Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 109 (2022) 383–388

www.elsevier.com/locate/procedia

32nd CIRP Design Conference

Geometric Variability in Parametric 3D Models: Implications for Engineering Design

Aritz Aranburu[a]*, Daniel Justel[a], Manuel Contero[b], Jorge D. Camba[c]

[a]*Mondragon Unibertsitatea, Arrasate-Mondragon 20500, Spain*
[b]*Universitat Politècnica de València, València 46022, Spain*
[c]*Purdue University, West Lafayette, IN 47907, United States*

* Corresponding author. Tel.: +34-627-794-579; fax: +0-000-000-0000. *E-mail address:* aaranburug@mondragon.edu

---

Abstract

Modern manufacturing companies operate in environments characterized by increasingly shorter development cycles and the need to develop highly customizable products at competitive prices. In this paper, we examine the role of parametric 3D modeling in the product development process, and highlight the importance of robustness, flexibility, and responsiveness to geometric variations, which are particularly relevant in the context of the Model-Based Enterprise (MBE). We discuss the often-inefficient parametric 3D modeling practices used in industry, their root causes and implications, and identify the detrimental effects of low-quality models on engineering design activities, specifically design changes during development, generative design algorithms, design optimization, simulation, product/part family configuration, AI-based parametric modeling, Model-Based System Engineering (MBSE), and parametric and adaptive encryption. Finally, we present future lines of research aimed at increasing the quality of parametric models.

Keywords: Parametric modeling; CAD quality; CAD reusability; modeling methodologies

---

1. Introduction

In the current global economy, manufacturers are continually challenged to offer innovative products at competitive prices in increasingly shorter development cycles. The development of complex products leads to more complex value chains on an international scale, which require cooperation between multiple stakeholders and engineering disciplines. In this context, Industry 4.0 initiatives are gaining significant traction. Industry 4.0 increases competitiveness by leveraging advances in computing and industrial technology and the ability to manufacture products on an individualized basis. It is characterized by increased flexibility, knowledge reusability, interconnectedness and shorter development life cycles.

Industry 4.0 is tightly coupled with the concept of the Model-Based Enterprise (MBE). In an MBE environment, the digital product representation is used as the vehicle for managing, communicating, and sharing design information. The digital product model becomes the central element of the enterprise around which all other activities revolve. It is also the main data acquisition source and enables activities in different disciplines and downstream processes. The deployment of the MBE paradigm poses several challenges [1]:

- Flexibility requires rapid redesign and/or change of the component and/or the manufacturing system. 3D model reusability, i.e. the ability to use the geometry of existing 3D models in other contexts and applications, and the degree of adaptability or flexibility of those geometries, becomes critical [2].

10.1016/j.procir.2022.05.266

- Interconnectivity between different areas and systems requires interoperability between disciplines and state-of-the-art technologies [3].
- Small inconsistencies between languages of different disciplines can lead to unintentional data errors which may result in additional costs when they occur in downstream processes [3].

In response to the aforementioned needs, Product Lifecycle Management (PLM) systems provide a digital environment to manage the entire life cycle of the product. The geometry of the digital product, however, is defined in a CAD system, which is often compatible and highly integrated with the PLM system. CAD systems have been employed since the 1980s, and the most widely used rely on feature-based associative parametric technology [2,4].

In this paper, we discuss the role of parametric 3D modeling in the product development process. The importance of robustness, flexibility, and responsiveness to geometrical variations is highlighted, particularly in a Model-Based Enterprise (MBE) context. We identify the inefficiencies of common industrial practices employed to construct 3D models, and discuss the impact of robust and flexible models on a series of engineering activities and disciplines that are particularly susceptible. Our goal is to expose the extent of the problem, which is generally acknowledged in industrial environments, but not necessarily well understood or even properly defined.

