Embracing Strategic Knowledge for Developing a Methodological Framework for Parametric Modeling Quality

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Abstract. In Model-Based Enterprise environments, 3D CAD models — specifically, native parametric solid models — become the primary carriers of design information for engineering and manufacturing activities. It is therefore critical that these assets are built to the highest levels of quality and explicitly meet the requirements for being: 1) usable, the model is valid, and it represents, without error, all the significant geometric aspects; 2) reusable, the model is consistent and concise and reasonable changes are facilitated; and 3) information-rich, the model clearly communicates its design intent both implicitly and explicitly with annotations. Current practices for parametric associative CAD modeling, however, barely address usability and only consider reusability at the simplest and most basic level. In this paper, we discuss the inherent limitations of current modeling methodologies and identify the challenges involved in creating a fully comprehensive strategy. Finally, we outline the basis of a theoretical framework that aims to overcome these issues.

1 INTRODUCTION

In the modern engineering enterprise, concurrent and iterative product development processes are leveraged to meet the demand for shorter development cycles and increasing levels of product customization. To maximize efficiency, many companies are transitioning to Model-Based Enterprise (MBE) environments, in which digital product models are used to manage, communicate, and share design information. These digital models drive all engineering activities, including the control and management of design changes, design optimization, simulation, product/part family configurations, digital manufacturing, and AI-based modeling [5].

Owing to their ability to efficiently build, manipulate, refine, and adjust the geometry of the 3D model [8], parametric CAD systems have become the standard technology in the engineering design industry [40]. In a parametric model, dimensions and geometric constraints control and drive the shape of the model. When used properly, these mechanisms become the tools that facilitate geometric changes.

Parametric modeling systems have been shown to improve productivity and ease complex part design [35,37], and as such, they have become a critical component of the product development process for the creation of native digital product models [7,40]. The construction process of a 3D model in a parametric associative CAD system (e.g., SolidWorks, Siemens NX, CATIA, SolidEdge, OnShape, Autodesk Fusion360, etc.) involves the iterative creation of features. These features are defined by parameters and constraints and can contain geometric and semantic elements. The associations that are generated between these features are defined by parent-child dependencies, which form an associative structure called the design tree.

According to Bodein et al. [7], designers can capture intentionality by using constraints, relationships between features, the tree structure or sequence, and other resources such as renaming features, folders, and annotations. Commonly known as design intent, this intentionality is a complex and multifaceted concept that was recently revisited by Otey et al. [25]. It is generally understood as the expected behavior of the model against possible design alterations and variations [23]. To achieve 3D model reusability, it is thus necessary to effectively convey the design intent.

In this regard, the quality of the models is paramount as these assets must be consumed (either directly or through derived models) by downstream processes. The term "quality," however, is difficult to define. Indeed, a comprehensive definition is yet to be agreed upon. In any case, the ability of a 3D model to react successfully to design changes depends on how it is built, which, in turn, is contingent on the skill and experience of the designer. After all, it is the designer who determines the modeling procedure, the parent-child dependencies, and the constraining strategies that will be employed to build the geometry. If these aspects are not properly considered, the robustness and flexibility of the model can be compromised, hindering the flow, time, and effort involved in product development activities [5].

To gain some perspective, we look back to the origins and evolution of descriptive geometry. Monge defined Descriptive Geometry as an art with two major objectives: (1) to obtain an exact representation (in two-dimensional media) of three-dimensional objects that require a rigorous definition and (2) to deduce the characteristics and properties of the geometric shape from the exact description of its bodies and their respective positions. However, in the words of Sakarovitch, from the "two main objectives," history only remembered the first, letting the second fall into nearly complete oblivion and restricting descriptive geometry to a graphical technique of spatial representation" [30]. Some exceptions do exist, however, most notably Hohenberg's Constructive Geometry in Technology [22], which focused on the constructive problems of objects represented through the techniques of descriptive geometry.

In 1973, Ricci [28] defined Constructive Geometry (CG) for Computer Graphics as a general approach to representing and manipulating 3D objects as a combination of simpler bodies through suitable sequences of Boolean operations (e.g., intersection and union). This initial definition of what is known today as Constructive Solid Geometry (CSG) focuses on obtaining an exact three-dimensional representation of three-dimensional objects (note the parallelism with Monge's first objective). However, the equivalent of the second objective (i.e., deducing all the characteristics and properties of the shape) was once again lost.

