INFLUENCE OF INFORMATION COLLECTION STRATEGY IN PROBLEM FORMULATION ON DESIGN CREATIVITY THROUGH MENTAL STRESS: A THEORETICAL ANALYSIS

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Abstract

Problem formulation is an important process in design. A right solution comes from a right problem statement; creative solution may come from a creative problem statement. In this paper, three strategies for collecting information in the problem formulation process are identified: depth-first, breadth-first and hybrid search. How each strategy affects the creativity through its impact on designer's mental stress is examined. Among the three strategies, the hybrid approach is found to be the best as it allows designers to minimize uncertainty and focus on important design components.

Keywords: Design methods, Conceptual design, Problem formulation, Information collection strategy, Mental stress

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1 INTRODUCTION

Design is a process of transforming the information derived from requirements into "a description of a structure which is capable of fulfilling these demands" (Hubka and Eder, 1996). Design problem is usually ill-defined and requires continuous formulation. The formulation process helps designers understand the design problem by determining relevant requirements and clarifying the problem boundaries. Expert designers usually spend considerable amount of time and effort on problem formulation (Atman et al., 2007; Cross, 2006).

Problem formulation is important because it affects creativity (Dorst and Cross, 2001; Schön, 1983) and is directly related to design quality (Atman et al., 1999). Volkema (1983) identifies several factors that impact the time and effort designers spent on the formulation stage. These factors are the complexity of problem, the capabilities of designers, environmental factors, and the formulation strategy chosen by the designers. Dinar and Shah (2012) defined five tasks in problem formulation: information collection, perception and assumption, problem decomposition, augmentation and support, and analysis and verification. In this work, we focus on the information collection in the problem formulation stage of a design process by identifying three information collection strategies and analyse how each strategy may influence design creativity. Our paper is organized as follows: Section 2 discusses relevant works, introduces the two postulates of the design creativity model. Section 3 presents the strategies for information collection. Section 4 presents the impact of each strategy on design performance and finally Section 5 concludes the paper.

2 RELATED WORKS AND THE DESIGN CREATIVITY MODEL

2.1 Related works

It was observed that good designers start the information searching process by first identifying important requirements before focusing on technical problems while they also frequently "checked and planned their approach" (Fricke, 1999). Howard et al. compared the engineering design process model with the creative process model of psychology and found that the most important stage for both models is the collection and analysis of information at the early stage of the process (Howard, Culley and Dekoninck, 2008).

Information collection can happen at any phase in the design process. Designers can search for information in the problem formulation stage or search for inspiring ideas in the solution generation stage. Our work focuses on the former whereas searching in bio-inspired design focuses on the latter. In the problem formulation stage, designers aim to define the problem by searching for relevant environment components. Therefore, the direction for the search such as which information should be further elicited and explored is the main objective. In bio-inspired design or biomimetic design, the main objective of the search is to find biological analogies that can be transformed to design solutions (Shu, 2010; Wilson et al., 2009). Thus, searching techniques such as choosing appropriate search queries or constructing databases to facilitate the search is its focus.

2.2 Design creativity model

The foundation of the current work comes from the design creativity model proposed in (Nguyen and Zeng, 2012). Our creativity model includes two postulates: the first is the postulate of design process and the second is the postulate of relationship between design creativity and designer's mental stress. We reasoned that there is no distinction between design creativity and design process. A design model should imply design creativity and a design creativity model should imply routine design. The reason is that creative solutions can be found during routine design and designers are not always able to produce creative solutions as they intend to (Nguyen and Zeng, 2014).

2.2.1 The first postulate: design process and nonlinear dynamics

The first postulate was derived from the design governing equation (Zeng and Gu, 1999) which was founded on the principle of recursive logic (Zeng and Cheng, 1991) and was formally represented using the axiomatic theory of design modelling (Zeng, 2002). This postulate states that a design process resembles a nonlinear dynamic system in which the outcome is sensitive to initial conditions. A slight change in initial conditions may result in unprecedented outcome due to the recursive update of the design state and the interaction between the evaluation and synthesis process (Nguyen and

Zeng, 2012; Zeng and Cheng, 1991). This postulate shows the relationship between the two successive design states and explains why the early stage of a design process has a significant impact on the design solution.

