Approaches that Help Students Generate New Design Solutions

Yong Zeng¹, Shengji Yao^{*2}, Michel Couturier³, and Frank Collins³

¹Concordia Institute for Information Systems Engineering

Concordia University

1455 de Maisonneuve Blvd. West, EV007.633

Montréal, Quebec H3G 1M8, Canada

zeng@ciise.concordia.ca

²Department of Mechanical Engineering

³Department of Chemical Engineering

University of New Brunswick

15 Dineen Dr, Fredericton

New Brunswick, E3B 5A3, Canada

E-mail: syao@unb.ca

Abstract

Recently a new design methodology, Environment-Based Design (EBD) [1, 2] has been developed. In using the model of EBD, three elements are important: primitive synthesis knowledge, primitive environment and primitive solutions. Based on the three elements, three design strategies have been validated in [3] for generating new design solutions: formulating design problems differently, changing the sequence of decomposition of the design problem and extending synthesis knowledge. Increasing the possibilities of generating new design solutions may increase the chance of getting creative design solutions. Thus the three strategies for leading to new design solutions can be introduced into our engineering design education for helping and inspiring students generate creative design solutions. In this paper, we will first briefly introduce EBD model and the three design strategies leading to new design solutions, then explain how EBD can be integrated into the design education of engineering students and elaborate how the design strategies can be used to help students generate different design solutions.

1 Introduction

Engineering students at universities are future engineers. Our engineering design education is to help students develop abilities and capacities to solve open-

ended engineering design problems. Most of engineering students do not have much design experience. How can we educate students to develop critical and creative design thinking as experienced designers? Design has to do with humans. How can designers identify human needs and requirements in the design process in an effective and accurate manner? Is there any efficient design theory or methodology designers can follow to solve design problems?

A variety of design theories and methodologies have been proposed since 1960s, such as, systematic design methodology [4], decision-based design theory [5-7], AI-based design theory [8], axiomatic design [9], dynamic product development [10], integrated product development [11], C-K theory [12] and science-based design theory [9, 13-21]. These design theories and methodologies require designers to follow a series of structured procedures to deliver a design solution. The structured procedures could add rigidity to the designer's thinking process. Thus, they have not been widely accepted in general design practices. On the one hand, design is a creative act; the freedom and the flexibility for exploring various avenues to achieve design goals appear to be critical for designers [22-25]. A great hope for resolving the contradiction in developing effective design methodologies lies in the thorough understanding of the designer's thinking and reasoning process such that the methodologies may either lead the designers to a better approach or assist

the designers in their natural manner for delivering creative solutions. A new design methodology, named environment based design (EBD), has been developed [1, 2]. The EBD methodology is derived by following logical steps from the axiomatic theory of design modelling [26]. The axiomatic theory of design modeling provides a formal approach that allows for the development of design theories based on mathematical concepts and axioms. EBD can guide designers from the gathering of customer requirements throughout the generation and evaluation of design concepts. It also can be a descriptive model of the natural design process that illustrates how designers conduct a design task.

EBD methodology can integrate designer's cognitive activities and user's requirements in the design process. Using this methodology, students can easily understand the characteristics of the design process and apply this methodology in solving design problems. The faculty of engineering at the University of New Brunswick has developed a new course for first year undergraduate students: Introduction of Engineering Design and Problem-Solving (ENGG 1015), starting from the fall of 2009. This course aims to teach students to use a systematic approach to engineering design and problem-solving and develop creative design thinking abilities, teamwork, project management and communication skills. EBD can be used as a framework to teach students to solve design problems in a systematic approach. From EBD, there are three routes leading to alternative design solutions. The three routes may lead designers to get significantly different design solutions by changing the conditions in design requirements [27], which is necessary for the innovative and creative design. The three routes for alternative design solutions can be used in this course as strategies to direct students' learning process and creative thinking in problem-solving.

The rest of this paper is organized as follows. Section 2 provides a brief introduction of environment-based design. Section 3 introduces the three strategies leading to new design solutions implied from EBD. Section 4 explains how EBD and the three strategies can be integrated in our design course. Finally summary and conclusions are given in Section 5.

2 Environment-Based Design

Different from traditional design methodologies, environment-based design [28] was logically derived from the axiomatic theory of design modeling [26],

which was founded on the recursive logic of design [29]. The EBD is a prescriptive model of design (which is a design methodology) that guides designers from the gathering of customer requirements throughout the generation and evaluation of design concepts. It is also a descriptive model of the natural design process that illustrates how designers conduct a design task [30].

Figure 1 Environment-based design: process flow.

