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VALIDATION OF ENVIRONMENT-BASED DESIGN (EBD) THROUGH PROTOCOL ANALYSIS EXPERIMENT

Di Feng, and Dr. Yong Zeng
Concordia University

ABSTRACT

In this paper, design data from a protocol analysis experiment is used to validate that Environment-Based Design (EBD) is a descriptive model of design. The EBD is developed as a design methodology for innovative and creative design based on the understanding of the generic design process. The validation of EBD is conducted by using it to describe and represent the design data collected from protocol analysis experiments. The result of this experiment shows that the EBD can naturally and smoothly represent the design processes demonstrated by different designers.

Keyword: Environment-based Design (EBD), design process, validation, descriptive model, protocol analysis experiment

1 INTRODUCTION

During the last four decades, a variety of design theories and methodologies have been proposed to model and to improve the design process, such as systematic design methodology [1], decision-based design theory [2], Theory of Inventive Problem-Solving (TRIZ) [3], axiomatic design [4], General Design Theory[5], Formal Design Theory [6] and Axiomatic Theory of Design Modeling [7]. Design methodologies are prescriptive models of the design process, which provide designers a series of structured procedures to deliver a design solution. Those structured procedures could add rigidity to the designer's thinking process; as a result, design methodologies may hinder designer's creativity by limiting their flexibility to explore freely various ideas. Therefore, a good design methodology should accommodate designer's cognitive process in addition to providing guidance to the design activities.

Environment-Based Design (EBD) is a methodology for innovative and creative design [8], which is logically derived from the axiomatic theory of design modeling [7]. It has been applied to software engineering [9], mechanical engineering [10], industrial engineering [11], quality management [12], and algorithm design [13]. The purpose of this paper is to validate through a protocol analysis experiment that the EBD also reflects the nature and characteristics of the design process.

The rest of this paper will be organized as follows: Section 2 introduces the theoretical foundations of this research, including design governing equation, Recursive Object Model (ROM), and mathematical representation of EBD. In Section 3, this research conducted a laboratory experiment based on the protocol analysis methodology. Then, by analyzing the data from the experiment, the section 4 represented the result of validation of EBD.

2 FORMAL MODEL OF DESIGN ACTIVITIES

As the foundation of experimental studies of design activities, a mathematical model was proposed for understanding the factors that lead to a creative design [14] by using the axiomatic theory of design modeling [7]. This mathematical model includes the design governing equation [15] and a new design process model - Environment-Based Design (EBD) [15-17]. The design process model solves the design governing equation, based on which the factors leading to the creative design can be identified. This model was implemented in a computer simulation, which studies quantitatively the factors that affect creative design [18]. This paper will be focused on a protocol analysis experiment.

2.1 Design Governing Equation

In this subsection, a mathematical representation of design activities is presented to explain the dynamic mechanism of design evolution. Design activities are involved with three main objects: designer, product, and the environment in which the product is to work and with which the product is to interact, as is shown in Figure 1. These three objects also interact with each other. Any research into design is to investigate either those three objects or their mutual relations (particularly including the relations from each object to itself).

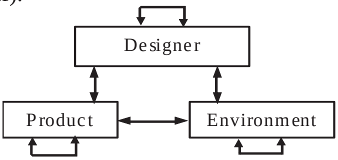


Figure 1 Design Activities

The axiomatic theory of design modeling is developed to represent such a structure as shown in Figure 1. A key concept in the axiomatic theory of design modeling 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 [7].

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

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. A product system can be illustrated in Figure 2. The product system is a part of the design activities shown in Figure 1. Obviously, design activities can also be represented as the structure of designer, product, and environment. The details are given in [7].

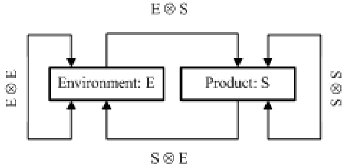


Figure 2 Product System [7]

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.

$$\oplus E_{i+1} = \oplus (E_i \cup S_i) \quad (4)$$

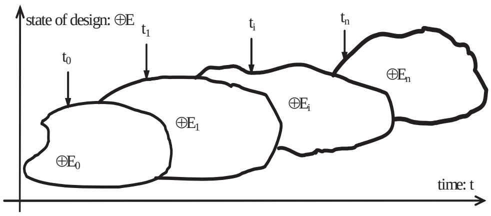


Figure 3 Environment based design: mathematical model [15]

This evolution process from the design state $\oplus E_i$ to the design state $\oplus E_{i+1}$ is shown in Figure 3 and is governed by the following design governing equation [15]

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

where K_i^s and K_i^e are synthesis and evaluation operators, 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 4.