2.2.2 The second postulate: designer mental stress and design creativity

The second postulate, built on the Yerkes-Dodson law (Yerkes and Dodson, 1908), states that the relationship between design creativity and designer's mental stress follows an inverse U curve (Zeng, 2005), as shown in Figure 1. This curve indicates that the chance of being creative is the highest when the designer's mental stress falls within an optimal range. Too high or too low mental stresses would reduce the probability for a designer to be creative.

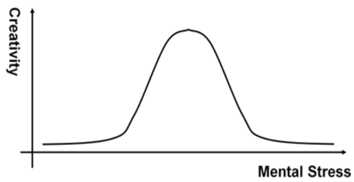


Figure 1. Relationship between creativity and mental stress (Nguyen and Zeng, 2012)

Nguyen and Zeng (2012) postulated that the mental stress is positively related with the workload perceived by the designer and negatively related with the designer's mental capacity. Furthermore, mental capacity is affected by designer's knowledge, skills and affect. The relation could be expressed as:

$$Mental\ stress = \frac{Perceived\ workload}{(knowledge+skill)*affect} \tag{1}$$

Or in mathematical form:

$$\sigma = \frac{L_p}{(K+S)*\alpha} \tag{2}$$

In the equation, the affect $\alpha \in [0,1]$ represents how much a designer can utilize the knowledge and skill in his/her mind. Positive emotion will result in a greater α than that for a negative emotion.
The inverse U shaped curve could be divided into 3 areas as illustrated in Figure 2 where σ_{LL} and σ_{UL} are the upper limit and lower limit of mental stress for a designer to be potentially creative.

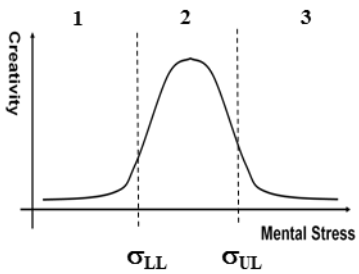


Figure 2. The three areas of the inverse U curve

According to Equation (2), the initial mental stress could be expressed as:

$$\sigma_0 = \frac{L_{p0}}{(K_0+S_0)*\alpha_0} \tag{3}$$

The state of low mental stress, i.e. when $\sigma_0 < \sigma_{LL}$, is possibly due to underestimated workload, and/or designer's vast knowledge and skill and high affect factor.
The state of high mental stress, i.e. when $\sigma_0 > \sigma_{UL}$, may be resulted from overestimated workload, limited knowledge and skills, and low affect factor.

3 STRATEGIES FOR INFORMATION COLLECTION

3.1 Overview of the strategies

Formulation of design problem requires collecting information related to the design product. According to Environment-Based Design (Zeng, 2011), searching for information related to the design product is to search for information associated with the product's environment components and their relationships. Figure 3 represents the structure of the environment. The environment is structured into two dimensions: in depth and in breadth. Along the depth dimension, more details for an environment component will be provided whereas along the breadth dimension more types of environment components will be identified. Such an environment structure is illustrated in Figure 3.

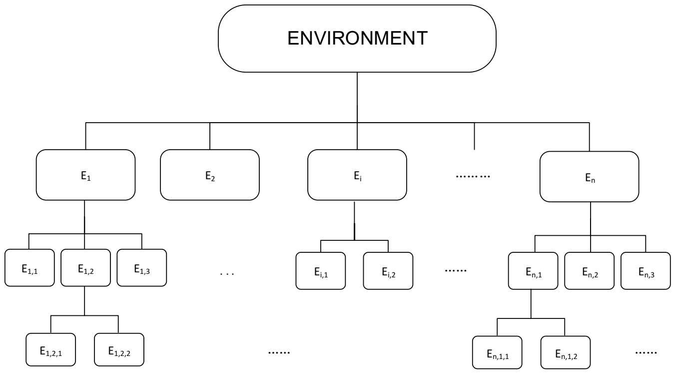


Figure 3. Environment structure

The two dimensional structure of the environment allows the search for the environment information to take place in three scenarios: depth-first, breadth-first and hybrid as described below:
- **Depth-first:** In this scenario, information will be collected from the top layer to the end along each branch before moving to another branch. The strategy explores the information in depth. This approach is shown in Figure 4(a).
- **Breadth-first:** In this scenario, all the information will be collected in the same level before moving to a lower level. The strategy explores the information in width, as illustrated in Figure 4(b).
- **Hybrid:** This scenario gives consideration of both depth and breadth of the information structure. Information might be collected from the breadth then dug into details for certain selected components, or in depth first then in breadth. Figure 4(c) shows the possible steps of this approach.