The knowledge related to how a process must be carried out is referred to as procedural knowledge. Strategic knowledge results from experience in domains where problem-solving and selecting between different possible actions is critical. In this regard, we contend that Declarative & Procedural CAD Command Knowledge [14,15] are equivalent to Monge's first objective, described earlier, while the desirable strategic CAD knowledge is related to the often overlooked second objective. Most, if not all, CAD users are taught to focus exclusively on geometry but ignore the purpose or function that geometry must play as a carrier of design, engineering, and manufacturing

information. In this regard, we argue that models should not be just shape representations but information-rich assets that can support redefinitions and contain the knowledge that will be considered throughout the design process.

According to the linguistic model by Contero et al. [18], 3D models can be classified in three levels of quality: (1) morphological, which relates to the geometrical and topological correctness of the CAD model; (2) syntactic, which evaluates the use of the proper modeling conventions, and (3) semantic/pragmatic, which considers the capability of the model for reuse and modification. Building on this classification, we consider CAD quality as a threefold construct, which involves both geometry and all related information. To qualify as quality, models must first be usable (i.e., they must represent, without error, all the significant geometric aspects of the object). This dimension encompasses the morphological (model is "valid" or error-free) and semantic (model is complete) levels of the linguistic model and parallels Monge's first objective. Second, CAD models must be reusable (or "semantic/pragmatic" in the sense of being consistent and concise and must facilitate reasonable changes and prevent unreasonable or unrealistic ones. This characteristic —unavailable in the days of descriptive geometry— leverages the ability to change and rebuild, which is provided by modern CAD paradigms (particularly procedural and parametric modeling). At the third level, the model must be clear (easy to understand) and semantically rich (supplemented by relevant information that is both explicitly conveyed through annotations as well as embedded implicitly within the geometry and in the construction process of said geometry). This characteristic ensures that models are not rigid representations of "pure geometry" but flexible assets that convey the function that the geometry must perform, which echoes Monge's second objective.

In this paper, we contend that current modeling methods and strategies only address the first and part of the second levels but completely ignore the third. To support this position, we summarize common industrial practices, review the fundamental principles of modeling strategies, and discuss the reasons why modeling strategies often fail to produce quality models.

2 COMMON INDUSTRIAL PRACTICES IN MODELING

Although parametric CAD systems have shown great potential for accelerating product development processes, the current industrial context shows a very different reality. With the objective of identifying the challenges, problems, and weaknesses in the use of CAD in the design process, Salehi and McMahon [31,32] conducted a five-month study involving 153 designers in the railway and automotive sectors. Their results showed that 71% of designers did not have a detailed strategy to construct 3D models. Despite employing a strategy, the remaining 29% reported that their models were not properly structured. In addition, only 24% of those interviewed indicated that they were able to find the correct parameters and associative relationships in large and complex CAD parts and assemblies. This problem was further magnified when the designers tried to make design changes to third-party 3D models. In this case, only 9% of the participants were able to identify and determine key information to complete the task because they found it difficult to modify parts and CAD assemblies created by others. Indeed, Jackson and Prawl [23] estimated that approximately half of all designers spend over four hours a week fixing 3D models, and 15% of those spend over 24 hours a week addressing design data issues. This issue has continued over time as CAD training, offered by vendors, universities, and vocational training centers, typically emphasizes feature usage rather than strategic approaches to creating robust, high-quality models [8].

Although these insights are significant and point to a serious issue, the magnitude of the problem still needs to be discovered. This is because, to the best of our knowledge, a no-cost model exists to objectively quantify the time, effort, and resources wasted due to ineffective modeling strategies [10]. Nonetheless, it is possible to identify the source of these inefficiencies, which arise from the intrinsic nature of the 3D model-building process in parametric associative CAD systems [5]:

- There are many possible solutions or modeling paths to construct the same geometry [2,8]. All solutions may be geometrically valid, but not all will behave in an equally robust and flexible manner in the event of design changes.

- The most common geometric modeling strategy is based on "trial and error," as described by Hartman [21], and/or relies heavily on the experience of the designer [2].
- The successful reuse of a 3D model is highly dependent on the modeling strategy of the original designer [7].