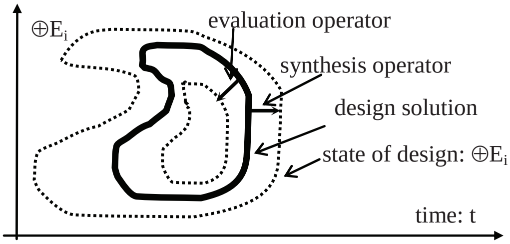


Figure 4 State space of design under synthesis and evaluation operators [19]

The design governing equation (5) is a recursive equation and is the mathematical form of the logic of design [20], which characterizes design as a process of simultaneously looking for design solutions and determining the solution evaluation criteria based on the found design solutions. This design governing equation governs design activities and underlies design processes in the same way as the differential equations do to classic engineering sciences. The design governing equation makes design problem solving as a search for fixed points under the design function $K_i^s(K_i^e(\cdot))$. Different design methodologies indeed solve the design governing equation (5) under different assumptions.

According to the recursive logic of design [20], at most stages of (conceptual) design, the evaluation operator K_i^e will be determined only after a (partial) design solution is generated, which will in turn trigger new synthesis operators K_i^s. As a result, a small change in the initial design problem may give rise to significant differences in the final design solutions, among which creative design solutions may exist [18].

2.2 Design Process Model: Environment-Based Design (EBD)

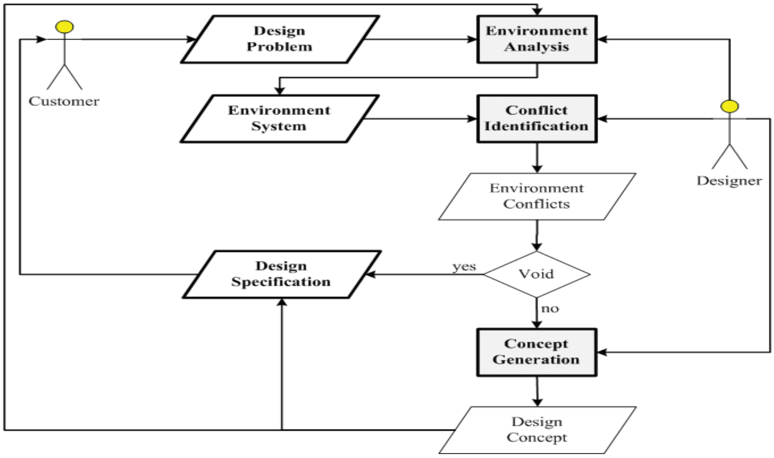


Figure 5 Environment-based design: process flow [8]

In solving the design governing equation (5), a new design methodology - Environment-Based design (EBD) was logically derived from the axiomatic theory of design modeling. As is illustrated in Figure 5, the environment-based design includes three main steps: environment analysis, conflict identification, and concept generation. These three steps work together progressively and simultaneously to generate and refine the design specifications and design solutions.

The following explains the three steps included in EBD [8]:

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

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

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}) 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.

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

Step 3: Concept generation: generate a design concept s_i by resolving a group of chosen conflicts through synthesis operator K_i^s. The generated concept becomes a part of 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., $C_i = \Phi$.

2.3 Recursive Object Model (ROM)

As was shown in Figure 4 and Section 2.1, a design process may evolve from the current design state forward to a refined one or backward to an old one. The former serves for the purpose of refining the design solution whereas the latter aims to identify the real intent behind the design problem. The driving force behind this evolution process is conflict identification based on which questions are usually asked. Researchers have found, through experiments or observations, that engineering design is a question-driven process [21]. As the recursive logic of design implies, design problem and design solutions are coupled throughout the entire design process [20]. Questions set up goals for each design stage, which leads to a new design state. A question asking strategy is proposed to address this problem in the EBD process [22].

Table 1 Types of symbols in ROM

Type		ROM symbols	Description
Object	Object	O	Everything in the universe is an object.
	Compound Object	O	It is an object that includes at least two objects in it.
Relations	Constraint Relation	ξ	It is a descriptive, limiting, or particularizing relation of one object to another.
	Connection Relation	ι	It is to connect two objects that do not constrain each other.
	Predicate Relation	ρ	It describes an act of an object on another or that describes the states of an object.