3.2 Examples

In this subsection, an example is provided hereafter to show the variation of design descriptions produced by the three strategies of information collection.
The design problem is initially stated as: *"Design a flying house that can easily fly from one location to another"*.

3.2.1 Steps of Information collection

Based on Environment-based Design method (EBD) (Zeng, 2011), a step-by-step procedure guiding the designers to collect information is listed below:
Step 1: Draw the ROM (Recursive Object Model) diagram for the design statement
Step 2: Identify the objects for information collection
Step 3: Ask right questions on the identified objects
Step 4: Collect answers
Step 5: Based on the answers, repeat Step 2-4
The details for the procedures are discussed in (Wang and Zeng, 2009; Zeng, 2008). The strategy of information collection determines which objects should be asked during the iteration. Consequently, the final description of the problem will vary depending on the strategy chosen.

3.2.2 Problem formulation

- Depth-first:

For the flying house design problem, the ROM diagram is shown in Figure 5.

We could choose “fly” as the object to refine first. Following the steps in Section 3.2.1, the following lists the questions and corresponding answers from the first few iterations of the problem formulation:

Q1: How to fly?

A1: Fly is to overcome gravity and drag force.

Q2: What is the gravity?

A2: Gravity is the force related with acceleration of gravity and the weight of the house.

Q3: How does the weight of the house influence fly?

A3: The weight of the house shall be reduced by adopting light-weighted material.

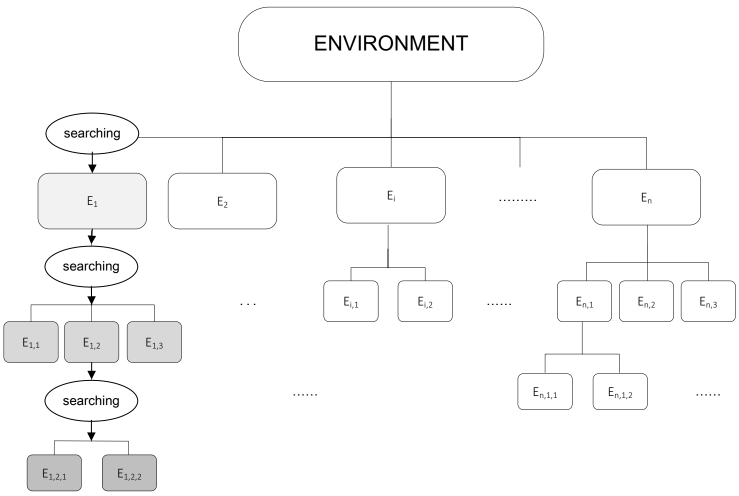
Q4: What is the light-weighted material?

A4: The material that has small density. However, they are normally less rigid.

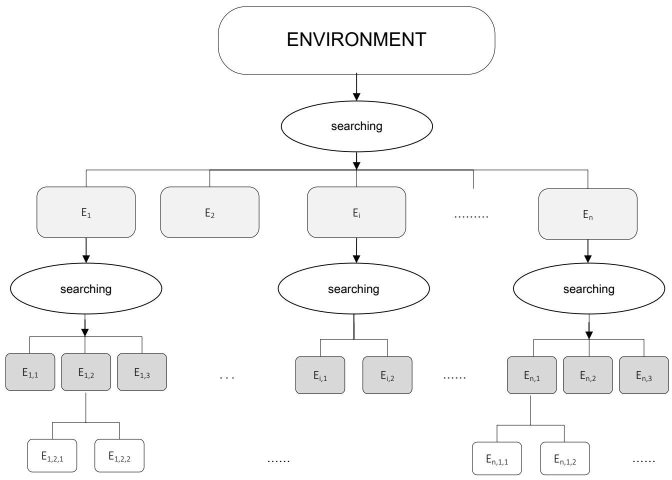
Q5: How to keep the material light-weighted but rigid?

A5: The material high rigidity-weight ratio shall be selected.

