A User Study to Examine the Different Approaches in the Computer-Aided Design Process

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Abstract. The computer-aided design process is in a complicated non-linear structure involving selections from a pool of configurations with optimized parameters. In order to understand and improve this decision-making process, this paper conducted a user study on students and expert professionals with more than three years of computer-aided design experience. The study revealed the common design problems and challenges faced by CAD designers. The findings also showed that the design approaches students and expert professionals used were different. Additionally, we found that computer-aided designers expect the system to be able to understand vast quantities of multivariate data, control high-quality products for low costs, manage the knowledge personalization and codification within the company, as well as prevent the design mistakes at the design stages. Our findings may lead to the future development of new approaches to improve the computer-aided design process and close up the gap between student and expert professionals in computer-aided design. This paper provides initial support for this future approach.

Keywords: User study · Computer-aided design · Design process

1 Introduction

Situated in the highly competitive industry markets, companies are facing many challenges such as reducing design time length and lead-times, quick design turnovers, and significant quality improvements. Computer-aided design (CAD) must be optimized to reduce development time while satisfying constraints and improving manufacturability. The engineering design process is a complicated non-linear model involving selections from a set of configurations. Thus, a deep understanding of design problems in computer-aided design is very important for researchers and practitioners to build a decision-making tool to assist the process.

Poli [1] introduced three basic engineering design problem types: conceptual, parametric and configuration designs. Conceptual design involves the gathering of customer requirements and transforming these statements into parameters [2]. The parametric design achieves optimal values for parameters and satisfies a set of

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requirements [3]. Configuration design selects and combines a set of pre-defined components to meet unique requirements [4]. Many design tasks that aim to solve these problems involve selection from a set of configurations followed by parametric optimization of the chosen configuration [5]. However, we see people use different ways to solve these design problems although they mostly follow the same general approach. In order to better understand this complicated design process, we conducted a user study to gather participants' descriptions of their design experience from both students and professionals in the CAD field.

2 Related Work

2.1 Scientific Foundations of Design

Many design problem can be informally described as a problem in which a set of needs and desires is given and where the solution is a description of some structure that satisfies these needs and desires [6]. Often, the needs and desires are specified in an informal way and leave much unsaid. The designer has to perform an analysis process that transforms the needs and desires into a more formal and complete set of requirements and constraints.

Some researchers utilized an input-output model to describe the design process [7]. The design process is to compute a set of performance parameters from a set of input parameters, based on a mathematical model. The design task is to specify a set of inputs that yield outputs satisfying specified criteria. These inputs typically include a configuration choice as well as values for the parameters associated with that configuration, called design parameters. Values for design parameters must satisfy constraints among variables arising from specialized engineering and other disciplines. The form of the constraints varies in complexity from heuristics to logical relations, to partial differential equations.

Some researchers are particularly interested in developing tools to assist the designer in the preliminary phase of engineering design, by making more information available on the performance of design alternatives than is available using conventional design techniques [8]. This technique calculates the approximate output quantities from the imprecise input parameters for each of the design alternatives and determines the qualitative relations between the input parameters and the performance parameters (outputs). The designer is able to rank the input parameters according to their impact on the performance parameters and to rate a design alternative according to its merit in relation to the others under consideration.

2.2 Computer-Aided Design in the Design Process

Computer-aided design (CAD) has been widely used to create 2D and 3D graphic representations from conceptual design to manufacturing. In addition to traditional drawing and sketching, both novice designers and highly experienced designers complete the concept design, embodiment design, and detail design phase through CAD tools [9]. However, as CAD tools are sophisticated, it still remains unanswered how CAD application affects the cognitive aspects of problem-solving in the design process and the final design. Veisz, Namouz, Joshi, and Summers [10] investigated the CAD design process through a case study of a senior design project. The researchers found that CAD tools positively contribute to design efficiency and effectiveness in the later design process. The use of CAD at the earliest stage of design may lead to a loss of design efficiency and effectiveness. Häggman et al. [11] asked eighteen experienced engineers and designers to generate concepts and address design task using sketches, prototypes, or CAD. The study aims to examine how designers generate and represent ideas, as well as the interplay between the choice of the design tool, design attributes, and user evaluations of design quality. Pei, Campbell, and Evans [12] conducted empirical research to reveal the inter-disciplinary collaboration pattern during new product development. They found that inspiration sketches were never employed by engineering designers. Sketches and drawings are mainly used at the concept design and development stage. Models and prototypes are commonly used at the embedment design and detail design stages.

Research has shown that the CAD design process demands the appropriate design tools and methods. In turn, different design tools affect the design exploration and final outcome. To better understand the impact of design tools on the design process, further empirical research on understanding CAD designers' design approach and strategy is recommended.

2.3 Knowledge-Based Capturing for CAD Design

In this paper, we also explore the formal foundations of methods to solve a class of design problems that require the assignment of values to a set of design parameters (parametric design). A general approach is to use knowledge-based systems to assess product design, determine tooling needs, complete their process designs and deliver products on time [13].