To support the identification of design conflicts and question asking, a graphic language- Recursive Object Model (ROM) is proposed to represent the semantic information implied in a natural language based design problem description [16]. Based on the axiomatic theory of design modeling [7], ROM can represent the linguistic structure of a free text through only syntactic analysis. Table 1 shows the graphic symbols in the ROM. In this paper, ROM is extended to represent the other relations between the components of a design. Examples are shown in Table 3 and Table 4 in section 3.3.

3. LABORATORY EXPERIMENT USING VERBAL PROTOCOL ANALYSIS

The objective of this section is to design a laboratory experiment for the validation of EBD as a descriptive model of design. A design process model is a descriptive model if it can be used to represent and describe the design processes happened to different designers. Therefore, our experiment data analysis will validate the Environment-based Design (EBD) as a descriptive model of the design process by verifying the following:

- T1: In each design state, by defining the current environment system $\oplus E_i$, the designer has a tendency to identify a number of components included in the environment E_i and their relationships. The identification of environment components directly related to the designer's experience.
- T2: In each design state, after the environment system $\oplus E_i$ is identified, the designer tends to identify unwanted conflicts between environment components by using evaluation operator K_i^e.
- T3: In each design state, the designer generates a design concept by resolving a group of chosen conflicts through synthesis operator $\mathrm{K}_\mathrm{i}^\mathrm{s}$. The generated concept becomes a part of new product environment for the succeeding design.
- T4: The three steps in T1, T2 and T3, continues with new environment analysis in the developed design state until all the unwanted conflicts are resolved.

The experiment approach that we used is Verbal Protocol Analysis. It is a rigorous psychological research methodology, which is used to generate the report in variable purposes by collecting verbalization data from the experimental participations [21]. This approach has been used in the design of surveys and interviews [23], behavior analysis [24], thinking in cognitive psychology [25] and cognitive science [26].

3.1 Experiment Setting and Approaches

In this experiment, the design problem was adopted by modifying the problem of designing a litter-disposal system for passenger compartment, originally created by Drost and Cross [27]. The main objective in this experiment is to design a disposal system convenient for the passengers to deposit and cleaners to collect the garages. Seven participants are selected from the graduate students who have various working experience and have learned at least one design methodology.

The experiment was conducted under a non-interruptive environment. Two sections are included in the experiment, design and interview. In the design section, the participants were provided general instructions describing how the exercise would proceed. In the interview section, a question asking strategy is used to ask questions to help the participant recall his/her unspoken thinking process.

After recording individual participant's background information and setting up the experiment environment, the design task was handed out to the participant. In addition, the experiment was video and audio recorded. During the experiment, an electronic tablet was offered to the participant to sketch. After the data is collected, the verbal protocol analysis is conducted which includes data transcription, encoding and analysis. Since the general procedures are similar to what are reported by many authors [27-32], the following subsections will focus on the data segmentation and analysis.

3.2 Segmentation of experimental data

Segmentation is an important part in the encoding phrase, which segments verbal protocol data into discrete meaningful episodes. The purpose of it is to segment the whole sequence data into meaningful unit for the aim of clear participator's intention and then interpret the data from the transcription. Based on this principle, this study uses design states to segment the experiment data, based on the mathematical formulation of design process shown in Figure. 3. An example is given in Table 2.

Since each segment is a design state, which is an environment structure $\oplus E_i$, as shown in Figure. 3. A design state includes design problem and the partial solutions at this state. It can be represented by an ROM diagram as was suggested in Section 2.3.

Table 3 shows the basic categories of components included in the design states whereas Table 4 defines the basic types of relations included in the design state.

Based on the basic category of components and the basic types of relations, all the verbal protocol data can be analyzed based on the ROM diagrams. In this manner, the bias and distortion in protocol data analysis are minimized. Figure 6 is an example showing the combination of linguistic information and its corresponding sketches with their ROM diagrams.