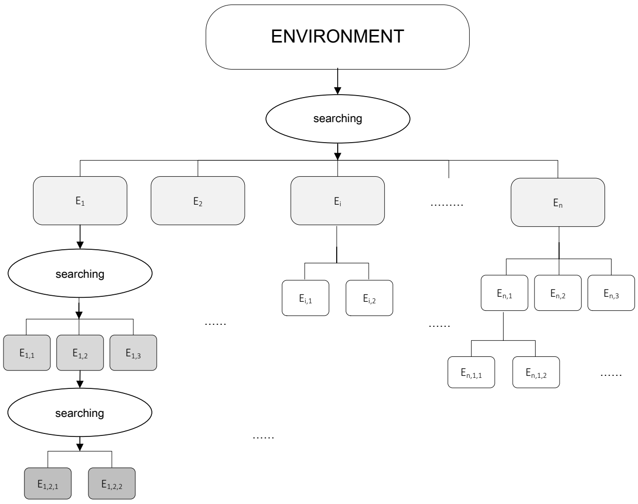
The objects selected for questioning in each iteration are shown in Figure 6(a).



(a)



(b)



(c)

Figure 4. Strategies of collecting information: (a) depth-first (b) breadth-first (c) hybrid

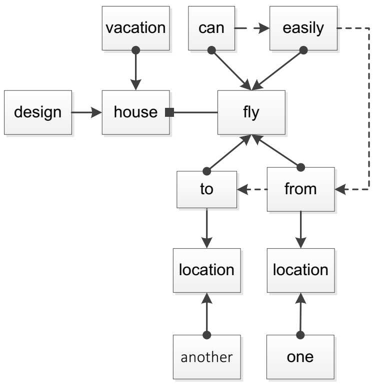


Figure 5. The ROM diagram of design problem

The answers form the description of the design problem as follows:

"Design a house that can fly from one location to another. The house will overcome the gravity and the drag force when moving upward and forward. The gravity is related with acceleration and the weight of the house. The house shall adopt light-weighted material in order to reduce the weight. Light-weighted materials are normally not rigid. To keep the rigidity of the house, material of high rigidity-weight ratio shall be selected such as aluminium. "

Following the EBD method, we can have problem formulations for breadth-first and hybrid strategies as follows.

- Breadth-first:

In the breadth-first strategy, all the objects related to the design problem are explored as shown in Figure 6(b). The design problem becomes:

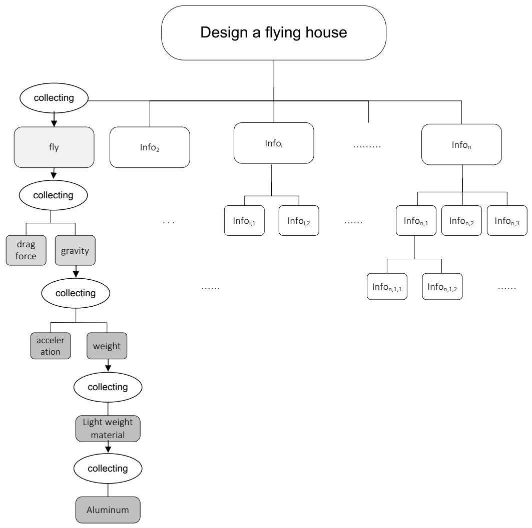
"Design a house that can easily move through the air from one location to another location, including road, beaches, lakes, forests, mountains and lawns. The house shall overcome the gravity and the drag force when moving forward. People, including children and adults, stay in the house and will operate the house. They do everyday activities, including sleeping, dining, cooking, washing, entertaining and exercising during their stay. The house will fly in suitable weather for flying. The road shall be in certain length and width for house landing and taking off. The beach could be sandy and rocky. The house could take off from the surface of water and also from land. The gravity is related with the acceleration and the weight. Drag force is related with the air viscosity, air density, velocity, shape of the house. Adults who pilot the house shall be certified. People will sleep on bed comfortably, cook instant food, wash themselves, do laundry, watch TV, surf internet and exercise in gym. The house

needs to fly in the weather condition of sunshine, raining, snowing but not thundering, windy and fogy."

