A NOVEL APPROACH TO QUANTIFYING DESIGNER’S MENTAL STRESS IN THE CONCEPTUAL DESIGN PROCESS

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ABSTRACT

The objective of this paper is to quantify designer’s mental stress during the conceptual design process. Quantifying the designer’s mental stress would assist the effort of understanding the designer’s creative and innovative process. In this paper, Recursive Object Modelling (ROM) is used as a formal tool to represent the designer’s mental state in each step of the conceptual design process. During the conceptual design process, designers usually describe the design states using natural language, combined with sketches. The description based on natural language will be transformed into ROM diagram through the lexical, syntactic, and structure analysis. A cognitive experiment, which is to design a new litter-disposal system in a passenger compartment located in the trains of NS (Dutch Railways), is built to study designer’s thinking process. ROM is used to analyze and quantify the designer’s mental stress based on the protocol data collected in the experiment. The validation through the cognitive experiment shows that ROM is an efficient design evaluation methodology, which reflects the nature and the characteristics of the design process. The designer’s mental stress presents dynamic, nonlinear, and spiral trend.

1. INTRODUCTION

Over the last few decades, various design methodologies have been proposed to assist designers in generating quality designs in a more effective manner [1-6]. There is no doubt that the existing methodologies have been greatly influencing the industrial product design process. Despite the success of those methodologies, a big challenge is faced by the effort to develop effective design methodologies. This lies in two contrasting facts. On the one hand, design is a creative act that is rooted in flexibility and freedom for exploring various avenues to achieve design goals [7-10]. On the other hand, any design methodology implies a set of well structured logical steps for solving a design problem. This contradiction between flexibility and structure is made even more complicated by an intrinsic nature of design: design solutions must pass an evaluation defined by design knowledge that is interdependently and recursively determined by the design solutions to be evaluated [11].

To develop a more effective design methodology, it is important to quantify the designer’s cognitive processes, particularly the designer’s mental stress. Mental stress can have either beneficial or degrading effects on designers’ performance, depending on the intensity of the stress. Under the pressure of tight schedule, complex tasks, or other strong stress, people may be stressed out and their performance may thus degrade, or even fail. Modest levels of supra-optimal stress can be counteracted by the performer by increased effort, resource mobilization, or straining [12-15].

Mental stress is the intensity of information imposed by environment on the brain. It is traditionally the research topic of cognitive science [15]. The study of mind can be traced back to the Ancient Greeks [16, 17]. Philosophers such as Plato and Aristotle tried to explain the mind and its operation with different opinions. Plato said: the mind relates to the realm of abstract ideals. Aristotle said: the mind is what the brain or body does. Yerkes and Dodson [18] developed the Yerkes-Dodson (Y-D) law, which shows that there is a U-shape correlation between arousal and performance. According to the Y-D law, the medium level stress addresses to a better performance. Sweller is known for formulating an influential theory of cognitive load [19]. Cognitive load theory (CLT) can provide guidelines to assist in the presentation of information.
in a manner that encourages learner activities that optimize intellectual performance. It is based on a cognitive architecture that consists of a limited working memory and an unlimited long-term memory. According to the theory, the limitations of working memory can be circumvented by coding multiple elements of information as one element in cognitive schemata, by automating rules, and by using more than one presentation modality.

In the domain of design, some researchers have attempted to discover designer’s cognitive model during the design process. Kirschner [20] focuses on the increase of germane cognitive load, which aims at further improving instructions by making designers take advantage of otherwise unused working memory during learning. Dong [21] attempts to quantify coherent thinking by using a latent semantic analysis in a conversation mode, and this measurement also reveals patterns of interrelations between an individual’s ideas and the group’s ideas. Stempfle and Badke-Schaub [22] study three laboratory teams solving a complex design problem to investigate the cognitive processes of design teams during the design process. Fuchs-Frohnhofen, et al. [23] use a methodology incorporating the taxonomy of mental models to analyze the user’s mental models in work setting and generate variants of human-machine interfaces to match the user’s mental models.

However, researchers with different backgrounds have different definitions of mental stress. There are three main shortages in the existing research:

- Mental stress is a result of an interdisciplinary study of brain, but different disciplines define the mental stress in their own way. The concept of mental stress has become increasingly important for investigating designer’s cognitive procedures. However, a concept that can cover different disciplines (philosophy, psychology, artificial intelligence, neuroscience, linguistics) has not been created yet.
- The observations and implications about designer’s mental model and cognitive process are based on some experiments or some beliefs from cognitive science. There is no method to systematically reflect the nature and characteristics of a design process and naturally accommodate designer’s cognitive activities.
- Few efforts have been seen on developing a quantitative model to define the designer’s mental stress.