Table 2 Design State Segmentation

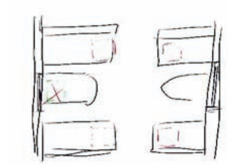
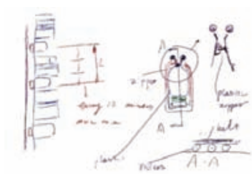
State	Time	Rationale	Solution
1	00:00:00–00:26:00	First, I got your design problem. The first point of the design problem is that I want to make clear what the thing to be designed is. We made clear that we need to design a garbage bin…. Then I think what the environment for this garbage bin is. In which place should it be put? Like this coach car or sleeping car? Then I consider the position of the coach car…. I just draw a garbage bin very simply. I think the garbage bin is put here.	
2	00:26:50–00:30:00	It will affect the movement of the passenger's legs if the garbage bin is put under the table. So the only place is under the seats. Put here (under the seats). These are seats and tables.	
3	00:30:45–00:39:20	Then I consider whether I should install one garbage window for every seat. But I consider installing it symmetrically, which is good for the whole design….	
4	00:39:30–00:51:38	Now I suddenly got an idea. When the garbage passes through the channel, how to pack the garbage? I cannot let the garbage pass on the belt directly. How to design? I suddenly think about the plastic zipper on the plastic bag. Then I consider whether I should install one garbage window for every seat. But I consider installing it symmetrically, which is good for the whole design.	
5	00:52:00–01:07:11	Now I consider the plastic bag, namely garbage bag for the whole compartment.	

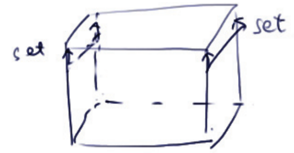
Table 3 Component Category

Category	Example
Passenger related components (PC)	people sit beside the passenger
Cleaner related components (CC)	cleaner; cleaning tool
Nature environment related components (EC)	seat; table; windows

Table 4 Type of Relation

Type of relation		Definition
Direct Relation	Negative constraint (NR)	It is a conflicted or limited relations of one or more components to the others
	Connection (CR)	It is to connect two or more components that do not constrain each other
	Prediction (DR)	It describes an act of one or more components on the others or that describes the states of the component.
Indirect Relation (IR)		It is no direct relation between components

The cleaners have to open inside and take the bag away. The bag should be bigger than the container. So it can be rolled over the edge of the container when the garbage is put more and more, it is heavier and heavier. So it is necessary that there is a set to fix the bag to prevent the bag falling down. The cleaner must open the set to take the bag out.