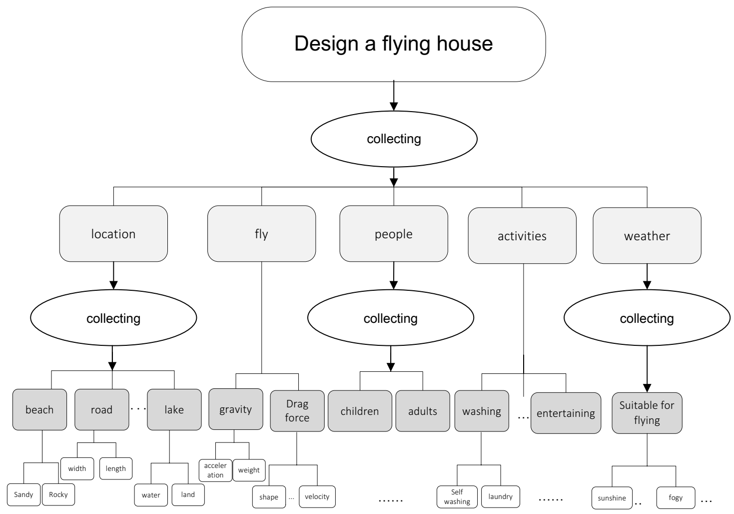
- Hybrid:

In this scenario, after general information is collected, the object "fly" is chosen for detailed search. The structure of the information is shown in Figure 6(c). Through the hybrid strategy, the design problem is reformulated as:

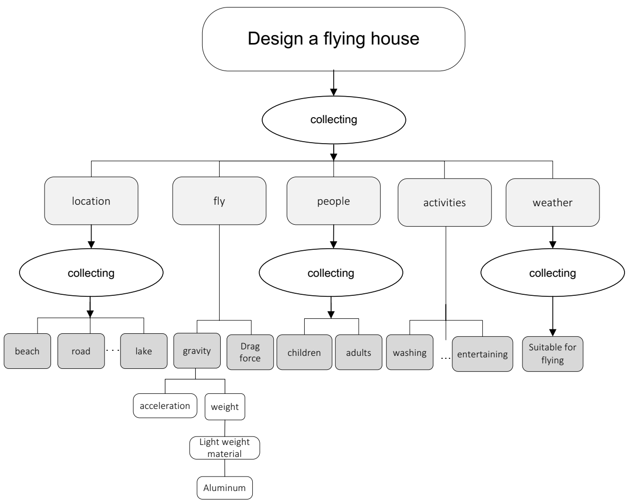
"Design a house that can easily move through the air from one location to another location, including road, beaches, lakes, forests, mountains and lawns. People staying in the house will move the house and they do everyday activities, including sleeping, washing, cooking, dinning, entertaining and exercising. The house shall overcome the gravity and overcome drag force when moving forward. Gravity is related with the weight and the drag force is related with the shape of the house, moving speed and the physical properties of the air. The streamlined shape will benefit the flying. The house shall adopt light weighted material to reduce the total weight."



(a)



(b)



(c)

Figure 6. Information collecting results: (a) depth-first, (b) breadth-first, and (c) hybrid

4 THE INFLUENCE OF INFORMATION COLLECTION STRATEGY

A right solution comes from a right problem statement. Likewise, a creative solution may come from a new problem statement. In this section, we examine how different information collection strategies adopted in the problem formulation stage may affect creativity. The analysis is based on the recursive characteristics of design process described in postulate 1 (i.e. the interdependence between the knowledge, workload, skill, affect and design state) and the relationship between creativity and mental stress described in postulate 2 (i.e. the inverse U curve) in (Nguyen and Zeng, 2012).

4.1 Depth-first

In the starting state of the design, the designer starts to look for information about the problem. As new information is available, the workload increases while the designer's knowledge of the problem increases at the same time. There are two possibilities:

1. If the increase in the workload exceeds the increase in the designer's mental capacity, the mental stress increases. Figure 7(a) illustrates this situation.
2. If the increase keeps the workload below the designer's mental capacity, the mental stress may stay the same or decrease as depicted in Figure 7(b).