To increase model quality and thus facilitate reusability and enhance collaboration among designers, some companies use custom (and often proprietary) CAD guidelines [8,9,11]. These guidelines structure the design tree and help third parties better understand the model. The models of the two-stroke engine block shown in Figure 1 were built following two different strategies. In the first model, no particular modeling criteria were used, whereas the second model was created according to a company's design guide. Because of the model structure and the design team's knowledge, the second model is more easily adaptable and flexible to design changes.
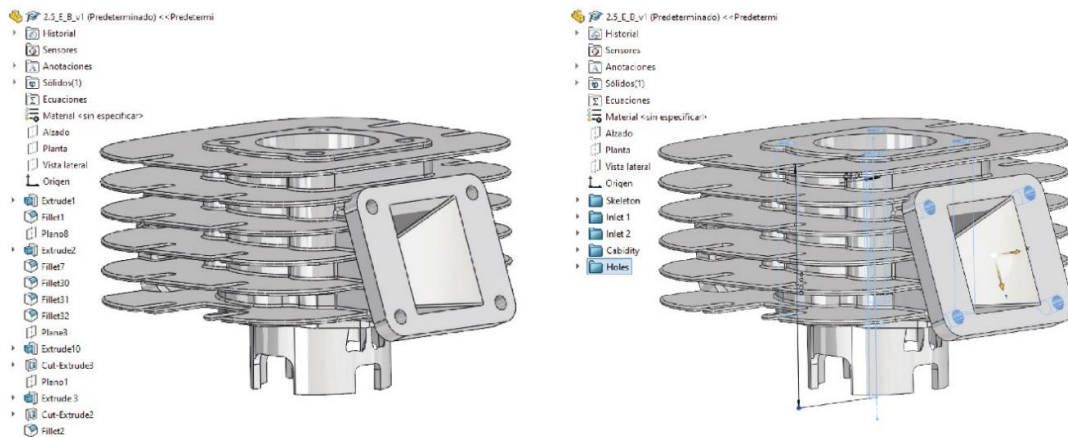

Figure 1: A two-stroke engine block. On the left is a model without any particular modeling criteria. On the right is a model created according to a company's design guide.

The level of detail of these ranges from basic naming conventions and strategies for homogenizing design trees to establishing a common modeling strategy across the organization. However, problems in reusing models persist because [31,32]:

- 3D models are frequently poorly structured, which leads to difficulties in modification and finding key design information.
- Designers have difficulties in identifying, determining, and representing key parameters and associative relationships.
- The created associative relationships are not well thought out and elaborated. Designers create many associative relationships between geometric entities without being aware of potential detrimental effects during design changes.
- Designers do not give sufficient consideration to the preparation of parameters and associative relationships.
- The challenges faced by designers during modeling are usually related to procedural knowledge of CAD and logical aspects of associations between features and parameters.

In the following section, we analyze the strategies available in the literature and compare the tasks addressed by each of them.

