

A review of the design intent concept in the context of CAD model quality metrics

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Abstract

From the perspective of Computer Aided Design (CAD), Design Intent is a term commonly defined as a model's anticipated behavior once it undergoes alteration (ex. will a cylindrical hole continue to share concentricity with a boundary arc should the dimensions be modified?). At present, a standardized manner in which to explicitly communicate or deduce a CAD model's design intent does not exist. The design tree (feature tree or history tree) in most parametric modeling applications offers implicit depiction of design intent, but not all descriptive information is adequately conveyed (ex. a sketch concentric constraint is not recorded in the design tree and is only accessible if the requisite sketch is opened and examined). An explicit representation would be immensely more valuable, especially for models with complex geometric features or for those working in a collaborative design environment. This paper reviews current understanding of design intent, with an exploration of its relationship to Design Rationale, in the context of product models and their quality enhancement.

Introduction

It is essential for engineers to describe not only the purpose of their designs, but also the justification for specific design decisions. Design Rationale is a term defined as an explicit documentation of the reasons behind decisions made when designing a system or artifact¹.

Although design rationale spans a number of diverse disciplines², it has been a significant issue primarily for software engineering³. However, software design requires different tools and approaches necessary to convey design rationale than those required for product design. Hence, a suitable way to convey design rationale for product design is still essential, a need that can be suitably accommodated with the concept of Design Intent⁴.

From our point of view, when considering virtual models and assemblies produced by 3D CAD applications, design intent is correlated to anticipated behavior or expected functionality of the artifact undergoing development. It represents what is to be achieved by a design and describes the expected behavior of the model when it undergoes later alteration. To the best of our knowledge, a standardized manner in which to explicitly communicate or deduce a CAD model's design intent does not exist. Hence, our current research is concerned with defining quality metrics to verify that design intent is properly incorporated in the modeling strategy to construct the CAD model. In this paper, a review of the current understanding of design intent, with its historical connection with design rationale is presented.

Design Rationale

Design rationale is a term that is conventionally understood to describe the purpose of a design, the reasons relating why certain steps were taken in artifact creation, and also aids communication in a collaborative environment, particularly for end users. This process is utilized

in various industries and is often accompanied by graphical structures which help illustrate specific design systems and processes.

Mostow, in investigating the global design progression, stated that design rationale is just one step in the design process⁵. According to Mostow, design rationale clarifies and justifies why a certain decision was made and why it was thought to be the correct path to take. Design rationales need to be both explicit (clearly defined goals) and appropriate (reasons given why a certain path was chosen). He states that any model of the design process should communicate the state of the design, the goal of the design process, specific design decisions and their justifications, the control of the process, and the role of learning in design. Mostow also claims that previous design rationales can be valuable in solving new problems, particularly when historical decisions and the reasons behind them hold true in future applications.

MacLean et al.¹ define the concept of design rationale, highlighting its role as an aid for both designers and end users. They also introduce a “semi-formal notation” aimed at representing design rationale. In a later work, MacLean et al. coined a process titled “Design Space Analysis” in order to characterize design rationale and this analysis was embodied by QOC Notation (Questions, Options, and Criteria)⁶. QOC Notation refers to questions identifying design concerns, options providing solutions to the questions, and criteria used to evaluate possible solutions. Design Space Analysis does not provide a written record of the design process, but is considered a co-product of the design and is required to be constructed alongside the artifact. Design Space Analysis supports not only the original design process, but also re-design and reuse by providing an explicit depiction of the process to assist reasoning about the design and the concerns of future alteration. It also provides a method for communication between the designers and system operators.

Lee and Lai placed the emphasis on “tasks” and developed a framework which allowed them to acquire and assess design rationale representations⁷. This framework increasingly discerns explicit elements of design rationale and supports multiple design tasks. They discuss and evaluate Decision Representation Language (DRL) in order to accomplish these tasks. DRL is used not only to support various design tasks, but can be used to assess and evaluate different design representations.

Henderson, in attempting to integrate physical and conceptual models, divided product models into physical and meta-physical domains⁸. The physical domain integrates all information related with a model’s actual manifestation, such as geometry, dimensions, and materials while the meta-physical realm refers to information that describes the structure and behavior of the model. It is argued that meta-physical modeling provides the capability to capture the function and design intent of systems, assemblies, parts, features, and even individual dimensions and tolerances. This modeling process uses Product Definition Units (PDU), which are shells in which to encapsulate information. Henderson indirectly defines design rationale, as he defines design intent as “the purpose or underlying rationale behind an object.” While this definition does not represent the current understanding of design intent, the term attempts to explain the difference between intent and functionality (“intent justifies a design decision whereas the functionality just tells what the design does”).

