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Assessing the impact of geometric design intent annotations on parametric model alteration activities

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ABSTRACT

The effective representation and communication of design intent plays a crucial role in CAD model alteration activities. In history-based parametric modeling systems, design intent information is usually expressed implicitly within the model. However, there is evidence that suggests that an explicit representation can increase productivity and quality and facilitate the transferring of design knowledge throughout the different stages of the product lifecycle. In this paper, we assess the effectiveness of 3D annotations as mechanisms for explicit design intent representation and examine their impact in model alteration processes that require a direct interaction with the model's geometry. We present the results of a series of studies aimed at measuring user performance and model quality in two scenarios. First, we hypothesized that annotations are valuable tools to provide design information when inadequate modeling assumptions can be made by designers. Second, we evaluated annotations as tools to communicate design decisions when multiple options are available. In both cases, results show statistically significant benefits of annotated models, suggesting the use of this technique as a valuable approach to improve design intent communication.

1. Introduction

In our modern globalized world, the development of new products is a fundamental activity for enterprise survival and competitiveness. Particularly, the transition towards a Model-Based Enterprise (MBE) represents an opportunity for increased performance and efficiency [1,2]. Current methods for new product development are largely based on the collaborative engineering paradigm, which relies strongly on the digital representation of the product, usually in the form of CAD models. In fact, it is the efficient use of these digital models what determines the benefits of a successful implementation.

A key factor in new product development activities is the ability to reuse and apply knowledge and designs obtained from previous processes [3]. The high pressure put on engineering firms for delivering better products faster and more economically is giving design reuse (particularly CAD model reuse) an essential role to achieve these objectives. In theory, modern CAD systems allow reusability of existing CAD elements, both as templates for new versions and configurations of the design and as a starting point for new product developments. However, the degree of reusability of a CAD model strongly depends on the modeling methodology and the proper definition and communication of the geometric design intent rather than the technology [4].

In feature-based CAD packages, design intent is typically conveyed implicitly within the CAD model in the form of parent-child relations between features of the model, which are typically displayed as a design tree or history tree in the interface of the parametric modeling software. Before the model can be altered, however, the designer must examine the model structure carefully to gain a thorough understanding of the modeling strategy and procedures used, which often requires a significant effort, even for simple alterations. This situation is particularly noticeable when the designer in charge of altering the model is not its original creator [5]. In order to overcome some of the obstacles of the internal representation of design intent, some authors have proposed the use of 3D annotations as a mechanism to embed this information into the CAD model's geometry, thus making it explicitly available [6–8].

In this paper, we present the results of a series of experiments that evaluate the effectiveness of 3D annotation techniques in

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terms of design intent communication and reusability. We begin by reviewing relevant work in the areas of CAD model reusability (and how it relates to model alteration), design intent communication, and 3D annotations in engineering design. Next, we describe the experimental setup and procedures, and define how annotations were used in the studies. For each experiment, we present a statistical analysis, which confirms the value of annotations as mechanisms to carry design intent information. Finally, we discuss our results and conclude with suggestions of future research lines.

2. Related work

2.1. CAD model reusability

Engineering design firms are under constant pressure to increase performance, product quality, and innovate while reducing development times and costs. To guarantee competitiveness in modern markets, new methods and processes need to be put into practice [2]. For example, collaborative design methodologies are rapidly replacing traditional sequential product development models, and the Model-Based Enterprise (MBE) paradigm is increasingly gaining popularity.

Modern collaborative design is typically accomplished by different individuals from various disciplines who work independently yet in combination with others in a network of design, modeling, and engineering efforts. In order to ensure that all pieces can fit and work together seamlessly in a final functional product, significant coordination and organizational efforts are required at all levels of the product life cycle, from the big-picture designs to the smallest details, which all demand time and resources. A highly effective approach to collaborative design relies on an efficient leveraging of 3D digital data. In this context, CAD models have become fundamental assets that can be shared among different stakeholders and moved throughout the different stages of the product lifecycle [9–11].