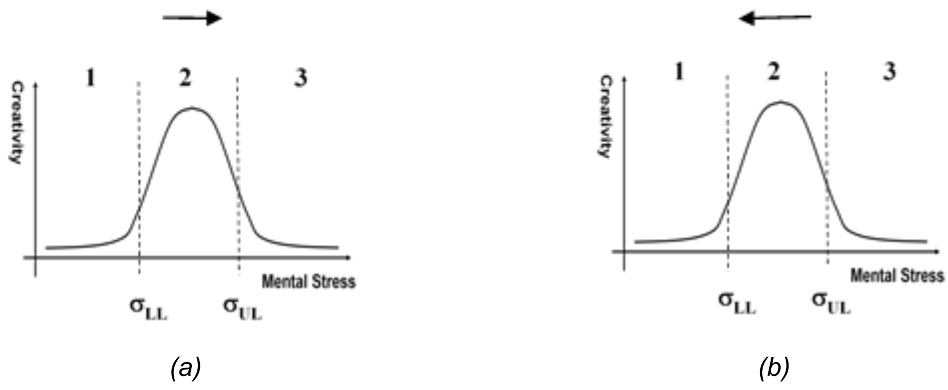


Figure 7. As more information of the problem is available, mental stress can either increase, stay the same or decrease

Depth-first activity focuses on one environment component at a time and searches information for that component in depth before moving to another environment component. As the designer moves along the depth dimension, it becomes more time demanding to acquire a piece of knowledge. In addition, some information and knowledge may be undefined since the scope of the design is yet to be defined

by other branches of the environment components. These factors may increase designer's workload and lower designer's affect.
The mental stress is expressed as:

$$\sigma_D = \frac{L_{p0}+\Delta L_D}{(K_0+\Delta K_D+S_0)*(\alpha_0-\Delta\alpha_D)} \quad (4)$$

where ΔL_D, ΔK_D and $\Delta\alpha_D$ are the change of workload, knowledge and affect brought by depth-first strategy.

4.2 Breadth-first

Similar to the depth-first search, in the starting state, the designer learns more about the problem. There are two possibilities illustrated in Figure 7: either mental stress increases because the workload exceeds designer's mental capacity or mental stress decreases or remains the same because the workload does not exceed designer's mental capacity.
Theoretically, at each step of the breadth-first search, the designer will cover all aspects of design problem. Thus, all relevant components are identified in the beginning. The scope of the problem is defined early, which will lower the sense of uncertainty and result in a higher affect. However, because all the information has to be identified and dealt with at the same time, the designer needs to be comfortable with the diversity of multidisciplinary knowledge, which could be emotionally stressful, leading to a lower affect.
The mental stress is expressed as:

$$\sigma_B = \frac{L_{p0}+\Delta L_B}{(K_0+\Delta K_B+S_0)*(\alpha_0\pm\Delta\alpha_B)} \quad (5)$$

where ΔL_B, $\Delta K_B$and $\Delta\alpha_B$ are the changes of workload, knowledge and affect brought by breadth-first information collecting strategy.

4.3 Hybrid

The beginning state of the hybrid strategy is similar to the depth-first and breadth-first strategies (see Figure 7). The hybrid strategy combines both the depth-first and breadth-first search. The designer starts the information collection in breadth, followed by searching certain information in depth. The breadth-first search identifies all relevant components of the design while the depth-first search focuses on important or interested components to reduce the complexity of the problem being dealt with.
The mental stress is defined as:

$$\sigma_H = \frac{L_{p0}+\Delta L_{H1}+\Delta L_{H2}}{(K_0+\Delta K_H+S_0)*(\alpha_0+\Delta\alpha_H)} \quad (6)$$

where, ΔL_{H1} and ΔL_{H2} are the workload changes due to breadth-first and depth-first search; ΔK_H and $\Delta\alpha_H$ are the changes of knowledge and affect brought by the hybrid strategy.
In the hybrid strategy, the designer minimizes uncertainty and expands only important components. In a review of several experimental results of expert designers, Cross (2004) concludes that experienced designers work "on adequate problem scoping and on a focused or directed approach to gathering problem information and prioritising criteria". This observation is in line with the idea of hybrid strategy. Yet the advantage of hybrid strategy strongly depends on the experience of a designer to determine the width of information to be collected, the components to concentrate on and the depth of the search. To maximize the advantage of the hybrid strategy, the designers need to be highly competent and experienced.