Karsenty evaluated the importance of representing design rationale in cases where the original design is reused⁹. His research questioned six designers about their need to understand previous design rationale, how archived design rationale was used, and how to effectively acquire design rationale. He states that design rationale could be beneficial for those requiring reinforcement for design-based decisions, but it is not adequate to be used as the sole support. In fact, he used the QOC Notation originally developed by MacLean et al.⁶ in order to document design rationale.

Regli et al. state that design rationale provides an explanation of why an object is designed in a certain manner². They explain that design rationale encompasses all information generated in product construction (reasoning, trade-offs, etc.) and facilitates communication with personnel who are involved in the artifact, but not in the design phase. An object is defined by its specifications or the way it operates, but often the methodology used to design the object is left unstated. A problem develops when design collaboration is needed and communication is absent. Design rationale is crucial to avoid these problems. They state that the need for design rationale is a collective problem, encountered in all industries, but design rationale systems are uncommon. Design rationale systems need to assess design approaches, representation schema, capture, and retrieval. A system which could capture such information would be important for those tasked with managing design data.

Bracewell et al. examined a Design Rationale Editor (DRed)¹⁰. This software instrument is used to archive decisions and rationale throughout the design process. DRed allows the designer to examine various decisions such as options considered and counterbalancing arguments. It then characterizes these decisions and records them in a graph illustrating various dependencies. They argue that the utility of DRed is based not only on acquiring design rationale, but synthesizing analysis, problem perception, developing solutions, and specific design tasks.

To summarize, Mostow⁵ first realized the importance of making the design rationale explicit, but his work was aimed at finding better models of the design process. On the other hand, MacLean et al.¹ focused on defining and representing design rationale. So they emphasize its importance, describe its benefits, and develop a representation to make it explicit⁶. Unfortunately, their representation is aimed at computer software design and does not consider product design peculiarities. Lee and Lai⁷ highlighted the importance of choosing a suitable representation, and provided a framework for evaluating a design rationale representation, but they still were also focused on software design. On the contrary, the work by Henderson⁸ defines design intent and design rationale for product models even though this definition does not represent the current understanding of design intent. A recent contribution on this context is due to Zhang et al.⁴, which is important because it not only highlights the relationship between design intent and design rationale, but also investigates why few design rationale systems have been implemented in industry. It appears that limitations exhibited by traditional approaches for capturing design rationale summarized by Karsenty⁹ and recently addressed by Bracewell et al.¹⁰ are still valid. Figure 1 illustrates an IBIS-like schema (Issue-Based Information Systems), created by the authors, summarizing the state of the art for design rationale and design intent. We note that the schema follows the IBIS style (first proposed by Kunz and Rittel in 1970¹¹) which is still the base on top of which new schemas are being developed (like ISAA (Integrated Issue, Solution,

Artifact, and Argument) by Zhang et al.⁴. It can therefore be seen that Henderson contributed to design rationale indirectly. Design rationale encompasses purpose, decisions, and communication. Functionality conveys purpose, and the literature on function reveals that this is a separate ambit where there exist many views of function, and not all of these views are made explicit¹². Design intent is also a stand-alone problem, which we will consider in the next section.