A critical factor for a successful implementation of collaborative product design methodologies in industrial environments is the ability to redesign existing products and apply knowledge from previous processes to new design challenges [3,10,12]. The importance of design reuse is particularly noticeable in the area of CAD modeling and representation of digital elements. According to the companies that participated in the study conducted by the Aberdeen Group [10], reusing design elements translates into significant savings. This study also reported that the top performing companies intentionally invest time and resources to capitalize on reusability. In the area of automotive engineering, for example, Bodein et al. [13] concluded that reusability of existing CAD models largely determines the modeling strategies followed by designers when creating new products.

There are, however, problems that need to be solved. The main obstacles that impede a practical and effective implementation of CAD model reuse (and thus design reuse) as well as general procedures that companies are putting into practice to overcome them were identified by [10] and are listed in Table 1.

Table 1
Challenges and responses to CAD model reusability (adapted from [10]).

Challenge	Procedure
1. Model modification requires expert CAD knowledge	Train users to increase CAD skills
2. Models are inflexible and fail after changes	Design for wide range of modifications
3. Users cannot find models to reuse	Centralize design data in library accessible structure
4. Only original designer can change models successfully	Detail design information in model

There is clear relationship between challenges 1 and 2, as they both involve the creation of better designed models. CAD users need to be trained in CAD methods, tools, and technology, and develop good modeling skills to create models that are reusable and easy to maintain. Challenge 3 can be classified as a data management problem that demands effective tools and information management mechanisms such as Product Lifecycle Management systems (PLM). Finally, challenge 4 requires formal methods to incorporate various types of design information (Geometric Dimensioning and Tolerancing, manufacturing instructions, etc.) within the CAD model. Recent Digital Product definition standards such as ASME Y14.41 [14] and ISO 16792 [15] and latest advances in the area of Model-Based Enterprise have facilitated this task to some extent since they have formalized how certain product information must be presented in a 3D model.

The long term vision of model-based engineering approaches is to use CAD models as carriers of design knowledge, where all product information is contained within the geometry. However, for this information to be useful, users wishing to use it must be able to understand the reasons behind modeling decisions and the rationale of the design. One of the key benefits of CAD is the ability to reuse models and designs, but those benefits depend in part on discerning design intent and understanding why the model was created in a certain manner [16,17]. As projects become more complex, teams more distributed, and workers more transient, capturing design knowledge becomes more important because team members will increasingly work with design knowledge created in part or in whole by other professionals.

In the following section, we examine the concept of design intent and how it relates to reusability. Next, we assess the importance of an explicit representation and explore the challenges we face when developing design intent and knowledge management mechanisms.

2.2. Design intent communication and design annotations

There is no general consensus on the exact definition of design intent, and many researchers on the subject have suggested their own definitions [18–22]. Nevertheless, the definition proposed by Iyer and Mills [17] after an extensive and comprehensive review that identified elements that were common to all interpretations in the domain of 2D CAD has been widely accepted: "Design intent contained in legacy CAD is the insight into the design variables (design objectives, constraints, alternatives, evolution, guidelines, manufacturing instructions and standards) implicit in the structural, semantic and practical relationships between the geometric, material, dimensional and textual entities present in the CAD representation." [17]. In this research, "design intent" or "geometric design intent" will be used indistinctly to express the reasons that motivate a designer to follow specific CAD modeling procedures so that the model behaves predictably as intended when modified.

The importance of design intent and the benefits of an explicit representation are undeniable. Researchers Pena-Mora et al. [23], summarize these advantages in the form of four points:

- Changes in complex projects require certain design decisions to be modified during the development process. When the justifications defined during the initial stages are lost, they need to be recreated, which has a negative impact on project costs and development times. The ability to store, process, and retrieve this information can significantly improve productivity.
- When design intent information is represented explicitly and is easily available for review, the overall quality of the product increases.