A Symbolic Structure of Design Creativity*

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ABSTRACT

In this paper the underlying mechanism behind design creativity is proposed with formal tools, based upon the existing cognitive studies. It is argued that the design process falls into the category of a chaotic dynamics and design creativity come from the change of design requirements as initial conditions. In the dynamics of design, the state is intermediate requirement and structure in design process and the dynamic is the mutual interaction between the synthesis and evaluation knowledge. Three potential routes to creativity are given: extension of primitive design knowledge set, order of requirement decomposition and redefinition operator.

Keywords: design creativity, chaotic dynamics, formalization, computational model

1. INTRODUCTION

The research into design and designers is not new. Particularly in 1960's, the concepts and methods of systems science influenced design studies significantly and led to many beneficial results, which cover philosophy, psychology, computer science, and so forth, ranging from the phenomena, nature, cognitive model and computation of design[1]. In most cases, these works came from the *inductive* investigation and have given us insight on the thorough features of design. Researchers have reached some widely accepted conclusions which characterise design, such as that design is a creative act full of style, that design problem is ill structured and that some of design works can be dealt with by information processing theory and some others can not[2,3,4]. The research of this kind is multiobjective. Some are for design education, some for design improvement and some for design automation. After all, these purposes, among others, rely upon an important common task that is understanding design. The task aims to answer questions like 'what is design?', 'what are the natures of design?' and 'how is a design task accomplished?', etc., in a logical and rational way. The contents of the research constitute the main parts of design science.

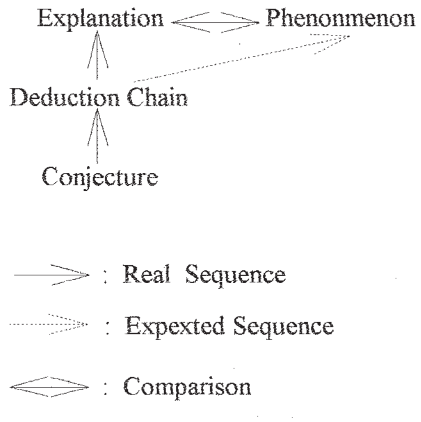

Fig.1 Schema of Scientific Research

A science studying design can be investigated and constructed with the methodology argued by, for example, Popper. According to Popper[5], in establishing scientific theory, a conjecture for some phenomena or experimental data should be made from which many conclusions will be deduced. If there is one conclusion found to be conflicted with the phenomena or experimental data then the conjecture should be rejected. Three elements are essential in Popper's proposal: *conjecture, conclusion from deduction chains* and *the comparison of the conclusion with the existing phenomena or experimental data.* From the computing science point of view, if the conjecture is proved true then *the deduction chains may imply a mechanical implementation of the explained phenomena.* The schema is shown in Fig.1.

In this paper, we do not intend to cover all aspects of design and it is indeed impossible to say so much in one paper. Instead we will focus our attention on design creativity. Our research strategy is same as that in Fig.1. We will base our work on existing cognitive studies concerned with the nature of design creativity and through making a conjecture on the underlying mechanism of design creativity

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attempt to get the corresponding *deductive* explanations. Consequently, the basic elements are investigated for a computational theory of design creativity.

In the following section, some results from cognitive studies of design creativity are reviewed. Then the dynamic mechanism of design is obtained by formalizing the general design process, based on which the observation on design creativity is formally explained in the framework of dynamical system theory. Three potential routes to a creative design are pointed out in the third parts. Finally some remarks and conclusions are made.

2. DYNAMIC OF DESIGN SYSTEM

2.1 Brief review of the nature of design creativity

In the Encyclopedia of Britannica, creativity is defined as 'the ability to make or otherwise bring into existence something new, whether a new solution to a problem, a new method or device, or a new artistic object or form.' But in the study of design cognition, what we are interested in are the basic natures of design creativity and the elements which lead to design creativity. Many authors[6,7] studied the problems from different points of view, based on which we can characterize design creativity as:

- *Conditions*: creativity arises under special conditions
- *Product*: the product of a creative act is novel and unusual in some sense
- *Act*: a creative act appears to be random and motivated by inspiration

In the observation, creativity is assumed to be measured through a *product*. The product should be new and novel compared with what have existed. There are two points to be noted for the comparison here. First, if the comparison is made between the product and the artifact in nature, then we can conclude a novel product, of social value, may be obtained. Second, if one can get a new form which did not exist in his mind then he is also taken as creative. The latter is our focus in studying the symbol structure of design creativity in the present paper. Then the problem we're confronted with can be more exactly proposed as *why do human beings create new things merely with the existing deterministic knowledge at their hands*. Or in Oxman's words[8]: 'The knowledge of the precedent is, by definition, of the past. How can it be used not only to explain, but to generate, the new?'

