this level is "cut-to-fit," which has the property of parametrization and, hence, describes the volumetric object.
3. The *products* layer illustrates the actual commercialized products. This layer is composed of multiple instances, and its total number depends on the project's complexity. There are two defined types of *products*:
   a) *Predefined products* are predominant in prefabricated construction and are mainly defined by "component sharing" and "component swapping" modularity. The module interface is significant in predefined products and needs to be particularly well-defined. A frequent example of *predefined products* is windows and doors. Another example of a *predefined product* could be a modular room in which "cut-to-fit" modularity might also be present but in which "component sharing" and "component swapping" modularity have a more significant influence.
   b) *Volumetric products* are predominant in on-site construction, and they are mainly defined by "cut-to-fit" and "sectional" modularity. Hence, the module interface has limited significance, and its principal characteristic is its parametric design. An illustrative example of a *volumetric product* could be the concrete used to build a wall.

Figure 4 illustrates the generic systemic framework using UML notation.

4.2. PVM in the construction industry

The generic systemic framework facilitates the modeling process in the PVM model by providing a better understanding of the construction product platform. *Layer 1*, site, and *layer 2*, construction, are described in the *Customer View* since they directly depend on customer preferences and choices. Likewise, *layer 3*, products, is depicted in the *Part View* as it represents all the physical components of the project. The three layers are closely related and utterly dependent on one another.

Figure 5 illustrates the applicability of the PVM information model in the construction industry. Besides, the generic systemic framework is reflected to envision its use in construction product platforms.

This reinterpretation of the PVM model can assist construction companies in portraying their product range, particularly in the early design phase of the information model. Hence, the PVM description could potentially reduce the time and resources invested in designing and organizing the modules and their relationship.

4.3. PVM application in industrial manufacturing vs AEC industry

Notable distinctions between the application of the PVM model in industrial manufacturing companies and its application in the construction industry have become evident. The following outlines the unique characteristics and novel approaches of the PVM model specifically tailored for the construction industry, in contrast to previous PVM applications, focused on mass-customized products in manufacturing:

- *Modularity*: Modularity in AEC projects relies heavily on design parametrization, i.e., cut-to-fit modularity.
- *Digitalization*: While configurators are widely employed by manufacturing companies to address mass customization, they are relatively unfamiliar tools in the AEC industry. Architects primarily rely on BIM (Building Information Modeling) tools, which are usually based on CAD systems lacking parametric history design capabilities, a crucial aspect considering the modular typification of construction projects.
- *Product structure*: The construction industry is distinguished by its offering of unique designs with a low degree of standardization in their building systems.
- *Stakeholder dependencies*: The construction value chain operates in more isolated siloes compared to the manufacturing industry. There are substantial interdependencies among architects, engineers, and constructors, requiring extensive coordination efforts.
- *Production process*: Manufacturing processes are typically standardized and tightly controlled in a manufacturing environment. In contrast, construction projects predominantly involve on-site construction, encompassing numerous disciplines, manual operations, and coordination, which can present challenges in mapping out the production process.
- *Production variability*: Construction products exhibit higher tolerances compared to manufactured products, necessitating allowances and adaptations due to site-specific conditions and project-specific requirements.
- *Production volume*: Mass customized products in manufacturing companies usually target customization at higher volumes. Conversely, the construction industry typically operates at lower volumes and on a project basis.
- *Product life-cycle*: AEC industry products are primarily designed for long lifespans, and consequently, maintenance and renovation processes have a significant influence on the overall product.

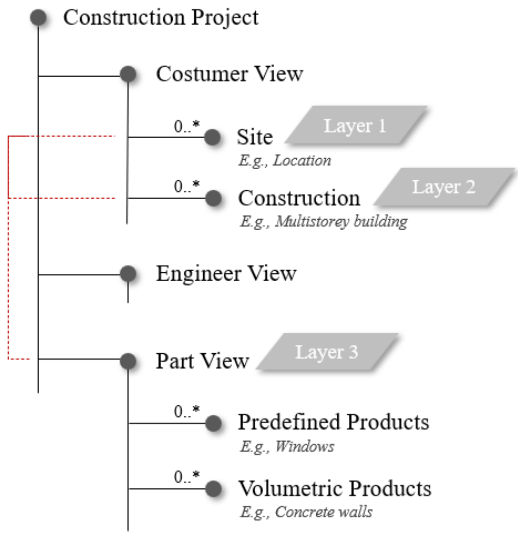

Figure 5: Applicability of the PVM information model in the AEC industry to depict construction product platforms.

These differences highlight the need for specialized approaches and considerations when applying the PVM model in the construction industry, acknowledging its unique characteristics and challenges.

5. Discussion and conclusion

In this paper, we conducted an analysis of construction product platforms and developed a systemic framework for their depiction using the PVM model. Although configuration project development methods have been used in the AEC industry, the suitability of the PVM model for representing construction product platforms has not been thoroughly studied. Previous literature shows limited application of the PVM model in construction projects and, moreover, it was originally designed for industrial mechanical products. Therefore, our study aims to analyze the validity and applicability of the PVM model rather than its feasibility for construction product platforms.

Our research has three main contributions and outcomes:

Firstly, we developed a generic framework that provides a systematic organization of construction product platforms into modules. This framework characterizes the relationship and cardinality of these modules, describing them based on their modularity and interface significance. Implementing this framework can enhance collaboration between knowledge representation experts and domain experts in the construction industry, leading to a better understanding of construction product platforms. Consequently, more robust, logical, and comprehensive models can be created, streamlining the modeling processes and providing deeper insights into the products themselves. Additionally, this development of IT tools, which was previously hindered by the challenge of representing complex structures in AEC products, can be considerably improved. This framework also addresses RQ 1.

Secondly, the framework helps answer RQ 2 by demonstrating the applicability of the PVM model in AEC cases. Despite being initially designed for industrial manufacturing projects, our observations confirm its suitability in the construction sector. Thus, we can describe the use of the PVM model in the construction industry and validate its applicability beyond manufacturing projects.

Thirdly, we address RQ 3 by uncovering that the application of the PVM model in the construction industry diverges from its usage in industrial manufacturing. The construction industry has different characteristics, including modularity, digitalization, stakeholder dependencies, production processes, variability, production volume, and product life-cycle. Consequently, applying the PVM model in the construction industry requires specialized approaches. It is essential to recognize these differences to effectively use the PVM model in the construction industry.

To conduct a comprehensive analysis of the research questions, we deliberately chose a smaller sample size. The observed variations among the three company cases provide further evidence supporting the generalizability of our findings. The validity of the research outcomes is reinforced by the advanced stage of development of the configuration tools. However, in order to strengthen the framework even further, it would be recommended to replicate and evaluate the proposed framework in additional cases.

Furthermore, it is important to emphasize that widespread use of the PVM model in the AEC industry can help streamline the fragmented value chain of construction projects, which often rely on siloed specification processes. Documenting construction product platforms using the PVM model can bring similar benefits to those achieved by manufacturing industries, such as easier maintainability and smoother development of the product platform. Additionally, this approach has the potential to reduce the modeling phase of the configurator. It is conceivable that other business fields beyond manufacturing or the AEC industry could benefit from the same rationale applied in this research. Therefore, further studies could contribute to the theory of information models, specifically investigating the applicability of the PVM model in fields such as logistics, services, or processes.

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