2. Common industrial practices

During the parametric modeling process, geometry is built by iteratively combining features (geometric or semantic elements) defined by parameters and constraints. The selection of appropriate features and the order in which they are created are critical, as they determine the parent/child dependencies that will be established in the model [4]. The process defines the modeling sequence, which is represented as a design tree in the CAD system. This design tree conveys the design intent of the model by capturing the expected behavior in the face of possible alterations and variations [5,6]. The general steps to construct geometry in a parametric CAD system were summarized by Hartman [7] as shown in Table 1.

Table 1. Common modeling procedure [7].

Common modeling steps
1. Determine sketching plane
2. Sketch profile
3. Add constraints/relations
4. Add dimensions
5. Apply feature form
6. Repeat steps 1-5 to add major features
7. Add material-removal features (holes, cuts, etc.)
8. Add finishing features (round, fillets, etc.)

While this is a valid procedure to develop new geometry, problems often arise if reusability is not prioritized during the modeling process. The fact that a particular model is geometrically and topologically correct does not necessarily mean that it will be easily editable or that it will react to changes in a predictable manner when future modifications are made. Indeed, designers must understand the internal structure of the model before being able to modify it [4]. Making a model reusable is challenging, especially as complexity increases [4]. Additionally, design intent must be properly captured, which is a difficult task for various reasons:

- There are many possible solutions to construct the same geometry [4,8], as shown in Fig.1. All solutions may be geometrically valid but not all will be equally robust and flexible to design changes.
- The geometric modeling process is often based on “trial and error” approaches and/or relies heavily on the experience of the designer [8].
- The successful reuse of a 3D model is dependent on the modeling procedure of the original designer [9].

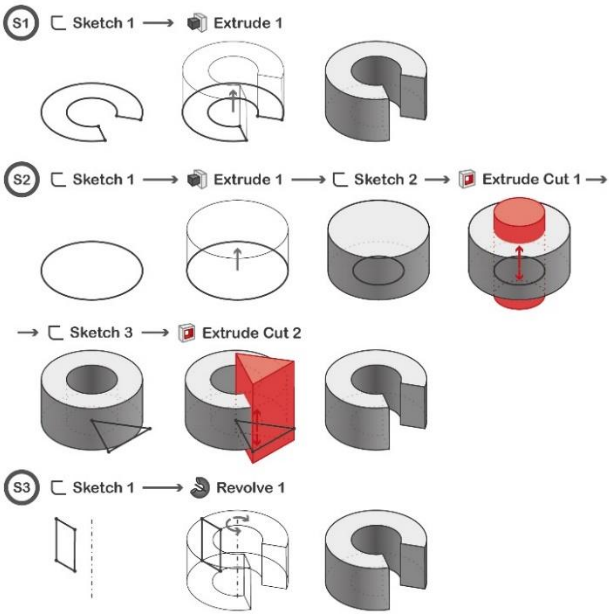


Fig. 1. Example of three different solutions to generate the same geometry.

To increase the reusability of 3D parts and enhance collaboration among designers, some companies use custom (and often proprietary) CAD guidelines [2],[4]. The level of detail in these ranges from basic naming conventions and strategies for homogenizing design trees to establishing common modeling practices across the organization. Furthermore, most organizations are aware of the complications of working with low-quality models and acknowledge the importance of CAD reusability. However, the extent of the problem remains largely unknown, partly because there is not a cost model to quantify the time, effort, and overall resources lost due to inefficient modeling procedures [10]. In a qualitative study by Salehi and McMahon [11,12] the authors concluded that:

- It is difficult for designers to identify, determine, and represent parameters and associative relationships.
- Designers face more challenges dealing with the relationships between parameters and associative geometries than with the product itself.
- Associative relationships are poorly thought out and elaborated. Designers are usually not aware of the consequences.

- Design trees are often poorly structured, and thus it is difficult for third parties to modify them or find information.

Some formal modeling methodologies have been proposed to mitigate the aforementioned problems, most notably horizontal modeling [13], explicit references modeling [4], and resilient modeling [14]. The first strategy consists of transforming the design tree by creating dependent relationships only between Cartesian planes and construction features [13]. The second strategy focuses on relating features to explicit references rather than existent geometry [4]. The final strategy is based on specific rules that categorize features according to their volatility, defined as the tendency of each feature to cause regeneration errors when the model is altered [14].