As is illustrated in Figure 2, the environment-based design includes three main stages: environment analysis, conflict identification, and concept generation. These three stages work together to progressively and simultaneously generate and refine the design specifications and design solutions. The objective of environment analysis is to find out the key environment components, in which the product works, and the relationships between the environment components. From the environment implied in the design problem described by the customer(s), the designer will introduce extra environment components that are relevant to the design problem at hands. The results from this analysis constitute an environment system. One of the key methods for environment analysis is linguistic analysis [31-33]. Following the environment analysis, conflicts should be identified among the relations between environment components [34]. At the third stage of EBD, a set of key environment conflicts will be chosen to be resolved by generating some design concepts. This process continues until no more unacceptable environment conflicts exist.

A key concept used in EBD is the structure operation, denoted by $\oplus$, which can be defined as the union ($\cup$) of an object O and the interaction ($\otimes$) of the object with itself [26].

where $\oplus O$ is the structure of object O .

Based on the structure operation, a product system can be defined as the structure of an object (Ω) including both a product (S) and its environment (E).

$$\Omega = E \cup S, \forall E, S [E \cap S = \Phi], \quad (2)$$

where Φ is the object that is included in any object.

The product system ($\oplus \Omega$) can be expanded as follows:

$$\oplus \Omega = \oplus (E \cup S) = (\oplus E) \cup (\oplus S) \cup (E \otimes S) \cup (S \otimes E), \quad (3)$$

where $\oplus E$ and $\oplus S$ are structures of the environment and the product, respectively; $E \otimes S$ and $S \otimes E$ are the interactions between the environment and the product [26]. A product system can be illustrated in Figure 3.

Figure 2 Product system [26].

In the design process, any previously generated design concept can be indeed seen as an environment component for the succeeding design. As a result, a new state of design can be defined as the structure of the old environment (E_i) and the newly generated design concept (S_i), which is a partial design solution.

Figure 3 Environment based design: mathematical model [1].

The evolution from the design state $\oplus E_i$ to the design state $\oplus E_{i+1}$ is governed by the following design governing equation [28],

$$\oplus E_{i+1} = K_i^s(K_i^e(\oplus E_i)), \quad (5)$$

$$\oplus O = O \cup (O \otimes O), \quad (1)$$

where K_i^e and K_i^s are evaluation and synthesis operators [35, 36], respectively.

The two operators K_i^s and K_i^e correspond to two major phases in the design process: synthesis and evaluation. The synthesis process is responsible for proposing a set of candidate design solutions based on the design problem. It stretches the state space of design. The evaluation process is used to screen candidate solutions against the requirements in the design problem. It folds the state space of design. The interaction of both synthesis and evaluation processes gives rise to the final balanced design solutions, which can be illustrated in Figure 5.

Figure 4 State space of design under synthesis and evaluation operators [35, 36].

The EBD process solves the design governing equation by following the procedures below [1]:

Step 1: Environment analysis: define the current environment system $\oplus E_i$.

$$\oplus E_i = \oplus(\bigcup_{j=1}^{n_e} E_{ij}) = \bigcup_{j=1}^{n_e} (\oplus E_{ij}) \cup \bigcup_{\substack{j_1=1 \\ j_2 \neq j_1}}^{n_e} (\oplus E_{ij_1} \otimes \oplus E_{ij_2}). \quad (6)$$

where n_e is the number of components included in the environment E_i at the i^{th} design state; E_{ij} is an environment component at the same design state. It should be noted that decisions on how many (n_e) and what environment components (E_{ij}) are included in E_i depend on designer's experience and other factors relevant to the concerned design problem.

Step 2: Conflict identification: identify undesired conflicts C_i between environment components by using evaluation operator K_i^e , which depends on the interested environment components.

$$C_i \subset K_i^e(\bigcup_{j_1=1}^{n_e} \bigcup_{\substack{j_2=1 \\ j_2 \neq j_1}}^{n_e} (\oplus E_{ij_1} \otimes \oplus E_{ij_2})). \quad (7)$$

Step 3: Concept generation: generate a design concept s_i by resolving a group of chosen conflicts through a synthesis operator K_i^s . The generated concept becomes a part of the new product environment for the succeeding design.

$$\exists c_{ik} \subset C_i, K_i^s : c_{ik} \rightarrow s_i, \oplus E_{i+1} = \oplus (E_i \cup s_i). \quad (8)$$

The design process above continues with new environment analysis until no more undesired conflicts exist, i.e., $C_i = \Phi$.

3 Design Strategies

It can be derived from the design governing equation (5) and be validated through computer simulation [3] that the following three routes may lead to significantly different design solutions: formulating the design problem differently; extending synthesis knowledge; and changing the sequence of environment decomposition. The three routes given above were first observed in studying the design of finite element model [37]. The following subsections will briefly review these three routes.