Rocca [14] provides a comprehensive review of Knowledge Base Engineering (KBE) in the purpose of extending the level of understanding of its technology fundaments. KBE system is developed towards the specific needs of the engineering design, which comes from a cross point of diverse fundamental disciplines of artificial intelligence (AI), computer-aided design (CAD) and computer programming. Some of the KBE features are caching and dependency tracking. KBE product model represents a generative design that it doesn't make up of fixed geometric entities, with fixed dimensions, in a fixed configuration, but it contains the engineering rules that at run-time we will determine the design of the product.

Bermell-Gracia and Fan [15], conduct a searching survey of a large international engineering consultancy firm and a leading PLM/KBE software vendor in order to understand the needs for future PLM-base Knowledge-based system and their associated interoperability issues. Due to the small data sample, the study focuses on a qualitative analysis of the data, which considering the background of the participants and the value of their inputs provide useful insights. All practitioners who are involved in functions of KBE/PLM integration were given a literature survey as initial data collection, and unstructured interviews as further data collection. The analysis of interview transcripts and meeting notes helps narrow down the selected practitioners for the final set of data. The final outcome of the study is a ranked set of business functionalities that the interviewed participants expect to be fulfilled from the KBE/PLM integration.

Toussaint, Demoly, Lebaal, and Gomes [16] developed an approach to accelerate routine processes in engineering design. In industrial companies, approximately 80% of the time spent in engineering is devoted to routine engineering activities and the remainder 20% is dedicated to innovation. The process from design to manufacturing requires important amounts of data and information, which mostly relies on the experience gathered from the development of previous projects. This knowledge often does not get captured or managed properly for future uses. Because only a limited number of "experts" have the information, organizations will run into time-wasting project delays. Product Lifecycle Management (PLM) approach integrates knowledge base on engineering features, such as expert rules definition or design experience feedbacks, in order to reduce costs, lead time, and also improve product qualities and values.

3 Methodology

3.1 The Semi-structured Interview

We aim to identify CAD design problems, especially for configuration and parametric design. The semi-structured interview allowed us to understand designers' attitudes and thoughts during the design process.

The subjects chosen for this study were graduate students, educators from Purdue University, and industrial CAD designers. All the participants have more than three years of CAD design experience. The 17 participants include three professional CAD educator, five CAD professional designers, nine graduate students. One-third of them are female.

A semi-structured interview allows participants to fully describe their personal experiences relating to the CAD design process. Each interview lasted about 30 to 40 min. The participants had the same interviewer and were put through the same interview process with the same interview questions. We started with general questions to gather demographic data about the participants' educational background and work experience (Table 1). Next, we asked open-ended questions focused on their design process, methods, and tools used to design a product, as well as design successes and failure (Table 1).

After gathering enough feedback from respondents, we read the transcripts and transformed the initial notes into emerging themes. A qualitative approach was essential here to capture potentially elusive qualities of individuals' design conceptions, with the goal of rich description. The bottom-up grounded theory was used to analyze our data. In the theme analysis, meanings rely on different design context. We picked up the most prevalent and important issues that contribute most to our analysis and deleted some overlapping items. We referred back to our transcription to reach a consensus that the selective codes are the most important ones affecting the overall user experiences. In the end, we refined the final categories by combining some relevant sub-categories together. The findings are reported in the next section.

Table 1. A list of interview questions.

Question number	Interview question
1	What is your name?
2	What is your role and position in the company/university? (for educator and CAD practitioner)
3	Tell us about your education background
4	How many years of experience do you have as a CAD designer?
5	Can you tell us about a recent CAD project you have been working on?
6	Can you walk through how you design a product?
7	What are your design approach and design strategy adopted in the project?
8	What has been your experience when it comes to planning out the key parameters of your design?
9	Describe the tools and methods used to design a product
10	What makes it difficult for you to design a product?
11	Names the success or failure factors in CAD design

3.2 Findings

There are three levels in our findings: (1) an overview of participants' description, (2) engineers' choices of the most and the least important design activities, and (3) problems and challenges during the engineering design process from both academic and professional practice perspectives.

The General Engineering Design Process

All the participants followed the general iterative design process that contains the steps of problem identification, ideation, design exploration, prototype development, to the refinement of design. Several of the design steps were heavily discussed during the interview.

Identifying Design Problems Through Benchmark, Customer Requirements and Design Research

The common strategies designers used were conducting interviews with potential customers, organizing focus groups, and observing similar products in use. It was important for them to identify the customer needs and wants, which included problems that customers were unaware of or accepted without questioning.

Brainstorming and Generating Product Concepts

In this process, engineering designers generated a number of product concepts while considering technical feasibility that matched the requirements of the target group. To narrow down the list, a comparison is made between the ideas based on the best product architecture and layout alternative.