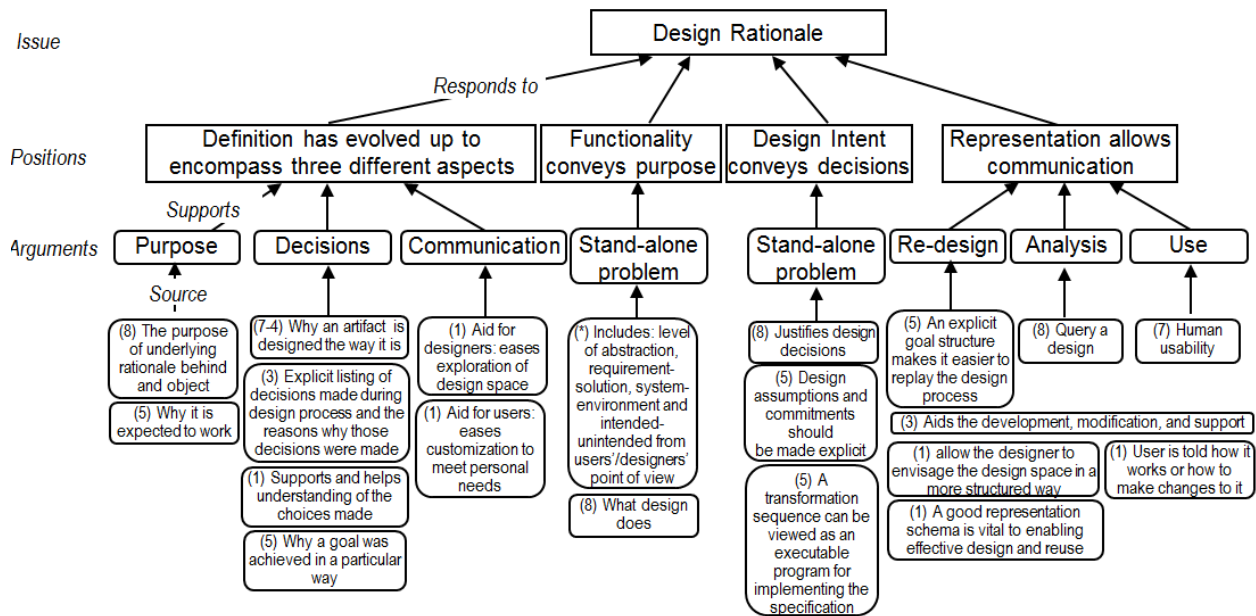


Figure 1. Schema illustrating current understanding of design rationale and design intent.

We note that the extent to which we can benefit from design rationale depends largely on the language we use to represent it⁷. The work by Karsenty⁹ is a significant contribution on measuring goodness of captured design rationale. The work by Bracewell et al.¹⁰ is also noteworthy as it describes a strategy to implement customized tools to capture, represent, and retrieve design rationale.

Finally, apart from an interesting review of the early contributions and the open problems, the work by Regli et al.² is also interesting as it clearly states the multidisciplinary nature of design rationale and attempts to abstract the place of systems and tools for design rationale capture and retrieval in the context of CAD tools.

Design Intent Definitions and Measurement

Design intent is commonly understood to describe a model's anticipated behavior once it undergoes alteration. Design intent is such a nebulous concept that applicable standards (ASME Y14.41-2003 and ISO 16792) do not provide a definition of design intent at all. While an official definition of design intent does not exist, many authors have attempted to define the term. In reality, it is a common assumption that a standard definition is understood already, as some

authors use the term without providing any definition: ex. Ault, in her paper on using geometric constraints capture design intent¹³.

Kimura et al. define design intent as the way original designers articulate the objectives of the design so that the manufacturer can understand the design process in order to ensure proper manufacturability without hampering design performance¹⁴. Design intent defined in this manner incorporates design requirements, behavior, and function while facilitating communication between designers and builders. They further state that design intent plays a vital role in communication in simultaneous design.

Rynne and Gaughran, in their research on modeling strategies in CAD pedagogy, define design intent as a description of how an object is modeled and also how it should perform once it is altered¹⁵. They also assert that CAD software records the succession of features used to create a model, which reflects the user's opinion of the best approach to accomplish a specific task. They further state that design intent should be more comprehensive than shapes and sizes of features, but must encompass consideration of manufacturing methods and relationships between features. A student's ability to accurately model an object correlates with their ability to visualize and assemble the objects cogently.

Zhang and Luo state that CAD illustrates design intent through its history, features, parameters, and constraints¹⁶. They state that design intent not only describes an artifact's requirements and constraints, but can also serve an expectant role in the design process. Their research examined methods used to share design intent information between models, but encountered difficulties resulting from an absence of standards and data-exchange procedures. Dorribo-Camba and Contero echoed these thoughts by stating that design intent is often embedded in the modeling approach and in the dependencies between features in the CAD software¹⁷. Their research details methods to represent annotations in order to enable increased design communication. These annotations are then housed and integrated in a Product Lifecycle Management (PLM) system.

While many authors have comparable definitions of design intent, they each rely on different methods in order to communicate this information to others. Some believe that the parametric modeling software can accurately record this data, but while the software can indeed reflect the specific steps taken to create the artifact, it cannot relate why certain commands were used (ex. why was it considered to be superior to "extrude" a profile rather than to "revolve" a profile?). In the authors' opinion, methods need to be developed so that this information can be documented and design justifications understood, and it would also be highly beneficial if this data extraction could be represented in a graphical format.

Even when commonalities exist between various definitions of design intent, oftentimes the manner in which it is assessed (if it is even assessed at all) is flawed. As just to name one example, design intent that is judged by the amount of features is inherently flawed, as the number of features could be independent of model efficiency.

Design Intent Instruction

There has been abundant research performed into methods to increase the amount of design intent available to be communicated, with much of this effort being aimed at beginning CAD learners. Condoor states that historically, there was one correct depiction of an artifact¹⁸. But with CAD, that artifact may be created using several different approaches, with some techniques being superior in that they more successfully reflect design intent. Condoor defines design intent as "the purpose or function of a feature in a part or of a part in an assembly." He determined that there is a substantial connection between the methodology used to create models and the inherent design intent. He proposes a procedure to instruct CAD learners to better reflect design intent by subdividing assemblies into parts, and parts into specific entities; identification of symmetry; proper datum plane orientation; design sequence; and hypothetical changes.