3.1 Different formulation of the design problem

The formulation of a design problem is included in the environment system $\oplus E_i$ [2]. The inclusion or exclusion of an environment component E_{ij} will lead to a change of $\oplus E_i$. In addition, in formulating a design problem, designers may choose to group different environment components as one assembly. This will also lead to a change of $\oplus E_i$. This can be seen from different activities between novice designers and expert designers. Since these two types of designers have quite different experience, they usually apply different methods to formulate the problem. As a result, they got different solutions. Even for the same designer, if he or she changes a perspective, the problem will be formulated in a different way and then the solution will be different. Consequently, the object C_i may be changed. This changes the initial condition of the design process, which could result in significant change of design solutions.

3.2 Extension of synthesis knowledge

The extension of synthesis knowledge will change the relation $\exists c_{ik} \subset C_i, c_{ik} \rightarrow s_i$. There are a few possibilities: first, more conflicts can be chosen at the same time to generate a design concept s_i ; and secondly, the same design conflict c_{ik} may be resolved by different design concept s_i . Both cases will update the environment system $\oplus E_{i+1}$ differently. When design conflicts are identified by analyzing the relations between environment and product, designers

will use their knowledge and experience to generate some candidate solution concepts. The number and quality of the design concepts largely depend on designers' knowledge and experience. That is also a big difference between novice and expert designers. The generated concepts need to be evaluated to satisfy the specified product requirements. Novice designers often lack the ability of evaluating the generated concepts correctly, and hence finally fail to generate a good design solution. When we compare designs by a novice designer and an expert designer, we can see a big difference in the design solutions. The newly generated concepts are considered as the environment components and analyzed by combining other identified environment components for generating other design concepts. This process is represented as $\oplus E_{i+1} = K_i^s(K_i^e(\oplus E_i))$, where K_i^s and K_i^e are synthesis and evaluation operators, respectively. We can see that some new and different primitive products may be generated for a specified environment part by extending knowledge. Therefore, extending knowledge can help designers generate more candidate solution concepts, and so increasing the probability of generating a good concept. As a result, a new design problem is generated, which may lead to new design solutions.

3.3 Sequence of environment decomposition

In environment-based design theory, after the design conflicts C_i are identified, there exist many ways to choose the conflict to be resolved, which is based on the decomposition of the environment. Generally, no two designers have exactly the same design knowledge, so they will use different ways to decompose the environment. Different sequences of environment decomposition may give rise to different reformulation of the design problem when designers apply their synthesis knowledge. As a result, the final solutions may be different.

4 Design Course

A new design course, "Introduction to Engineering Design and Problem-Solving" will be implemented in the Faculty of Engineering at the University of New Brunswick in the fall of 2009 for the first year undergraduate students. This course will introduce students the characteristics of the engineering design problems, the design process, and the design approaches. From this course, we aim to stimulate students' interests in engineering problems-solving and integrate with their onwards regular scientific and technical courses to solve real-life engineering problems. Students will take one hour lecture and two

hours lab every week. The lectures will teach students to understand engineering design problems and gradually study systematic approaches to solve design problems. The lab has two parts. One part is a big project throughout the semester; and the other part is to solve small open-ended problems in class. The problems used in the lab will add complexity gradually.

The EBD methodology will be introduced in this course to help students understand the design process in a systematic way and guide them to solve problems. The first year undergraduate engineering students do not have much experience in solving open-ended problems. Their problem-solving behaviour may go back and forth to the design problem and modify the design solutions. EBD can show them design is a recursive process and easily integrate designer and user's roles into the design process. In using the model of EBD, three elements are important: primitive synthesis knowledge, primitive environment and primitive solutions. Based on the three elements, three strategies were given for creating different design solutions: formulating design problems differently, changing the sequence of decomposition of the design problem and extending synthesis knowledge. These strategies can help students generate different design solutions in different perspectives. Increasing the possibilities of generating different design solutions may increase the chance of getting creative design solutions, which will help develop students' critical and creative thinking abilities in problem-solving.

We expect to have about 250 students for this course in the fall of 2009. All students enrolled in this course will be asked to complete an extensive questionnaire at the end of the semester. Especially, their experience in using EBD methodology and applying the three strategies for solving design problems will be analyzed to improve this course.

5 Conclusions

In this paper, we introduced a new design methodology: environment-based design and three strategies for helping students generate new design solutions and explained the EBD methodology could be integrated into the course of Introduction to Engineering Design and Problem-Solving for the first year engineering students at the University of New Brunswick. In our future studies, we plan to examine the impact of using EBD methodology and the three approaches leading to new design solutions on students' learning process through students' evaluations and feedbacks.

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