In the present research, a formal definition of mental stress using axiomatic theory of design modeling [5, 24] is proposed. Furthermore, a graphic language, namely recursive object modelling (ROM) [25], is used to describe the nature and characteristics of the design process and to quantify the designer’s mental stress during the design process. ROM has a recursive structure. Protocol analysis, a major technique in the current research for attempting to identify the role of designer’s thinking and reasoning in the design process, is used to collect and analyze design data.

The rest of this paper is organized as follows. Section 2 introduces the modelling tool used in this research, which is the axiomatic theory of design modeling with the support of the recursive object modelling (ROM) language. Section 3 presents a framework for analyzing mental stress. Section 4 reviews experiment procedures. Designer’s mental stress is quantified in Section 5. The last section concludes this paper.

2. MODELLING TOOL

In this paper, Recursive Object Modelling (ROM), which is derived from the axiomatic theory of design modeling, is utilized as a main tool to quantify the designer’s mental stress in the conceptual design process. To facilitate the presentation of the research results introduced in this paper, the axiomatic theory of design modeling and ROM will be briefly reviewed in this section.

2.1 Axiomatic Theory of Design Modeling

Axiomatic theory of design modeling is a logical tool for representing and reasoning about object structures[5]. It provides a formal approach that allows for the development of design theories following logical steps based on mathematical concepts and axioms. The primitive concepts of universe, object, and relation are used in the axiomatic theory of design modeling, based on which two axioms are defined in the axiomatic theory of design modeling.

[Axiom1] Everything in the universe is an object.
[Axiom 2] There are relations between objects.

Structure operation is developed in the axiomatic theory of design modeling to model the structure of complex objects. Structure operation, denoted by the symbol ⊕, is defined by the union (∪) of an object and the interaction (⊗) of the object with itself.

\[ ⊕O = O ∪ (O ⊗ O), \]

where ⊕O is the structure of an object O. Both the union and interaction are specific relations between objects.

Since the object O may include other objects, Equation 1 indeed implies a recursive representation of an object.

The following three theorems are derived from the axiomatic theory of design modeling by logical steps based on mathematical concepts and axioms.

- **Theorem of recursive logic of design.** A design solution must pass an evaluation defined by the design knowledge that is recursively dependent on the design solution that is to be evaluated [11].

Based on this theorem, a design process is composed of a series of design states defined by both product descriptions and product requirements, as is shown in Figure1 [26].

![Figure 1: Evolution of the design process.](image)

- **Theorem of dynamic structure of design problem.** In the design process, design solutions to a design problem may change the original design problem, if the design solutions are different from their precedents, either by refinement or by alteration [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.

\[ \oplus E_{i+1} = \oplus (E_i \cup S_i), \quad (2) \]

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,

\[ \oplus E_{i+1} = K^e_i (K^s_i (\oplus E_i)), \quad (3) \]

where \( K^e_i \) and \( K^s_i \) are evaluation and synthesis operators, respectively.

**Theorem of environment-based design.** A design process continues until no undesired combined conflicts exist in an environment system.

This theorem can be illustrated in Figure 2.

**2.2. Recursive Object Modelling (ROM)**

In engineering applications, design states are usually described by using natural language. It is not feasible to ask designers to describe design states in the form of mathematical formulation proposed in the axiomatic theory of design modeling. Hence, it is essential to have a graphic language to represent the objects and relations for the designers to formulate their design process, based on which a step-by-step process can be developed to formalize a design problem described by natural language into this graphic language.

ROM is a graphic representation of linguistic structure, derived from axiomatic theory of design modelling. Through the lexical, syntactic, and structure analysis of natural language descriptions of a design process, the formalization process decomposes the description of a design problem and solutions into environment components, and then reveals their inherent relations. To formalize a design problem, Table 1 shows the graphic symbols in the ROM[25].

