Title:
Are we Using Effective Modeling Strategies in Parametric Associative CAD?

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Introduction:
Parametric modeling systems have been shown to improve productivity and ease complex part design [26,27], and as such, they have become a critical component of the product development process for the creation of native digital product models [6,30]. In this regard, the quality of these CAD 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, an agreed-upon definition is still missing, although many authors tend to agree on some of its most relevant aspects, such as robustness, flexibility, and responsiveness to geometric variations. In any case, the ability of a 3D model to react successfully to design changes depends on how it is built, which is contingent on the skill level and experience of the designer. After all, it is the designer who makes the decisions to determine 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 model's robustness and flexibility can be compromised, hindering the flow, time, and effort involved in product development activities [5].

In our view, most studies to date have focused on developing efficient methods to represent geometry but have ignored the purpose of the geometry that is being represented. To put things in perspective, we look back at the origins and evolution of descriptive geometry. Descriptive Geometry was defined by Monge as an art with two major objectives: (1) to obtain an exact representation (on two-dimensional media) of three-dimensional objects that require a rigorous definition and (2) to deduce all 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" [23]. It is worth mentioning some exceptions, most notably Hohenberg's Constructive Geometry in Technology [16], which focused on the constructive problems of objects represented through the techniques of descriptive geometry.

In 1973, Ricci [21] 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). The equivalent to the second objective (i.e., deducing all the characteristics and properties of the shape), however, was once again lost.

The knowledge related to how a process must be performed is referred to as procedural knowledge. Alternatively, strategic knowledge results from experience in domains where problem solving and selecting between different possible actions is critical. In this regard, we contend that procedural CAD knowledge is 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 trained 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. [13], 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 CAD model’s capability for reuse and modification. Building on this classification, we consider CAD quality as a threefold construct, which involves both geometry as well as all related information. In this regard, models must be *usable* (i.e., they must represent, without error, all the relevant 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 to facilitate reasonable changes and prevent unreasonable or unrealistic ones. This characteristic, which was not available in the days of descriptive geometry, leverages the ability to change and rebuild that is provided by modern CAD paradigms (particularly procedural and parametric modeling). In the third level, models 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 such geometry). This characteristic ensures that models are not rigid representations of "pure geometry" but flexible assets that convey the function that the geometry must play, 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 justify our 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.

Common industrial practices in modeling:

The construction process of a 3D model in a parametric associative CAD system (e.g.: SolidWorks, Siemens NX, CATIA, SolidEdge, OnShape, Autodesk Fusion360, etc.) requires the iterative creation of features. These features are defined by parameters and constraints and can contain geometric and/or 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. [6], 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. This intentionality is known as design intent. Design intent is a complex and multifaceted concept that was recently revisited by Otey et al. [19]. It is generally understood as the expected behavior of the model against possible design alterations and variations [17]. To achieve 3D model reusability, it is thus necessary to effectively convey the design intent.

Although parametric CAD systems have shown great potential for accelerating product development processes, the actual situation in the industry shows a different reality. With the objective of identifying the challenges, problems, and weaknesses in the use of CAD in the design process, Salehi and McMahon [24,25] conducted a 5-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 magnified when the designers tried to make design changes to third-party 3D models. 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 [17] 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 fixing design data. This issue has continued over time as CAD training, offered by vendors, universities, and vocational training centers, emphasizes feature usage rather than strategic approaches to creating robust, high-quality models [7].

Although these insights are significant, the full extent of the problem is largely underexplored because no cost model currently exists to objectively quantify the resources wasted due to ineffective modeling strategies [9]. 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 [2,7]. All solutions may be geometrically valid but not all will behave in an equally robust and flexible manner under design changes.
- The most common geometric modeling strategy is based on "trial and error" as described by Hartman [15], and/or relies heavily on the experience of the designer [2]; and
- The successful reuse of a 3D model is highly dependent on the modeling strategy of the original designer [6].

To increase model quality and thus facilitate reusability and enhance collaboration among designers, some companies use custom (and often proprietary) CAD guidelines [7,8]. Their level of detail 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 [24,25]:

- 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.

<u>Design process and review of modeling strategies:</u>
Part modeling is one of the tasks executed during the design process of a product. Therefore, any critical review of the modeling strategies available in the literature should be conducted in the general context of the product design process. Pahl and Beitz [20] organized the design process into four phases: i) planning and clarifying the task, ii) conceptual design, iii) embodiment, and iv) detail design. Authors Aleixos et al. [1] proposed a five-step process by dividing the embodiment phase into two: i) earliest product planning and organization, ii) establishment of the product conceptual design, iii) arrangement of specification principle into a hierarchical-fundamental structure, iv) integrating the hierarchical-fundamental structure to a CAD structure and v) integrating modeling detailed design. It can be deduced 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. [12]), and/or through structured notes, as in [11].