The value of formal methodologies has only been studied through the lens of manual design changes. For example, research has shown that CAD models are significantly easier to change and alter when they are built according to a formal modeling methodology [2,4,15]. However, the effect and impact of CAD quality and reusability on other downstream processes have received comparably less attention.

In addition to formal parametric modeling methodologies as a strategy to tackle the problems caused by common industrial practices, some CAD systems are incorporating direct editing modules [16]. However, the functionality of these systems is rather limited for industrial applications [17]. Although recent works are beginning to resolve some of the inconsistencies in direct modeling [18–20], the topology of the 3D models used in these studies is relatively simple. The peculiarities of direct modeling make it more appropriate for: 1) conceptual design phases, 2) editing non-parametric models without complex topology in real time, and 3) any case where the result of CAD data exchange is a B-REP model [21].

In this paper, we examine the impact of CAD quality on eight design activities and discuss how low-quality parametric models can significantly affect the flow, time, and effort required to complete these activities.

3. Impact of CAD quality on design activities

3.1. Design changes during development

Increased complexity and shorter product development cycles have forced organizations to migrate from classic linear processes to concurrent engineering paradigms [22]. Concurrent processing, while more agile and time efficient, is also more difficult to manage, as interdependencies between tasks call for greater collaboration between different disciplines and working groups. The course of execution becomes non-linear and iterative, and the inherent complexity of concurrency means there is no guarantee that the iterations will converge to the requirements of the objective [22]. Thus, in each iteration, the requirements are fulfilled to a greater or lesser extent and the design evolves until the objective is progressively achieved.

Design verification is a concurrent activity which occurs throughout the project life cycle. When attempting to meet the requirements in each iteration, geometric modifications are often made to the 3D model in response to review feedback. Likewise, change management processes generally involve modifications to the product geometry, and consequently, changes in the 3D model. Some reviews are minor and require little effort to implement, but in the worst-case scenario, the designer will need to go back to the drawing board and remodel from scratch.

In these previous situations, geometric modifications are performed manually by designers. It is thus in the modification stage that the quality of the 3D model becomes evident. A quality model requires minimal time and effort to edit, whereas low-quality models are difficult to edit, require expert users, or are not cost-effective to modify due to error propagation in the design tree. In this regard, the goal of constructing quality parametric 3D models is to maximize reusability, ensuring that every iteration is executed with optimum efficiency.

3.2. Generative Design Algorithms

Although CAD systems are essential tools used by designers in the development process, design decisions are entirely in the hands of the human operator. In recent years, however, computers have begun to participate in a more integrated manner in the creative process [23].

In generative design approaches, designs are constructed by algorithms [24] which may be executed automatically or in collaboration with the designer [23]. Automated methods such as Krish's [25] can help designers explore design options from the early conceptual stage and generate alternative solutions automatically without any human intervention.

The key factor for the successful execution of algorithms is design parametrization and the definition of the design space. However, it is hard to maintain the original physical form of a model with a vast number of parameters during parametric modification [26]. The design space may be too restricted to enable the construction of the 3D model in the conceptual phase, particularly when creativity and innovation may be key requirements.

In the strategy proposed by Khan and Awan [24], important features are first parametrized with a large number of geometric parameters. After some iterations, problematic parameters which might disrupt the underlying structure of the model or might be less relevant to the overall variation, are eliminated. Furthering this strategy, Khan *et al.* [26] focused on the development of a psycho-physical distance metric for candidate designs, which was based on capturing user preferences using geometric constraints and reducing the design space in each iteration, as illustrated in Fig. 2.