<table>
<thead>
<tr>
<th>Type</th>
<th>Graphic Representation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object</td>
<td>O</td>
<td>Everything in the universe is an object.</td>
</tr>
<tr>
<td>Compound Object</td>
<td>O</td>
<td>It is an object that includes at least two objects in it.</td>
</tr>
<tr>
<td>Constraint Relation</td>
<td>( \xi )</td>
<td>It is a descriptive, limiting, or particularizing relation of one object to another.</td>
</tr>
<tr>
<td>Connection Relation</td>
<td>( t )</td>
<td>It is to connect two objects that do not constrain each other.</td>
</tr>
<tr>
<td>Predicate Relation</td>
<td>( \rho )</td>
<td>It describes an act of an object on another or that describes the states of an object.</td>
</tr>
</tbody>
</table>

**3. ANALYSIS OF MENTAL STRESS**

We define the mental stress as the intensity of information imposed by environment on the brain. For the discussion of mental stress, the first step is to identify where the mental stress comes from. In general, after a task is assigned to an agent, the agent will produce a result. In the context of design, the task can be replaced by a design problem, the agent can be replaced by designer(s), and the result can be replaced by solution.

Intuitively, the stress level is in direct proportion to workload and inverse proportion to mental capacity. The more workloads assigned by the environment, the more mental stress may be exerted on the designer’s brain. The relationships between mental workload, mental capacity, and mental stress are illustrated in Figure 3.

**Figure 3: Mental stress.**

Figure 4 shows how to analyze mental stress using axiomatic theory of design modeling. Mental stress is the physical reaction of the brain to the workload imposed by the environment. Different environments impact brain in different ways whereas different brains react differently to the same environment.

The mental stress can be represented by the following formula.

\[ M \subset B \oplus E, \quad (4) \]

\( \oplus \): Structure operation,

\( \oplus \): Interaction operation,
Figure 4: Analysis of mental stress.

M: Mental stress, 
E: Environment, and 
B: Brain.

This stress can be measured by various means. In this research, we assume that the description of the design process by the designer can be taken as an indication of his/her mental stress. As an example, the following text is extracted from our protocol data:

Now I consider the convenience for the cleaner to pick up the garbage bin. Cleaners walk along the aisle. Then I think to put the garbage bin under the table.

The environment components and their mutual relationships imply the designer’s mental stress; therefore, the identification of environment components and their relationships behind the description above could be useful for quantifying the designer’s mental stress. The following lists all those objects by using the axiomatic theory of design modeling: 

e1=cleaner, e2=table, e3=aisle, e4=a garbage bin, 
Ei=e1∪e2∪e3∪e4, 
si=the location of the garbage bin: to put the garbage bin under the table, 
Si=Si-1∪si=the location of the garbage bin is specified to be under the table, 
b1=R(e1, e4)= cleaners pick up the garbage bin, 
b2=R(e1, e3)=cleaners walk along the aisle, 
b3=R(e2, e4)=garbage bin is put under the table, Bi=b1∪b2∪b3.

The mental stress behind this description will be analyzed later in this paper.

4. EXPERIMENT PROCEDURE

An experiment is designed to verify the calculation of mental stress. We adopt the design problem used by Dorst and Cross [7], because it is feasible, realistic and challenging enough for the subjects. The problem is rephrased to be more easily understood by our subjects. The content of the design problem is “to design a litter-disposal system for the passenger compartment. This system should be convenient for the passengers to deposit their garbage and for the cleaners to collect the garbage.” The structure of the passenger compartment is also shown on the paper to the subjects. The design problem is shown in Figure 5. Since it is difficult to determine the necessary amount of subjects in human factors study, different population have been used in different experiments. Considering general factors, seven graduate students with various working experience (5-10 years) are taken as the subjects in our experiment. They are from different backgrounds, such as mechanical engineering, electrical engineering, and computer engineering. All the subjects have certain knowledge of one or two design methodologies.

The experiment includes design session and retrospection session. During the both sessions, three webcams are used to record the entire process including audio and video information from different angles. An experimenter can communicate with the subjects all the time.

In the design session, subjects work alone to solve the design problem in a quiet room. The subjects are asked to draw or write anything on a tablet screen as shown in Figure 6. They can use references or Internet to find the required resources. The text and the draft done by the subjects on the tablet screen are recorded by the software My Screen Recorder. One of subjects’ drafts is shown in Figure 7. In the retrospection session, subjects are asked to recall and report what they were thinking at each step of their design process by watching the videos of their actions and the screen activities. If the subjects miss any information, they will be reminded or asked to clarify their problem-solving behaviors. All the information collected from the video, audio media and screen recording video during the two sessions is organized for protocol analysis.