3   THE DESIGN PROCESS AND REVIEW OF MODELING STRATEGIES

Part modeling is one of the tasks executed during the design process of a product. Therefore, any critical review of the modeling strategies presented in the literature should be conducted in the general context of the product design process. Pahl and Beitz [27] organized the design process into four phases: i) task planning and clarification, ii) conceptual design, iii) embodiment, and iv) detail design. These general phases were used to determine the workflow in the Verein Deutscher Ingenieure design guides VDI2221 [38] and VDI2222 [36]. Building on this structure, Aleixos et al. [1] proposed a five-step process by dividing the embodiment phase into two sub-steps: i) earliest product planning and organization, ii) establishment of the product conceptual design, iii) arrangement of the specification principle into a hierarchical-fundamental structure, iv) integration of the hierarchical-fundamental structure into a CAD structure and v) integration of modeling detailed design. The proposal is illustrated in Figure 2, which shows that in each phase, the uncertainty of the project is reduced, and more information, definitions, and details of the product are acquired. For the model to remain the primary view, the acquired information should be linked to it through enrichment of the model itself (making the model tree clearer, as proposed by Company et al. [17]) and/or through structured notes, as in [16].
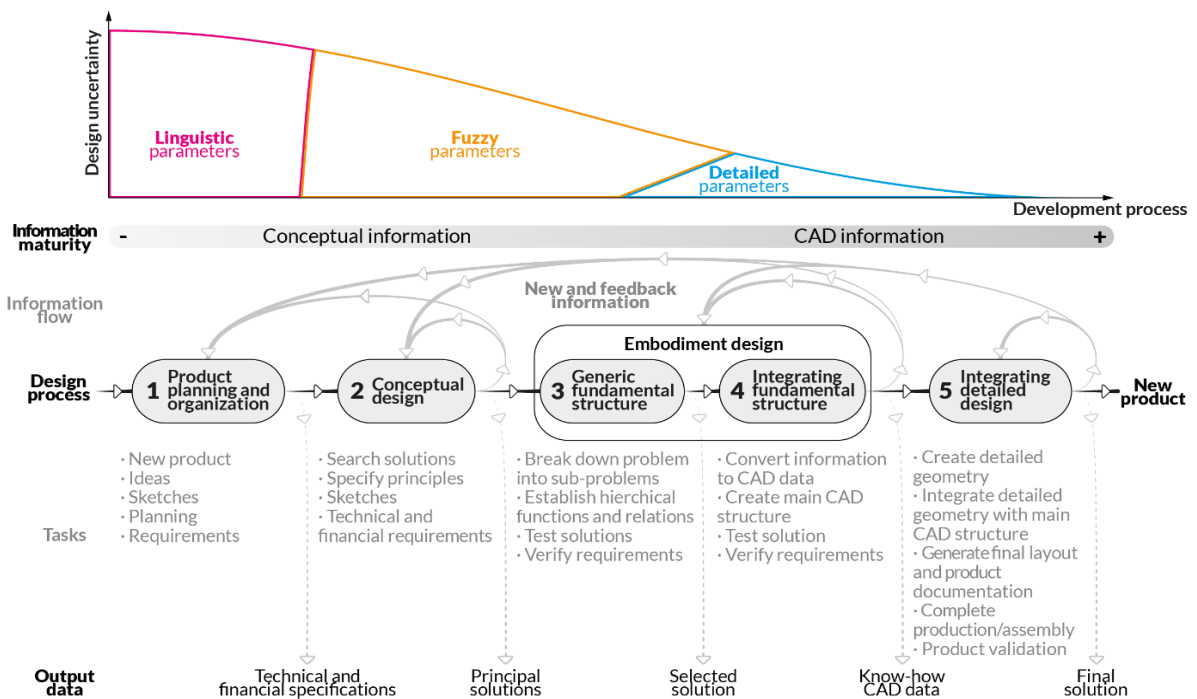

Figure 2: Steps in the product design methodology inspired by Aleixos et al. [1], including the uncertainty during design process steps, adapted from [33].

Various modeling strategies can be found in the published literature to guide the 3D model building process, and the most notable examples are described below. Modeling strategies guide designers during the design process and their objective and tasks are focused on different design process phases.

The so-called "Horizontal" modeling methodology consists of transforming the design tree by creating dependent relationships only between Cartesian planes and construction features [24]. Alternatively, the Paramass methodology helps to categorize and make explicit the relationships between parameters and classes that are available in different CAD parts, assemblies, and their

relationships to each other [32]. The Resilient methodology is based on specific rules that categorize features according to their instability, defined as the tendency of each feature to cause regeneration errors when the model is altered [19]. Explicit Reference Modeling focuses on relating features to explicit references rather than existent geometry [2]. The Functional Feature methodology guides designers in building CAD models to represent functional design considerations [12,13]. Finally, the Improved Explicit Reference methodology proposes two strategies that prevent inefficient Explicit Reference interpretations, increase robustness, and reduce the regeneration time of CAD models, achieving quality models for various engineering activities [3]. The tasks addressed by each of these methodologies are summarized in Table 1.

Phase	Objective	Tasks	Horizontal [24]	Paramass [32]	Resilient [19]	Explicit Reference [8]	Functional Feature [12,13]	Improved Explicit Reference [3]
Conceptualization and embodiment	Define the design rationale of the part to be modeled to identify possible constraints for capturing design intent.	Use mathematical models to understand the behavior of the part as a whole and describe phenomena					x	
		Evaluate design specifications and functional requirements to define functions					x	
		Deconstruct geometry by functions and by specifications.				x	x	x
		Parameter Structure Matrix (PSM)		x				
		Associative Structure Matrix (ASM)		x				
		Define abstract geometrical features of the model					x	
		No. of tasks	0	2	0	1	4	1
Detailing design, modeling	Construct the 3D model by capturing the design intent effectively. Verify model robustness and flexibility	Create skeleton of the model			x			
		Determine references	x		x	x		x
		Determine parameters			x	x		x
		Determine restrictions			x	x		x
		Manage/relate dependencies between operations	x		x	x		x
		Relate geometry-function				x		x
		Build geometry			x	x		x
		Design tree structure			x			
		Organize operations according to their instability			x			x
		Name operations and rename features to be self-explanatory			x			
		Verify geometry and requirements			x			
		Perform geometric variations			x			x
		No. of tasks	2	0	11	6	0	8