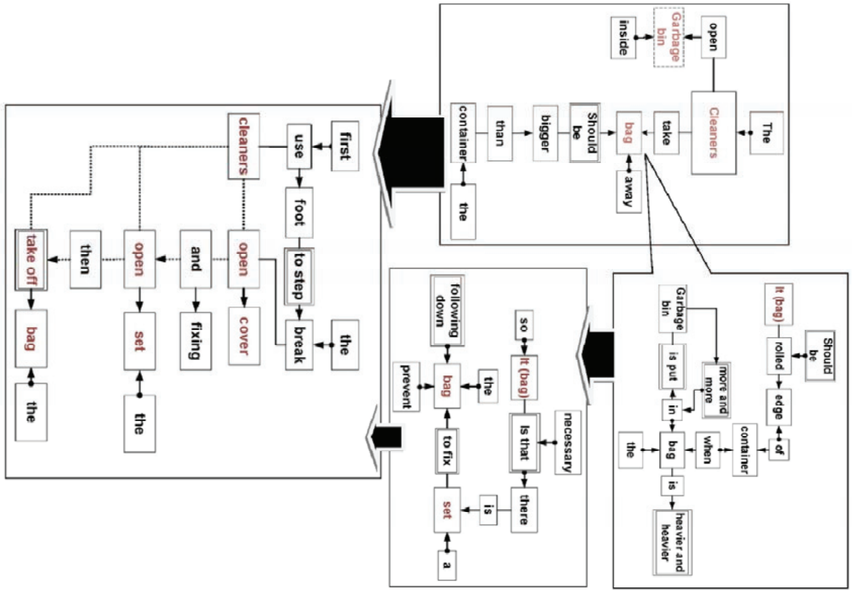


Figure 6 ROM Example

Table 5 Result of Participant 2

Subject 2	Component																		Relation				
	e(2)1 PC	e(2)2 EC	e(2)3 CC	e(2)4 PC	e(2)5 EC	e(2)6 PC	e(2)7 EC	e(2)8 EC	e(2)9 EC	e(2)1 0EC	e(2)1 1EC	e(2)1 2EC	e(2)1 3PC	e(2)1 4CC	e(2)1 5CC	e(2)1 6EC	e(2)1 7EC	S	NR	CR	DR	IR	Solution based relation
design state 1	⊙	⊙	⊙																1	1		1	NR
design state 2	⊙		⊙	⊙	⊙													S1	9		1		NR
design state 3						⊙	⊙											S2	1	1	1		NR
design state 4	⊙							⊙	⊙	⊙								S1	3	3	1	3	NR,CR
design state 5				⊙						⊙	⊙	⊙	⊙					S4	3	5	2	5	NR,CR
design state 6							⊙						⊙					S5	3				NR
design state 7	⊙		⊙											⊙				S6,S3	5	2	3		NR,CR
design state 8			⊙											⊙	⊙			S7	3	1		2	NR
design state 9														⊙	⊙			S3,S2	1	2		3	NR
design state 10				⊙												⊙	⊙	S8,S9	2			8	NR

e(2)1	garbage	e(2)11	short distance train	S1	garbage bin
e(2)2	train	e(2)12	no table	S2	open from underneath
e(2)3	collector	e(2)13	small garbage	S3	a latch for the bin
e(2)4	Passenger	e(2)14	taking mechine	S4	on the window side and between the seats
e(2)5	train moving	e(2)15	button	S5	under the window
e(2)6	no passenger	e(2)16	size of garbage bin	S6	plastic bag inside the bin
e(2)7	no garbage	e(2)17	wall	S7	solution of taking out the bag
e(2)8	chair			S8	no cover for the bin
e(2)9	two chairs in front			S9	no botton on the bin
e(2)10	window			S10	restrict the size of the bin

3.3 Analysis

Data analysis is to develop an understanding of the design activities based on the segmented data. As is indicated in the beginning of Section 3, we can validate the EBD by showing that various designers follow the three steps included in the EBD: environment analysis, conflict identification, and concept generation. Table 5 and Table 6 give the analysis results of two participants' design process data, which includes environment components and their relations for each design state, the types of component relations (NR, CR, and DR), and the solutions corresponding to conflicted relations (NR). In the tables, the correspondence between a solution and relations is given. It should be noted that all the solutions are a part of a design state, which drives the generation of the further solution.

In Tables 5 and 6, e(i)j represents the j^{th} component considered by the i^{th} participant. S_i is a solution, which is further adopted as a part of a later design state. The relation columns demonstrate the number of existed relations between the components in each category.

Table 6 Result of Participant 4

Subject 4	Component																										Relation				
	e(4) 1EC	e(4) 2EC	e(4) 3PC	e(4) 4CC	e(4) 5EC	e(4) 6EC	e(4) 7EC	e(4) 8EC	e(4) 9EC	e(4) 10EC	e(4) 11EC	e(4) 12EC	e(4) 13EC	e(4) 14EC	e(4) 15CC	e(4) 16PC	e(4) 17EC	e(4) 18PC	e(4) 19PC	e(4) 20PC	e(4) 21CC	e(4) 22CC	e(4) 23CC	e(4) 24CC	e(4) 25EC	S	NR	CR	DR	IR	Solution based relation
design state 1	⊙	⊙	⊙	⊙	⊙																						3	2	2	3	NR
design state 2	⊙					⊙	⊙																			S1	2	2	1	1	NR
design state 3								⊙	⊙																	S2	2			1	NR
design state 4			⊙																							S3	1				NR
design state 5					⊙					⊙																S1	2			1	NR
design state 6											⊙															S3,S5	1	1		1	NR,CR
design state 7											⊙	⊙															1				NR
design state 8																										S7,S6	1				NR
design state 9													⊙	⊙												S8	1		1	1	NR
design state 10			⊙					⊙							⊙	⊙										S9	5	1	2	2	NR
design state 11			⊙					⊙			⊙					⊙	⊙	⊙	⊙							S4,S10	20	12	3	1	NR,CR
design state 12				⊙			⊙													⊙						S11	2	2	1	1	NR
design state 13																			⊙		⊙					S12	2			1	NR
design state 14																						⊙	⊙			S1, S11,S13	4	2	3	1	NR
design state 15																					⊙					S11	1				NR
design state 16	⊙						⊙																			S12	1	1	1		NR
design state 17	⊙				⊙																			⊙	⊙	S16	2	3	1		NR,CR
design state 18																							⊙			S17	1				NR
design state 19																			⊙							S18	1				NR
design state 20																										S14 S15 S19	3				NR