Hartman, in a two-part study attempting to determine how experienced CAD designers achieved their current level of expertise, states that new CAD learners need curriculum that provides instances where models are created, altered, and model geometry can be manipulated so that they can be adequately prepared for real-life design complexity^{19 and 20}. Curricular exercises need to be created so that the correctness and acceptability of an artifact can be related to the model's response to future design changes, both expected and unexpected.

Johnson and Diwakaran state that while rapid model creation is valued, creating designs quickly adversely affected design intent and model perception²¹. They state that the quality of a model should correlate with the amount of time needed for revision, which attempts in some way to quantify design intent and its communication between users. In a continuation of their research, Diwakaran and Johnson state that CAD models must be easy to change so that design alterations in the product development cycle are accomplished quickly²². It was determined that using simpler features increase the time required to model the original artifact, but increase the reuse of the model in future incarnations. Additionally, simple features, along with use of reference datum and correct feature sequence increase model understanding when undergoing alteration by secondary users. Feature alteration and reuse is positively correlated with model perception.

Li et al. researched methods to detect design intent by primarily using symmetry²³. They emphasized identifying design intent by locating prospective geometric abnormalities. Li et al. state that design intent can be properly articulated by geometric constraints and associations between edges, faces, and dependent geometries of CAD models. Their work focused on models bounded by planes, spheres, and cylindrical surfaces, but did not focus on common curved geometries.

Leahy conducted research on methods to encourage best modeling practices on CAD learners in order to ensure proper design intent²⁴. Leahy suggested that well-timed feedback of student performance is needed so that students can incorporate best practices for design intent. He suggests that this feedback be non-graded in order to encourage students to strive for deeper knowledge instead of being motivated only by higher marks.

Company et al. conducted a pilot study and found that instructing beginning CAD users to employ parametric modeling software oftentimes does not include appropriate levels of

instruction on model assessment and evaluation²⁵. They suggest simultaneous introduction of proper modeling strategies when learners are beginning to model, using specific rubrics in order to evaluate a model's representation of design intent. It was also determined that instruction of proper modeling strategies does not necessarily imply that proper model evaluation techniques were also imparted.

Conclusions and Future Work

As a result of the review of the design rationale subject, we can state that design rationale related to product design is now a well-established subject, which has inherited most of its approaches and strategies from design rationale of software design processes, but which is now becoming a stand-alone subject with particular needs, methods and tools.

One of its main peculiarities is the fact that design intent is a main aspect of design rationale of product design. Design intent is commonly, but not always, understood to describe a model's anticipated behavior once it undergoes alteration, but the manner in which it is assessed (if it is even assessed at all) is flawed. There is a consensus that modeling tools and strategies greatly influence design intent. There is also agreement in the convenience of introducing design intent through proper modeling strategies when learners are beginning to model. Strategies and approaches aimed at adding design intent into CAD models to enhance their quality, together with metrics aimed at evaluating its efficiency, are now receiving some attention.

Plumed et al. researched methods to determine design intent embedded in 2D sketches²⁶. A drawing can be dissected into its features and analysis of these combinations of features can illuminate design intent. The most common features can then be catalogued and identified. Continuing research will attempt to examine the feasibility of creating algorithms which mimic designers' experience and knowledge to deduce design intent from sketches.

It would appear that rubrics would be an exceedingly useful tool in order to facilitate standardized design intent communication. Goodrich, in her pioneering research on rubrics, defined them as tools for assessment that not only specify important curricular concepts, but gradations between quality levels²⁷. Rubrics are important not only for assessment, but also for communication of expectations.

Of current interest, and a topic of particular focus, is how to define qualities of design intent (and model quality) in such a manner that lends itself to easy assessment. More precise definitions of these terms are vital to any productive research being accomplished. What is envisioned is further development of these concepts in order to construct assessment rubrics to accurately represent comprehensive model quality and design intent depiction, with the goal of standardizing such definitions and assessment strategies. These rubrics must be hierarchical in nature, allowing distinct levels of detail, seamlessly woven into the curriculum allowing for cumulative assessment.

The final product of this research would be development of detailed protocols for learners, so that they could self-assess whether their models achieve expected quality criteria. An advanced goal would be to produce design tools which would check and repair intermediate models with

missing quality criteria. It is our conviction that CAD model quality should not be a correlative goal only to be attempted after basic skills are cultivated, but should be a principal goal from the inauguration of instruction.

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