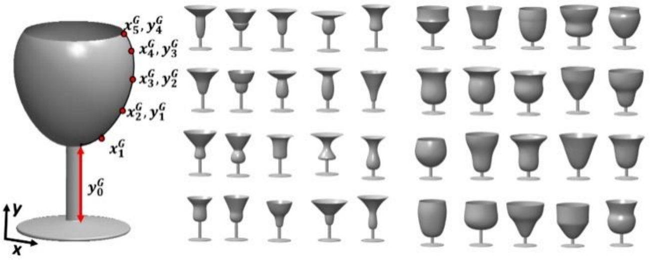


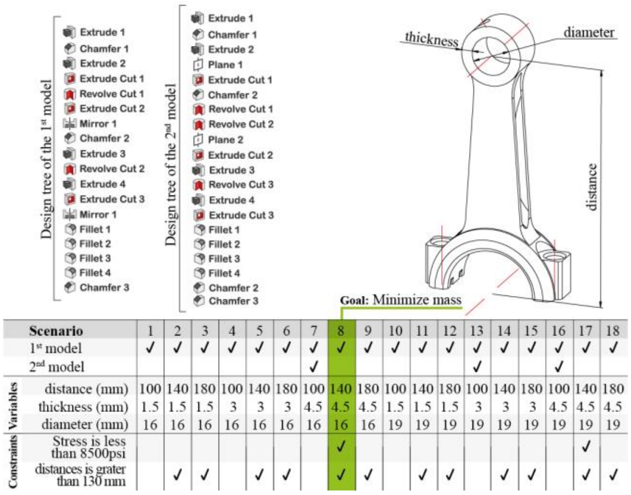
Fig.2. Parametric representation of a wine glass model and various design alternatives generated automatically (adapted from [24]).

Naturally, if high-quality robust models can be built deliberately in the face of geometric variations and used as the basis for generative design techniques, these algorithms can contribute beyond the conceptualisation phase and have applications in sectors such as naval (e.g., the parametrization of hull's geometry [27]) and railway (e.g., for the aerodynamic design of the heads of high-speed trains [28]).

3.3. Design optimization

Design optimization tools enable the automatic generation of geometric variations from a source 3D model by specifying a set of design criteria that the new models must meet, and the parameters and dimensions of the model that are allowed to change. These tools evaluate and optimize designs by automatically manipulating the geometry using various combinations of the input values and determining the output for each combination and/or the optimal combination of values that meet the design goals specified by the user. Goals and criteria can be dimensional (e.g. width of the model must be below a particular value) or engineering constraints (e.g. the stresses on a part must not be greater than a specified value). An example of a design optimization tool is shown in Fig.3.

The success of design optimization tools that use parametric models as input depends largely on the robustness and overall quality of the constructed geometric models. A parametric model that is not robust and flexible will likely cause geometry regeneration errors during optimization processes, which means that many design scenarios will not be processed successfully. The designer will then be required to fix the original geometry manually, or worse, disregard the potentially valuable design alternatives that failed to process.



	Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	1st model	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2nd model							✓						✓			✓		
Variables	distance (mm)	100	140	180	100	140	180	100	140	180	100	140	180	100	140	180	100	140	180
	thickness (mm)	1.5	1.5	1.5	3	3	3	4.5	4.5	4.5	1.5	1.5	1.5	3	3	3	4.5	4.5	4.5
	diameter (mm)	16	16	16	16	16	16	16	16	16	19	19	19	19	19	19	19	19	19
Constraints	Stress is less than 8500psi								✓									✓	
	distances is grater than 130 mm		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓		✓	✓

Fig. 3. Design optimization results in SolidWorks Design Studies

3.4. Simulation

Simulation software uses digital models to evaluate and predict the performance and behavior of part/products based on physical laws to assess key design and manufacturing factors. Simulation tools assist in the development of better products, ensure the process is faster and cost effective, and delimit the part/product design space [26].

The continuously increasing power of computing technology coupled with the development of more sophisticated and accurate simulation tools have significantly expanded the range of applications and the amount of simulations performed during the development of a product. With simulation, designers can verify whether design requirements are converging into the objective. In many cases, simulation and analysis can replace physical testing for design validation. However, analysis and simulation often involve design changes, which frequently require changes to the geometry of the model, particularly when these tools are used in early stages of the design process or as part of digital twins or generative design strategies.