e(4)1	train company	e(4)11	talbe	e(4)21	take out	S1	garbage bin	S11	gabage bin system solution
e(4)2	train	e(4)12	size	e(4)22	ork flow of cleane	S2	less cost material	S12	container for the bin
e(4)3	passagers	e(4)13	aisle	e(4)23	dirty	S3	square shape of the bin	S13	drawer in the container
e(4)4	cleaner	e(4)14	:ollection truck	e(4)24	durable	S4	cover	S14	bag inside of container
e(4)5	contractor	e(4)15	usage	e(4)25	cost	S5	easy to produce	S15	container material with iron
e(4)6	cost	e(4)16	chair			S6	box shape of bin	S16	handle for the container
e(4)7	material	e(4)17	small garbage			S7	size of the bin	S17	material with stainless iron
e(4)8	space of train	e(4)18	big garbage			S8	restrict the size for box shap	S18	square shape of the cover
e(4)9	shape of bin	e(4)19	convenient			S9	smaller that aisle	S19	restrict the edge
e(4)10	produce	e(4)20	clean			S10	two kinds of the bin	S20	fianl solution

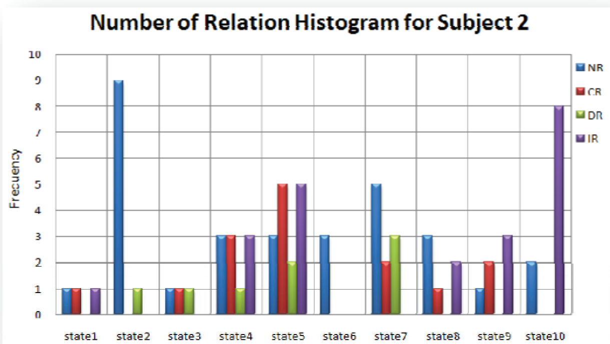


Figure 7 Number of Relation Histogram for Participant 2

The data corresponding to the participants are further illustrated in Figure 7, 8, and 9. Figure 9 shows the evolution process of design solutions in the participant 2's design processes.

Based on the participant's background information, the participant's experience can be evaluated by three factors: problem related experience, design experience, and work experience. Through liner regression, the relation between experience and the number of components is shown in Figure 10.

The sample correlation coefficient is $\hat{\beta}_1\sqrt{\frac{S_{xx}}{SS_T}} = 0.8969,$ shows a strong positive correlation between participant's experience and the number of generated components.

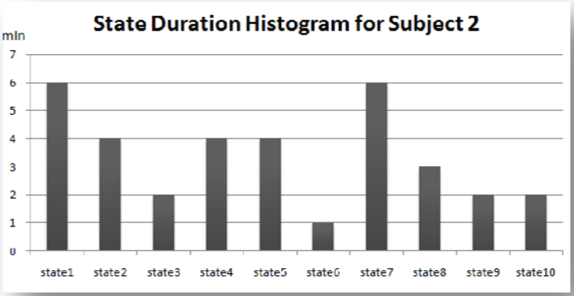


Figure 8 State Duration Histogram for Participant 2

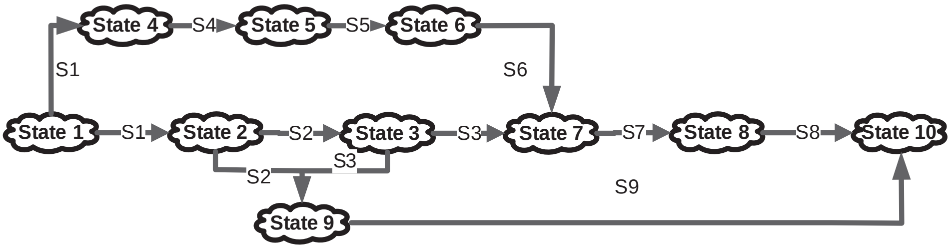


Figure 9 Design State Roadmap for Participant 2

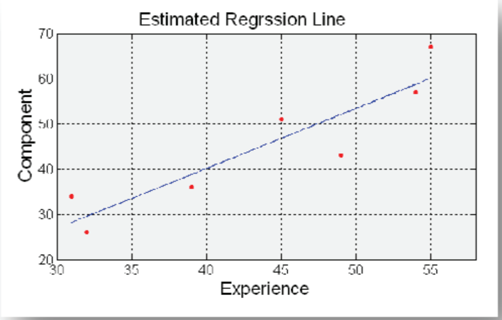


Figure 10 Linear Regression of Component vs Experience

3.4. Validation of EBD

The analysis results from Section 3.3 provide the basic data to validate the EBD. Table 5 and 6 provide a comprehensive description of the participant's activities in the design process. Obviously, the two different participants' design processes can be smoothly and naturally described and represented by the EBD, which has three main steps. The analysis of other participants shows the same conclusions.