Table 1: The task addressed by the methodologies grouped into two phases: i) conceptualization and embodiment and ii) detailing design and modeling.

4   DISCUSSION

To the best of our knowledge, no existing modeling methodology fully addresses the phases of the design process in parametric associative CAD. This incomplete nature often yields experienced CAD users who still use sub-optimal modeling methods that are often time-consuming and difficult to modify, thus producing CAD models that need to be of sufficient quality to support design changes [14]. Rynne & Gaughran [29] consider that for efficient use of parametric associative CAD systems, it is necessary to acquire strategic knowledge (i.e., the ability to know how to approach the construction of the model) beyond the procedural knowledge (i.e., mastering the functionalities of the CAD system). We go one step further to categorize three types of knowledge, thus agreeing with Chester [14,15]:

- **Declarative command knowledge.** This knowledge is indifferent to a particular CAD system and is valid for the most part for all Parametric Associative CAD. It focuses on knowing the availability of the commands or algorithms. In order to use a particular feature or command, one must know that it exists.
- **Specific procedural command knowledge.** It focuses on the designer having the ability to apply and combine the features of the CAD system. This knowledge is specific to each CAD system and may vary from one version to another. CAD vendors' instruction and formal training focus on this type of knowledge.
- **Strategic knowledge.** It includes metacognitive processes such as planning, monitoring, and reviewing. It also includes predictions of model behavior in the face of geometric variations. These metacognitive processes and predictions help the designer to create models that maintain their robustness and effective reusability. That is, the more strategic knowledge a designer has, the more likely they will be able to select the most efficient modeling routes to achieve higher quality models.

The process of acquiring strategic knowledge can vary drastically from one designer to another since the capabilities and skills of each individual (innate or acquired) can differ significantly. Spatial abilities [6], the ability to deconstruct geometries, drawing skills, and technical training and experience, among others, impact development and may explain why, for certain designers, some methodologies can be more effective than others.

The Explicit Reference modeling methodology allows greater construction flexibility, and hence complex models that are difficult to analyze in previous phases are more easily managed. On the other hand, A Resilient modeling strategy is stricter and more specific in its application, therefore, it is easier to apply in models with well-defined parameters and less complexity. Therefore, depending on the case, excessive definition or structuring of modeling strategies can hinder the model construction process.

Product design processes that are commonly followed in the industry may not be linear or as extensive as represented in Fig. 1. Instead, depending on the sector, more iterative and agile design approaches may be used. Indeed, the phases proposed by Aleixos et al. [1] may sometimes be repeated several times, and not all may be applied in an exhaustive manner. As a result, the parameters to be considered in the CAD model will remain vague for a longer period of time, which increases the uncertainty in later phases. We are thus facing a paradigm that has not been considered in the literature, yet it is prevalent in industry. The construction of CAD models is often performed without a clear notion of the key parameters or even without having a fully conceptualized geometry. The embodiment process occurs almost in parallel to modeling. In this regard, there needs to be more strategic training and knowledge focused on constructive geometry since the designer's knowledge of descriptive geometry is insufficient and not the actual task they will be performing. We note here that descriptive geometry involves explaining what an object looks like, whereas constructive geometry involves determining how it can be constructed. Therefore, the designer can only use CAD at a strategic level with a strategic knowledge of geometry, which consists of using geometry constructively instead of descriptively. In other words, the designer cannot visualize the

model directly during the construction process using features without previously imagining the model.