In addition to the inherent variance in how different CAD systems process data, poor modeling practices can significantly contribute to the propagation of low-quality models which often leads to issues during simulation stages. Indeed, it is estimated that roughly half of all engineers spend over four hours a week fixing design data and 15% of those spend over 24 hours a week fixing design data [29]. These numbers indicate that repairing design data is a problem that costs the engineering industry millions of dollars every year.

As the complexity and efficiency of engineered products increases, it is no longer possible to study a single aspect of performance or a single part in isolation. Modern simulation software allows designers to assess the overall performance of a product by simulating all influences simultaneously. As a result, instead of using simulation to verify a particular design, engineers use these tools to analyze thousands of possible alternatives until the optimal design is identified. As such, the ability of the digital model to vary and adapt to changes in order to respond effectively to these studies is key. In fact, in a recent study, the lack of robust CAD was identified as a critical barrier for the use of FEA-based variation simulation tasks [30]. Only by maximizing the quality of the model can designers minimize manual editing times and remodeling tasks.

3.5. Product/part families and configurations

Configurations are used to quickly establish a family of similar parts or assemblies by defining variations of an original model that respond to new needs or other cases of application, as shown in Fig. 4. These derived versions are made after the first model has been validated.

Fig. 4. Multiple configurations of an MP3 player [25]

In a CAD system, configurations are generated by identifying the parameters and features that will vary between the different models and assigning the corresponding values to these parameters. Configurations can be defined and controlled internally within the geometry of the original base model, or externally, through a spreadsheet-like data grid stored as a separate file. Once again, the successful generation of configurations depends mainly on the robustness of the parametric model. High-quality models enable the creation of new variations easily from configuration tables without the need to build and/or edit the 3D model from scratch.

3.6. AI-based parametric modeling

Artificial Intelligence (AI) allows software to become more accurate at predicting outcomes without being explicitly programmed to do so. In CAD, AI can accelerate the design process via generative modeling of associative parametric structures and by enabling new tools such as autocompleting, constraint inference, and conditional synthesis [31].

Using Machine Learning (ML) techniques, a branch of AI, organizations can leverage historical data to train algorithms, which gradually learn to be increasingly more accurate and make data-driven decisions with minimal human intervention. However, these programs are complex and require large datasets and considerable amounts of time to train the models.

Some studies have explored the application of ML to 2D sketching [31–35] by using drawings as a reference for creating geometric primitives (e.g. points, lines, arcs and curves) and relations between them (e.g.: tangency, symmetry, coincidence, parallel and orthogonal). Some authors limit their study to primitives without considering geometric constraints [35]. Others consider both [31,33,34].

In the study by Seff *et al.* [31], the authors explored the use of AI as a mechanism to accelerate the design process by focusing on autocompleting, constraint inference, and conditional synthesis. Similarly, Willis *et al.* [36] compared available databases and proposed a method to reconstruct 3D models based on human modeling sequences. The systems proposed by these authors succeeded in generating parametric sketches automatically.

Surprisingly, the few studies published on the use of ML in parametric CAD are grounded in datasets of models that have not been filtered through rigorous quality control checks [31,36]. Consequently, the models generated by these systems will also lack the quality and robustness required for effective reusability. In this regard, it is necessary to ensure that a quality-based parametric 3D model dataset is used for training. Otherwise, ML algorithms would replicate and further reinforce the current paradigm of inefficient modeling sequences and practices.

3.7. Model-Based System Engineering (MBSE)

Model-Based Systems Engineering (MBSE) is a paradigm which uses a formal methodology to develop a unified model that can coordinate architectural, behavioral, structural, functional, verification and other discipline-specific aspects of a system across the lifecycle.

System models are conceptualized as diagrams and graphs, which are created with sophisticated tools and standardized languages such as SysML. Information from these models must then be communicated to the rest of the organization and the various engineering disciplines (e.g. mechanical, electrical, software, etc.), which will complete the corresponding detailed engineering using specialized tools, including CAD. In this context, communication, traceability, and interoperability of MBSE data between systems engineering and the specific disciplines are fundamental.