4.1. Experiment Analysis

The collected protocol data are transcribed, segmented, and encoded to validate the nature and the characteristics of the
design process. Considering the theorem of dynamic structure of design problem, we identify each design state in the design process to segment and to analyze the protocol data. The concept of design state is used in our experiment analysis as the basic unit for the segmentation of protocol data.

4.2. Transcription

We transcribe all the verbal information provided by subjects during the retrospective stage into text documents. However, these documents may contain some vague and inconsistent information due to insufficient presentation from the subjects of their cognitive process. To solve the problem, we add some annotation to explain their non-verbal intentions to make the transcript more consistent. We ask three operators to do cross-checking to ensure the accuracy and consistency of the transcript and produce the final formalized transcript.

4.3. Segmentation

The objective of segmentation is to break the transcribed text into segments, which are further encoded with a coding scheme. As mentioned in Section 2, a design process is characterized by a series of design states, so each transcript is divided into separate design states. The following paragraph is an example for segmentation.

Original text: “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 structure of the coach car.”

Segment 1: 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.

\[ S_1 = \text{a garbage bin} \]

\[ E_1 = \Phi \]

\[ B_1 = \Phi \]

Segment 2: 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 structure of the coach car.

\[ e_1 = \text{coach car, location of the garbage bin}, e_2 = S_1 = \text{garbage bin} \]

\[ s_2 = \Phi, S_2 = s_2 \cup S_1 = \text{garbage bin} \]

\[ B_2 = \text{considering the structure of the coach car when a garbage bin is put there} \]

Another two segments are identified in the same way.

4.4. Encoding

Encoding is an important and critical part to analyze subject’s protocol data. Most of the current protocol studies devise the coding schemes according to specific design problems. If the design problem is changed, the coding scheme will also be changed and therefore cannot be extended for other applications. As a result, experiments from different sources are not comparable, which brings a lot of subjectivity into the study. The encoding scheme in the present paper is developed based on the concept of design state comes from the axiomatic theory of design modelling [5] and ROM. The graphic symbols proposed in the ROM are sufficient and necessary to represent all the linguistic elements in technical English. Therefore, ROM is used to collect, organize, and interpret protocol data, especially analyze the characteristics by inferring from multiple object relationships. The designer’s description using natural language will be transformed into ROM diagram, which enables us to systematically code the designer’s actions. Furthermore, mental stress is quantified by estimating the result from ROM.

As mentioned in Section 2, three major relations are implicated by ROM. Table 2 shows an example of the predicate relation, the constraint relation and the constraint relation in the English language.

When using words in a natural language to describe a design process, it always has inherent sequence. There are eight major types of words in English grammar: noun, verb, adjective, adverb, pronoun, determiners, preposition, and conjunction. All the words are objects and can be coded with a sequence. Hence, we define the objects as a serial number to identify the logic. The serial number is represented by a capital alphabetical letter plus Arabic numerals. However, in many cases, multi-relationship exists for one object. In order to differentiate the relationship, each one is given a number respectively. The rules for defining the relationships are shown in Table 3.

The ROM diagram of the following example is shown in Figure 8: “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 structure of the coach car.”
Table 2 Example of constraint relation

<table>
<thead>
<tr>
<th>Natural Language</th>
<th>Relations</th>
<th>ROM</th>
</tr>
</thead>
<tbody>
<tr>
<td>I design a garbage bin</td>
<td>predicate relation</td>
<td>design garbage bin a</td>
</tr>
<tr>
<td>coach car or sleeping car</td>
<td>constraint relation</td>
<td>car sleeping coach or</td>
</tr>
<tr>
<td>the environment for this garbage bin</td>
<td>connection relation</td>
<td>garbage bin this for environment the</td>
</tr>
</tbody>
</table>

Table 3 Code eight major types of words

<table>
<thead>
<tr>
<th>Part of Speech</th>
<th>Example</th>
<th>Numbering</th>
</tr>
</thead>
<tbody>
<tr>
<td>noun</td>
<td>environment</td>
<td>N+number</td>
</tr>
<tr>
<td>verb</td>
<td>think</td>
<td>V+number</td>
</tr>
<tr>
<td>Link verb</td>
<td>is</td>
<td>L+number</td>
</tr>
<tr>
<td>adjective</td>
<td>red</td>
<td>J+number</td>
</tr>
<tr>
<td>adverb</td>
<td>then</td>
<td>D+number</td>
</tr>
<tr>
<td>pronoun</td>
<td>I</td>
<td>P+number</td>
</tr>
<tr>
<td>determiners</td>
<td>the</td>
<td>A+number</td>
</tr>
<tr>
<td>preposition</td>
<td>for</td>
<td>T+number</td>
</tr>
<tr>
<td>conjunction</td>
<td>or</td>
<td>C+number</td>
</tr>
</tbody>
</table>