Selecting the Final Product Concept

Engineering designers assessed the trade-off between various design attributes. The final specification result of the trade-off was made between technical feasibility, expected service life, projected selling price, and the financial limitations of the project. This specification may keep on changing until all product attributes were satisfied. During this process, a virtual prototype was developed.

Detail Design Process

Figure 1 displays the result of frequently used terms in respondents' description of the design in their interviews. Most of the respondents talked about how to understand the design problem, how to get all the constraints, how to communicate with customers, and how to seek information and make a decision. It is interesting to note that "problems" was ranked higher than others.

Fig. 1. The word cloud of frequently used terms.

For most graduate CAD design students, sketches, drawing, and prototypes were mainly concerned with the design and technical information. Engineering designers often created their own sketches on paper in order to visualize the product. While sketching, they specified the critical dimension according to the product specification and product function. While building a CAD model, they use sketches and spreadsheets for product specification to manage the product information.

For the experienced CAD practitioners and educators, the process is a little different. Instead of creating new parts, the company tends to reuse the CAD models they built before. This model is kept on being modified until it satisfies the requirements. This method saves the company time, effort, and money on designing the product from sketch while providing a boundary of design practices among the company's products. These design boundaries are common company's knowledge and practice base standard, cost, supply chain, material, etc. They always use PDM and PLM systems such as Teamcenter to manage the product information. Table 2 shows the differences in the detail design process between graduate CAD design students and experienced CAD practitioners and educators.

Table 2. The differences in the detail design process between graduate CAD design students and the experienced CAD practitioners and educators.

Categories	Graduate CAD design students	CAD practitioners and educators
How to form design concepts	Use less structured forms of representations such as sketches and models	Reuse the previous product CAD model they have already created
How to specify the critical dimension	Based on product specification and product function	Based on the product requirement and customer needs
How to manage the product information	Sketches and spreadsheets	PDM and PLM systems such as Teamcenter

Common Design Problems and Challenges

We found that CAD designers have some common challenges during the process of designing and managing the product's CAD design.

Understanding Vast Quantities of Multivariate Data

In the CAD design process, there is a huge amount of multivariate data. Multivariate data, also termed hypervariate data, is defined for a high dimensionality of three or above. Modeling the data in a 3D space is the most straightforward way, but problems arise with displaying it in a two-dimensional representation. Mathematicians consider dimension as the number of independent variables in an algebraic equation. Engineers take dimension as measurements of breadth, length, height, and thickness.

As products become complex, it is very difficult for CAD designers to interpret the vast quantity of information. It still requires extensive work to create visualizations to best display the data in a meaningful and comprehensible way.

Controlling the Manufacturing Cost of High-Quality Products

In order to be more competitive, there is a demand to create an expensive product but cheap to manufacture. Creating such a product means to have the best quality while reducing the number of necessary components, streamlining the design, eliminating redundancies, reusing parts from the previous project and promoting standard parts.

Managing the Knowledge Personalization and Codification Within the Company

This refers to the product knowledge that the company has been collected over the years. The information is either stored in the company's databases (product information and knowledge) or personalized (individual's knowledge and experience over years). The biggest challenges are finding the right people who have the resources.

Though codifications are stored in the computer for long-term use, personalize knowledge is not. To access these personalize knowledge, it required different communication methods such as face-to-face conversation, email, CSWS, etc. The biggest challenges are finding the right people who have the answer. When these people are retired or remove from the company, the organization loses the resources from them.

Preventing the Design Mistakes at the Early Design Stages

Engineering designers usually have a difficult time to discover design mistakes until much later in the process, which lead to more costs and more time to recover the product. For example: when a part is designed to a wrong dimension, the designer might not able to discover until the manufacturing process that the part cannot be assembly.

Attitudes to Parametric Modeling

Some designers thought that parametric modeling tools such as Pro/ENGINEER were very hard to learn because it is script-based and requires training. However, almost all the designers loved to use Grasshopper since it uses a very visual plug and plays interface to automate the scripting. Since Grasshopper is very flexible, users can set up almost any kind of relationship they like. The graph visualization platform in Grasshopper is also helpful for engineering to view all the completed relationship. It inspired us to find a solution and provide a visualization way to allow designers to generate models more easily. Experienced designers can re-compute the outputs once the inputs are changed in a reasonable time but are usually unable to generate multiple solutions.

We summarized the features that CAD designers desired to generate parametric models:

- Automatic computation of several sets of inputs that achieve the desired targets.
- Need a reference or standard model for comparison. The configuration will be changed based on different perception.
- Use of an explicit optimality criterion.
- Faster re-calculation of outputs when inputs are changed.

4 Conclusions

The CAD design process is complex and dynamic. We reviewed the current problems and challenges in the CAD design area and presented the students' and professionals' solutions. Our study may benefit the community in two directions. Firstly, educators should fill the gap between students and professional designers by introducing more collected scenarios and strategies. Secondly, we should explore new approaches to handling the complex engineering design problem, especially during this large data era, the product itself and the design process may carry a large amount of information. Handling such information visually may improve engineering design.

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