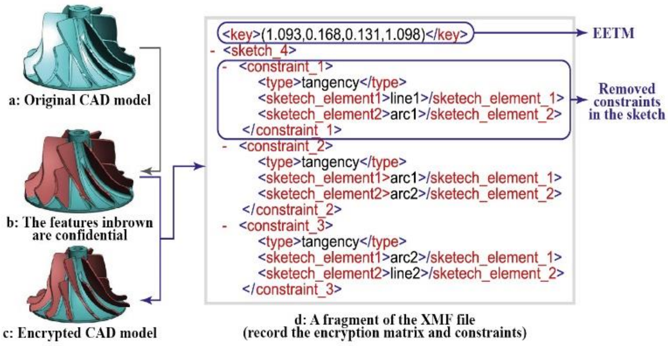
Some authors have attempted to improve interoperability and traceability of MBSE data within the product life cycle. For example, Brahmi *et al.* [37] proposed a methodology to facilitate continuity in product development between the design specification level and the detailed design level by facilitating data exchange. Likewise, authors Bajaj *et al.* [38] demonstrated: i) the seeding of mechanical design models (CAD) from system specifications as a starting point for mechanical design, ii) the definition of model-based connections between system and mechanical design parameters, iii) the abstraction of a system architecture from mechanical assemblies for transitioning projects to MBSE, and iv) the use of persistent, connections between system architecture and mechanical design models for continuous verification and communication.

Although MBSE data cannot yet be used to generate detailed 3D models automatically, it can serve as a seeding mechanism for producing the basic geometric structure of the part. Nevertheless, a major roadblock to interoperability between system architecture and CAD models continues to be the parameterization of 3D models, as identified by Bajaj *et al.* [38]. It is, therefore, essential to incentivize design teams to produce quality CAD models for connecting upstream with downstream tasks (e.g. System Engineering with simulation).

3.8. Parametric and adaptive encryption

When a 3D model is shared in the cloud for collaboration, it must be protected to ensure accuracy, privacy, and ownership. As such, the quality of a parametric CAD model plays a critical role in cybersecurity, particularly in the domain of parametric and adaptive encryption.

Researchers Cai *et al.* [39] presented a novel encryption approach based on geometric transformations of feature-based CAD models, where the 3D model is altered based on a set of encryption rules. When the rules are applied, the 3D model must regenerate successfully with no errors to ensure the geometric validity of the encrypted model while hiding key information in plain sight, as shown in Fig.5. Otherwise, when confidential features are not responsive to dimensional variations, the geometry of the "encrypted" model becomes invalid. This strategy can facilitate cloud collaboration between organizations while protecting intellectual property, as long as high-quality parametric models are used.



```
<key>(1.093,0.168,0.131,1.098)</key>
- <sketch_4>
 -  <constraint_1>
        <type>tangency</type>
        <sketech_element1>line1>/sketech_element_1>
        <sketech_element2>arc1>/sketech_element_2>
    </constraint_1>
 -  <constraint_2>
        <type>tangency</type>
        <sketech_element1>arc1>/sketech_element_1>
        <sketech_element2>arc2>/sketech_element_2>
    </constraint_2>
 -  <constraint_3>
        <type>tangency</type>
        <sketech_element1>arc2>/sketech_element_1>
        <sketech_element2>line2>/sketech_element_2>
    </constraint_3>
```

Fig. 5. Encryption process of a rotor part (adapted from [39]).

4. Conclusions and future research

In this paper, we discussed the detrimental impact of low-quality parametric 3D models in various engineering activities and pointed out the root causes derived from common industrial practices. In addition to the implementation of formal modeling methodologies [2,4,15] that prioritize quality and reusability (both in terms of manual changes and automated processes), four lines of research are identified:

- Define new objective quantitative metrics and formal processes to evaluate the robustness, flexibility, and responsiveness of parametric 3D models to geometric variations.
- Develop a comprehensive database with verified high-quality models for Machine Learning (ML) research.
- Create an accurate cost-model to quantify the time, effort, and overall resources lost due to inefficient modeling procedures [10].
- Develop detailed formal modeling methodologies to tackle the often-inefficient parametric 3D modeling practices.