Various modeling strategies can be found in academic literature to guide the 3D model-building process. Modeling strategies guide designers during the design process, and their objectives 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 [18]. Alternatively, the *Paramass* methodology helps to categorize and make explicit the relations between parameters and classes that are available on different CAD parts, assemblies, and their relationships to each other [25]. 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 [14]. *Explicit Reference* Modeling focuses on relating features to explicit references rather than existent geometry [7]. The *Functional Feature* methodology guides designers in building CAD models to represent functional design considerations [10]. Finally, the *Improved Explicit Reference* methodology proposes two strategies that avoid inefficient Explicit Reference interpretations, increase the robustness, and reduce the regeneration time of CAD models, achieving quality models for various engineering activities [3]. The methodologies address phases that are grouped into two: i) conceptualization and embodiment and ii) detailing design and modeling.

It can be observed that the different tasks proposed by the modeling strategies focus on the pre-modeling or modeling phases. In addition, Paramass [25] and Functional Feature [10] focus on the phases previous to modeling. On the other hand, the Horizontal [18], Resilient [14], Explicit Reference [7], and Improved Explicit Reference [3] strategies focus on the modeling phase. These strategies are known as formal modeling methodologies. With the exception of Horizontal [18], which is based on deliberately avoiding the creation of associations that are not to Cartesian planes, the strategies of both phases are compatible with each other. The exceptions are Explicit Reference and Improved Explicit Reference, as they mention the task of deconstructing the geometry by functions and constructing the model by functional geometries. Although the improved version of explicit reference modeling is more detailed, from a practical standpoint, these strategies do not address the pre-modeling phase.

Previous studies have concluded that among modeling strategies that focus on the modeling phase, the horizontal methodology is comparatively ineffective when facing manual and automated design changes [4]. Resilient, on the other hand, has proven to be an efficient strategy for simple models in scenarios that involve manual design changes [4,8]. Finally, Explicit Reference modeling, particularly its improved version, can achieve the highest quality models in the context of geometric variations [4]. It is an effective methodology for complex models in scenarios that involve both manual and automated design changes [3]. The Paramass and Functional Feature strategies have not been evaluated as comprehensively as the other strategies. Furthermore, they could not be compared with the others since they focus on different phases of the design process.

<u>Discussion</u>

To the best of our knowledge, no modeling methodology fully addresses the phases of the design process in parametric associative CAD. This incomplete nature often yields CAD models that are not of sufficient quality to support design changes. We agree with Rynne & Gaughran [22] in that the effective use of a CAD system requires two types of knowledge, procedural (i.e., mastering the functionalities of the system) and strategic (i.e., the ability to know how to approach the construction of the model). Acquiring strategic knowledge, however, can change drastically from one designer to another since the capabilities and skills of each individual (innate or acquired) can vary significantly. Spatial abilities, the ability to deconstruct geometries, drawing skills, and technical training and experience, among others, have an impact on development and may explain why for certain designers, some methodologies can be more effective than others.

Explicit Reference allows greater construction flexibility, so complex models that are difficult to analyze in previous phases are more easily approachable. On the other hand, Resilient 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 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 the geometry fully conceptualized. The embodiment process occurs almost in parallel to modeling. In this regard, there is a lack of 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 cannot use CAD at a strategic level without having a strategic knowledge of the geometry, which consists of using geometry constructively instead of descriptively. 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. Given the variability in feature types, their combinations, and associations across different CAD systems, it is essential to develop heuristics to guide designers. Additionally, current modeling methodologies and their evaluation need reassessment—not only at the final stages but also during each iteration—to ensure cumulative alignment with design intent, thereby improving the success rate.

Conclusions:

We believe that a methodology can be developed that, on the one hand, addresses the three levels of quality, while, on the other hand, takes the best of each of the current strategies to cover all stages of the design process.

Much work is still required to create a formal modeling strategy with a theoretical framework, but correcting some important and glaring flaws in current methodologies can be taken as a starting point for developing the list of objectives:

- Reduce the modeling paths of the same geometry and try to hack the "system errors".
- The model building process cannot be "trial and error".
- The quality of the model for reusability must be checked in a structured way, to detect undue associations that negatively affect the quality of the model.
- Structure design trees and models in a way that better communicates Design Intent.
- Assist in the process of embodiment with strategic knowledge and parameter detection [10].

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