5 CONCLUSION

Depth-first, breadth-first and hybrid are three strategies we defined for collecting information during the problem formulation process. Each strategy influences creativity through its impact on designer's mental stress due to different influence on the upcoming workload, knowledge and affect. Among the three strategies, the hybrid search may be the best one because it incorporates the advantages of both breadth-first and depth-first approaches. However, to fully benefit from this strategy, the designers need to be experienced. In the future, tools can be developed to guide designers to work with the hybrid strategy effectively. Experiments need to be conducted to further quantify the relations between information collection strategies and the quality of design solutions.

REFERENCES

Atman, C.J., Adams, R.S., Cardella, M.E., Turns, J., Mosborg, S. and Saleem, J. (2007) Engineering Design Processes: A Comparison of Students and Expert Practitioners, Journal of Engineering Education, Vol. 96, No. 4, pp. 359-377.

Atman, C.J., Chimka, J.R., Bursic, K.M. and Nachtmann, H.L. (1999) A comparison of freshman and senior engineering design processes, Design Studies, Vol. 20, No. 2, pp. 131-152.

Cross, N. (2004) Expertise in design: an overview, Design Studies, Vol. 25, No. 5, pp. 427-441.

Cross, N. (2006) Designerly Ways of Knowing: Springer.

Dinar, M. and Shah, J.J. (2012) A Model of Problem Formulation Strategies in Engineering Design, Advances in Cognitive Systems, Palo Alto, California, December 6-8, 2012.

Dorst, K. and Cross, N. (2001) Creativity in the design process: co-evolution of problem-solution, Design Studies, Vol. 22, No. 5, pp. 425-437.

Fricke, G. (1999) Successful approaches in dealing with differently precise design problems, Design Studies, Vol. 20, No. 5, pp. 417-429.

Howard, T.J., Culley, S.J. and Dekoninck, E. (2008) Describing the creative design process by the integration of engineering design and cognitive psychology literature, Design Studies, Vol. 29, No. 2, pp. 160-180.

Hubka, V. and Eder, W.E. (1996) Design science: introduction to needs, scope and organization of engineering design knowledge: Springer.

Nguyen, T.A. and Zeng, Y. (2012) A Theoretical Model of Design Creativity: Nonlinear Design Dynamics and Mental Stress-Creativity Relation, Journal of Integrated Design and Process Science, Vol. 16, No. 3, pp. 37-60.

Nguyen, T.A. and Zeng, Y. (2014) A physiological study of relationship between designer's mental effort and mental stress during conceptual design, Computer-Aided Design, Vol. 54, No. 0, pp. 3-18.

Schön, D.A. (1983) The reflective practitioner: how professionals think in action: Basic Books.

Shu, L.H. (2010) A natural-language approach to biomimetic design, AI EDAM, Vol. 24, No. Special Issue 04, pp. 507-519.

Volkema, R.J. (1983) Problem Formulation in Planning and Design, Management Science, Vol. 29, No. 6, pp. 639-652.

Wang, M. and Zeng, Y. (2009) Asking the right questions to elicit product requirements, International Journal of Computer Integrated Manufacturing, Vol. 22, No. 4, pp. 283-298.

Wilson, J., Chang, P., Yim, S. and Rosen, D.W. (2009) Developing a bio-inspired design repository using ontologies, ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, San Diego, California, USA, American Society of Mechanical Engineers, pp. 799-808.

Yerkes, R.M. and Dodson, J.D. (1908) The relation of strength of stimulus to rapidity of habit-formation, Journal of Comparative Neurology and Psychology, Vol. 18, No. 5, pp. 459-482.

Zeng, Y. (2002) Axiomatic theory of design modeling, Transaction of SDPS: Journal of Integrated Design and Process Science, Vol. 6, No. 3, pp. 1-28.

Zeng, Y. (2005) Concordia Univeresity.

Zeng, Y. (2008) Recursive object model (ROM)—Modelling of linguistic information in engineering design, Computers in Industry, Vol. 59, No. 6, pp. 612-625.

Zeng, Y. (2011) Environment-Based Design (EBD), ASME Conference Proceedings, Vol. 2011, No. 54860, pp. 237-250.

Zeng, Y. and Cheng, G. (1991) On the logic of design, Design Studies, Vol. 12, No. 3, pp. 137-141.

Zeng, Y. and Gu, P. (1999) General Design Governing Equation, NSFC Grantee's Conference on Design and Manufacturing Engineering, Vancouver, BC, Canada.