References

[1] Vogel-Heuser B, Hess D. Guest Editorial Industry 4.0–Prerequisites and Visions. IEEE Transactions on Automation Science and Engineering 2016;13:411–3.

[2] Camba J, Contero M, Company P. Parametric CAD Modeling: An Analysis of Strategies for Design Reusability. Computer-Aided Design 2016;63:18–31. doi:10.1016/j.cad.2016.01.003.

[3] Zou M, Li H, Vogel-Heuser B. A Framework for Inconsistency Detection Across Heterogeneous Models in Industry 4.0. IEEE International Conference on Industrial Engineering and Engineering Management 2019:29–34. doi:10.1109/IEEM44572.2019.8978930.

[4] Bodein Y, Rose B, Caillaud E. Explicit reference modeling methodology in parametric CAD system. Computers in Industry 2014;65:136–47. doi:10.1016/j.compind.2013.08.004.

[5] Alducin-quintero G, Rojo A, Plata F, Hernández A, Contero M. 3D Model Annotation as a Tool for Improving Design Intent Communication: A Case Study on its Impact in the Engineering Change Process. ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Chicago: 2012, p. 1–8.

[6] Otey J, Company P, Contero M, Camba JD. Revisiting the design intent concept in the context of mechanical CAD education. Computer-Aided Design and Applications 2018;15:47–60. doi:10.1080/16864360.2017.1353733.

[7] Hartman NW. Defining expertise in the use of constraint-based CAD tools by examining practicing professionals. ASEE Annual Conference Proceedings 2005:2763–75. doi:10.18260/1-2--13970.

[8] Amadori K, Tarkian M, Ölvander J, Krus P. Flexible and robust CAD models for design automation. Advanced Engineering Informatics 2012;26:180–95. doi:10.1016/j.aei.2012.01.004.

[9] Bodein Y, Rose B, Caillaud E. A roadmap for parametric CAD efficiency in the automotive industry. CAD Computer Aided Design 2013;45:1198–214. doi:10.1016/j.cad.2013.05.006.

[10] Camba JD, Contero M, Company P, Hartman N. The cost of change in parametric modeling: A roadmap. Computer-Aided Design and Applications 2021;18:634–43. doi:10.14733/cadaps.2021.634-643.

[11] Salehi V, McMahon C. Action research into the use of parametric associative CAD systems in an industrial context. International Conference on Engineering Design, Design ICED'09, Palo Alto, CA, USA: 2009.

[12] Salehi V, McMahon C. Development and application of an integrated approach for parametric associative CAD design in an industrial context. Computer-Aided Design and Applications 2011;8:225–36. doi:10.3722/cadaps.2011.225-236.

[13] Landers DM, Khurana P. Horizontally-Structured CAD/CAM Modeling for Virtual Concurrent Product and Process Design (75) 2004.

[14] Gebhard R. 122 - A Resilient Modeling Strategy 2013.

[15] Camba JD, Cosin A, Contero M. An evaluation of formal strategies to create stable and reusable parametric feature-based 3D models. ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE) 2014;11:1–8. doi:10.1115/IMECE2014-37859.

[16] Shah JJ, Mäntylä M. Parametric and Feature-Based CAD/CAM: Concepts, Techniques, and Applications. 1st ed. New York: Wiley-Interscience; 1995.

[17] Ault H, Phillips A. Direct Modeling: Easy Changes in CAD? Graphical Expressions of Engineering Design 2016 2016:110.

[18] Zou Q, Feng H. Push-pull direct modeling of solid CAD models. Advances in Engineering Software 2019;127:59–69. doi:10.1016/j.advengsoft.2018.10.003.

[19] Zou Q, Feng HY. A decision-support method for information inconsistency resolution in direct modeling of CAD models. Advanced Engineering Informatics 2020;44:101087. doi:10.1016/j.aei.2020.101087.