Validation of T1: Firstly, in the experiment, the each design state is traded as the environment system $\oplus E_i$, and then, as description in T1, by analyzing the coding after the segmentation, the researcher can easily identify the components in each design state and analysis the component relations, such as NR DR CR and IR columns in the Table 5and 6, by considering current $\oplus E_i$. The result is shown in Table 5 and 6. In addition, for finding the relation between the environment components and designer's experience, which is represented in T1, a statistical analysis in Figure 10, demonstrates a strong and significant sample correlation coefficient (r=0.8969) between the two parameters. Therefore, the number of the considered components that was defined by the participant is positively related to their experience.

Validation of T2: In considering T2, the analysis presented in Figure 7 and Table 5, 6 demonstrate that at the beginning a number of conflict relations (NR) were identified by the participants in each design state before design solutions can be found. Moreover, as the definition of the confliction, all of those NRs share one common property, which hinders the designers from the solution generation. All of these fulfill the description of T2. However, for the evaluation operator K_i^e [15], there is no significant pattern in the data to show that one conflict is advantageous over the others as to the creativity of design. In other words, the conflicts, which were identified by the participant, depend on the participant's interested environment components. The further analysis note that by combining Figure 7 and 8, a sample correlation coefficient (r=0.8761) from participant 2. It shows that the duration of each state positively depends on the complexity of component's relation, except of state 1 because participant 1 needs to take time to understand the design problem.

Validation of T3: The validation of T1 and T2 establishes the necessary context for considering T3. As description in the T3, in Table 5 and 6, the solution based relation column present a clear roadmap that all of the solution S_i, were generated directly related to the NR. However, in the case of constraint relation (CR) being high or being crucial for the concerned design state, solution S_i does not depend on the conflict relation (NR) alone. In other words, the CR will become the constraint factors for restricting the solutions which are generated based on the NR. In addition, for validation last description in T3, from the Figure 9, it can be seen that the solution S_i can always be treated as a part of environment components for the proceeding design state in most of case.

Validation of T4: As described in T4, the experiment result, S column in Table 5 and 6, shows that solution S_i is always treated as a part of environment components in the following or later design state i+n. Thus, a new loop form T1 to T3 can be repeated as shown Table 5 and 6.

4. CONCLUSION

This paper has shown our preliminary efforts in validating that Environment-based Design (EBD) is a descriptive model of the design processes. The basic logic behind this validation is that if the EBD can be used to describe and represent the design processes data collected from protocol analysis data naturally, then it is descriptive. This validation used the data from a protocol analysis experiment conducted in the authors' research group. The data analysis shows that design processes from different participants of various design backgrounds can all be systematically modeled by the EBD, which includes three main steps: environment analysis, conflict identification, and concept generation.

New cognitive experiments are being conducted in our research group to include physiological measurement equipments and controlled tests. More participants will be tested and analyzed to get statistically meaningful conclusions.

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Contact: Yong Zeng
Concordia University
Concordia Institute for Information Systems Engineering
1455 de Maisonneuve West, EV.07.633
H3G 1M8, Montreal
Canada
Phone: +1-514-848-2424 #5801
Fax: +1-514-848-3171
E-mail: zeng@ciise.concordia.ca
URL: http://users.encs.concordia.ca/~zeng/index.html

Dr. Yong Zeng is an Associate Professor in the Concordia Institute for Information Systems Engineering at Concordia University, Montreal, Canada. He received his B.Eng. degree in structural engineering from the Institute of Logistical Engineering and M.Sc. and Ph.D degrees in computational mechanics from Dalian University of Technology in 1986, 1989, and 1992, respectively. He received his second Ph.D. degree in design engineering from the University of Calgary in 2001. His research interests include the science of design, requirements engineering, human factors engineering, computer-aided product development, product lifecycle management, computational geometry, and finite element modeling.