5 QUANTIFYING DESIGNER’S MENTAL STRESS

The objective of this section is to use ROM to quantify the mental stress based on our experimental results. Each designer’s transcripts are segmented and encoded and the consistency of the experiment is guaranteed in this way: three people deal with the protocol data in parallel and then cross-check their results. After all of the transcripts have been analyzed, the transcript from one typical subject is chosen to illustrate how ROM is working. The analysis result of all subjects will be presented separately.

Table 4 gives the statistical results of the nouns, verbs, and relationships in the selected transcript. Five design states are obtained based on the segmentation; and the numbers of verbs, nouns, and multi-relationships are identified in each state, respectively. Each state has a duration represented by a start time and an end time in the format of hh:mm:ss. The relationships are calculated by multiplying the numbers of the objects and their relationships. The index of multi-relationship is calculated by summing up the total number of the relationships.

Based on Table 4, we can plot the trend of the numbers of verbs, nouns, and multi-relationships in the five design states in Figure 9. To some extent, we map the trend to the mental stress that occurs to the subject during the design process. In stage 1, the subject is trying to understand the design problem and the mental stress is relatively low. In stage 2, he has a preliminary design idea, which is putting the garbage bin under the passenger seat or under the table. However, after that, he found that it is not good to put the bin aside or inside because one has to install a lot of garbage bins in every blocks. Therefore, he rejected this design idea, which can explain the decrease of the mental stress in the state 3. Then he started a new design to use a conveyor belt under the window to automatically collect the garbage rather than using a bin. In this state (state 4), the mental stress is higher than those of the other states. In state 5, he finalized his design scheme and finished the design process. It can be observed that the designer’s mental stress is positively related to the numbers of verbs, nouns, and relationships that he/she used to describe the design progresses. But it should be noted that the analysis results presented here are preliminary. More comprehensive analysis is required to correlate different factors appearing in this process.

6. CONCLUSIONS AND FUTURE WORK

This paper presents a formal definition of mental stress using ROM. A formalization procedure is proposed to transform a design process described in natural language into a formal specification. A quantification of designer’s mental stress is calculated by using ROM. The validation through the cognitive experiment shows that ROM is an efficient design evaluation methodology, which reflects the nature and the
characteristics of the design process. The designer’s mental stress presents dynamic, nonlinear, and spiral trend. More analysis is to be conducted in our future work, which will be correlated with our on-going experiments with other instruments for cognitive experiments.

Table 4 Statistical data in different design states

<table>
<thead>
<tr>
<th>Design state</th>
<th>Noun</th>
<th>Verb</th>
<th>Multi-relationship Relationships</th>
<th>Index</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31</td>
<td>29</td>
<td>1×8 2×4</td>
<td>16</td>
<td>00:26:50</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>2×6 4×4</td>
<td></td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2×10</td>
<td></td>
<td>00:30:00</td>
</tr>
<tr>
<td>2</td>
<td>72</td>
<td>57</td>
<td>2×4 1×5</td>
<td>107</td>
<td>00:30:45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2×8 1×7</td>
<td></td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1×9 1×10</td>
<td></td>
<td>00:39:20</td>
</tr>
<tr>
<td>3</td>
<td>77</td>
<td>35</td>
<td>1×4 1×5</td>
<td>47</td>
<td>00:39:30</td>
</tr>
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<td></td>
<td>1×8 1×11</td>
<td></td>
<td>–</td>
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<td></td>
<td></td>
<td></td>
<td>1×12 1×14</td>
<td></td>
<td>00:45:16</td>
</tr>
<tr>
<td>4</td>
<td>186</td>
<td>117</td>
<td>4×4 1×5</td>
<td>156</td>
<td>00:47:30</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>1×6 1×7</td>
<td></td>
<td>–</td>
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<td></td>
<td></td>
<td></td>
<td>1×9 1×11</td>
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<td>00:1:38</td>
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<tr>
<td>5</td>
<td>39</td>
<td>21</td>
<td>1×14 2×4 1×5</td>
<td>27</td>
<td>01:05:50</td>
</tr>
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<td></td>
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<td>–</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>01:07:11</td>
</tr>
</tbody>
</table>

Figure 9: Quantification of designer’s mental stress.

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REFERENCES