The approach by Aranburu et al. [3] achieves satisfactory results but demonstrates that creating holistic quality models and reducing inefficient modeling paths cannot be addressed solely from a procedural CAD knowledge perspective to try to "hack" all the inefficient modeling paths and rebuild errors. Since certain types of features, their combinations, and their associations may produce different results depending on the commercial CAD system used, it is necessary to develop proper heuristics that can guide the designer throughout the process. Here, given the variability and the uncertainty of the parameters and the construction process (which is also not fully defined) it becomes necessary to reassess the existing modeling methodologies and the proposed steps so they can be refined. Moreover, approaches to evaluate the validity of transitional models should also be rethought, i.e., not only evaluating the model at the end of the construction process but also during each iteration to determine whether the design intent expectations are met cumulatively, thereby increasing the success rate.

A natural tendency when facing modeling problems might be to bypass the issue. Direct modeling is initially a viable proposal that could help achieve agile design changes. Although the benefits of this approach are worth considering for specific cases, the quality and flexibility of the resulting model cannot improve beyond the morphological level. It is unclear how the derived model will react if the designer makes subsequent changes whether through direct editing or parametric mechanisms. Furthermore, in the case of complex models, the effectiveness of direct editing becomes questionable.

5 CONCLUSIONS

We believe that a general parametric modeling methodology can be developed that: (i) addresses the three levels of quality, and (ii) takes the best of each of the current strategies to cover all stages of the design process. That said, we are fully aware that much work is needed to create a formal modeling strategy with a theoretical framework. Nevertheless, correcting some important and glaring flaws in current methodologies can be taken as a starting point for developing the following list of six objectives:

- Designers and trainers must be aware of the three categories of knowledge and where their skills are in relation to these categories at any moment. To this end, they must develop metaknowledge (the knowledge about the different levels of knowledge) and metacognition (being aware of when it is appropriate to switch between different levels of knowledge). In addition to their intrinsic value for formal training, formal methodologies should consider the different characteristics of each type of knowledge to avoid switching between them involuntarily. We propose leveraging the categorization of the necessary levels of knowledge proposed by Chester [14,15]: (1) Declarative Command Knowledge (WHAT), (2) Specific Procedural Command Knowledge (HOW), and (3) Strategic Knowledge (WHAT FOR). As stated by Abraham Maslow, "If the only tool you have is a hammer, you tend to see every problem as a nail," or in this case, "If the only feature you know is "extrude," you are going to construct every model based on extrusions." This limitation on the part of the designer would be conscious ignorance [20,39] and Meta-ignorance [34], which authors Mardorli and Otto addressed through Negative Knowledge [26].

- Reduce the modeling paths of the same geometry and try to hack the "system errors." Formal modeling strategies exhibit intrinsic volatility [3] due to a lack of definition in their theoretical frameworks and the potential for alternative interpretations by the designer. As a result, designers following the same strategy might model the same geometry with significantly distinct modeling paths. Thus, it is critical to reduce the number of these possible modeling routes. Moreover, the available features and operational methods vary slightly for each parametric CAD software package. We argue that it is necessary to discern which routes

are the most efficient to achieve quality models and integrate this knowledge into the theoretical framework of existing modeling strategies.

- Ensure that the model building process is not "trial and error." When creating a new geometry, the designer must have clear notions of how to logically structure the process of creating functional bodies. The designer must establish criteria to determine where to start building the model and which features should be used to be able to obtain a high-quality model (or at least avoid inefficient modeling paths [3]).

- Assist in the process of embodiment with strategic knowledge and parameter detection and association [12,13]. The designer must address and be guided by strategic knowledge in the construction of geometry. Such knowledge includes, but is not limited to, an understanding of the logic and correlation between parameters, associations, and geometry. This requires training and the acquisition of knowledge through reflective critical thinking.

- Review the potential reusability of the model to detect associations that negatively affect the quality of the model. The associative-parametric structures (graphs) that are built during the modeling process are highly complex, and the parametric CAD interface hinders a detailed understanding of the associations [2]. For this reason, the robustness of the model constructed automatically should be continuously verified with commercial geometric variations such as SolidWorks Design Studies. At present, however, automated verification of the design intent is almost impossible to perform [4]. Design intent has not been made tangible and no tool exists for this purpose.

- Structure design trees and models in a manner that better communicates Design Intent. We observed that properly structured and labeled design trees can facilitate model reusability when using the Resilient strategy [9]. However, the process involves considerable work in complex models, and there is no evidence that this practice ensures model robustness. Therefore, the communication of the Design Intent must be improved semantically whilst ensuring that the syntax is not damaged.

6 ACKNOWLEDGEMENTS

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