[20] Qin X, Tang Z, Gao S. Automatic update of feature model after direct modeling operation. Computer-Aided Design and Applications 2021;18:170–85. doi:10.14733/cadaps.2021.170-185.

[21] Renno F. Feature-Based, Surface and Direct Modeling: an Aeronautic Point of View. 2017.

[22] Stjepandić J, Wognum N, Verhagen WJC. Concurrent Engineering in the 21st Century. Wageningen: Springer; 2015. doi:10.1007/978-3-319-13776-6.

[23] Mountstephens J, Teo J. Progress and challenges in generative product design: A review of systems. Computers 2020;9:1–23. doi:10.3390/computers9040080.

[24] Khan S, Awan MJ. A generative design technique for exploring shape variations. Advanced Engineering Informatics 2018;38:712–24. doi:10.1016/j.aei.2018.10.005.

[25] Krish S. A practical generative design method. CAD Computer Aided Design 2011;43:88–100. doi:10.1016/j.cad.2010.09.009.

[26] Khan S, Gunpinar E, Moriguchi M, Suzuki H. Evolving a psycho-physical distance metric for generative design exploration of diverse shapes. Journal of Mechanical Design, Transactions of the ASME 2019;141:1–13. doi:10.1115/1.4043678.

[27] Khan S, Gunpinar E, Mert Dogan K. A novel design framework for generation and parametric modification of yacht hull surfaces. Ocean Engineering 2017;136:243–59. doi:10.1016/j.oceaneng.2017.03.013.

[28] Wang R, Zhang J, Bian S, You L. A survey of parametric modelling methods for designing the head of a high-speed train. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 2018;232:1965–83. doi:10.1177/0954409718756558.

[29] Jackson C, Prawel D. The 2013 State of 3D Collaboration and Interoperability Report. 2013.

[30] Nerenst TB, Ebro M, Nielsen M, Eifler T, Nielsen KL. Exploring barriers for the use of FEA-based variation simulation in industrial development practice. Design Science 2021;7:1–22. doi:10.1017/dsj.2021.21.

[31] Seff A, Zhou W, Richardson N, Adams RP. Vitruvion: A Generative Model of Parametric CAD Sketches 2021.

[32] Seff A, Ovadia Y, Zhou W, Adams RP. SketchGraphs: A Large-Scale Dataset for Modeling Relational Geometry in Computer-Aided Design 2020.

[33] Para WR, Bhat SF, Guerrero P, Kelly T, Mitra N, Guibas L, et al. SketchGen: Generating Constrained CAD Sketches 2021.

[34] Ganin Y, Bartunov S, Li Y, Keller E, Saliceti S. Computer-Aided Design as Language 2021.

[35] Willis KDD, Jayaraman PK, Lambourne JG, Chu H, Pu Y. Engineering Sketch Generation for Computer-Aided Design 2021:2105–14. doi:10.1109/cvprw53098.2021.00239.

[36] Willis KDD, Pu Y, Luo J, Chu H, Du T, Lambourne JG, et al. Fusion 360 Gallery: A Dataset and Environment for Programmatic CAD Construction from Human Design Sequences. ACM Transactions on Graphics 2021;40. doi:10.1145/3450626.3459818.

[37] Brahmi R, Hammadi M, Aifaoui N, Choley JY. Interoperability of CAD models and SysML specifications for the automated checking of design requirements. Procedia CIRP 2021;100:259–64. doi:10.1016/j.procir.2021.05.064.

[38] Bajaj M, Zwemer D, Cole B. Architecture to geometry - Integrating system models with mechanical design. AIAA Space and Astronautics Forum and Exposition, SPACE 2016 2016:1–19. doi:10.2514/6.2016-5470.

[39] Cai XT, Wang S, Lu X, Li WD, Liang YW. Parametric and adaptive encryption of feature-based computer-aided design models for cloud-based collaboration. Integrated Computer-Aided Engineering 2017;24:129–42. doi:10.3233/ICA-160535.