In explicating the conditions and mechanisms that give rise to creativity, Oxman[8] attribute the design creativity to 'the classification of prior solutions in memory as abstract and generalized knowledge stored in a structure of abstraction level'. She argued that the high level abstraction of knowledge can contribute to the creative application of prior experience in design. In accomplishing a design task, through the process of typification according to some structured representation of precedents the goals and constraints of the design are redefined. A novel reformulation of goals and constraints may make a creative design connection with precedents. Thereupon, she established a dynamic model of desgn. Furthermore, she discussed two mechanisms: refinement and adaptation, and the organization approach of precedent knowledge to facilitate the task[9,10]. Akin[6] also explored the importance of expertise in design creativity, and he listed three elements the expertise contributes to creativity: recognition skill, problem restructuring, and procedural knowledge.

An operational definition of design creativity is crucial for the computational model besides the empirical speculations such as that in above discussion. To do so we're recalled of the statements made by Crutchfield *et al*[11] that 'Innate creativity may have an underlying chaotic process that selectively amplifies small fluctuations and models them into macroscopic coherent mental states that are experienced as thoughts. In some cases the thoughts may be decisions, or what are perceived to be the exercise of will. In this light, *chaos provides a mechanism that allows for free will within a world governed by deterministic laws.*'

Naturally, if the formal connection can be constructed between the theory of dynamical systems and designing then the mechanism underlying design creativity is possible to be refined. To do so we must answer the question: does design have the same underlying mechanism with chaotic dynamics?

2.2 Basic concepts of dynamic systems theory[11]

Classical sciences were built up on the basis of deterministic law, from which the Laplace's statement[11] was deduced

> The present state of the system of nature is evidently a consequence of what it was in the preceding moment, and if we conceive of an intelligence which at a given instant

> comprehends all the relations of the entities of this universe, it could state the respective positions, motions, and general affects of all these entities at any time in the past or future.

The literal application of Laplace's dictum to human behavior led to the philosophical conclusion that human behavior was completely predetermined: free will did not exist, no speaking of creativity. Then a question may be posed as what is the origins of random behavior and further human creativity.

At the turn of the century the French mathematician Poincaré[11] argued that certain mechanical systems whose time evolution is governed by deterministic law may display chaotic motion. Chaotic dynamics provides a major reason for the randomness of natural behavior.

> A very small cause which escapes our notice determines a considerable effect that we cannot fail to see, and then we say that the effect is due to chance. If we knew exactly the laws of nature and the situation of the universe at the initial moment, we could predict exactly the situation of that same universe at a succeeding moment. But even if it were the case that the natural laws had no longer any secret for us, we could still only know the initial situation approximately. if that enabled us to predict the succeeding situation with the same approximation, that is all we require, and we should say that the phenomenon had been predicted, that it is governed by laws. But it is not always so; it may happen that small difference in the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible, and we have the fortuitous phenomenon.

By now, it is widely recognized that this phenomenon is abundant in nature and has far-reaching consequences in many branches of science.

One can understand chaos from the theory of dynamical systems. A dynamical system consists of two parts: a *state* and a *dynamic*. The state is the essential information about a system, the components of which are the coordinates of an abstract construct of a state space. The change of state with time is described as the orbit in the state space. The evolution of a system can be visualized in the state space by representing the behavior of the system in geometric form. In general the coordinates of the state space vary with the context; for a mechanical system they might be position and velocity, but for design they might be requirements and structures which will be explained in the later part of the paper. The dynamic is a rule that describes how the state evolves with time. The temporal evolution may happen in either continuous time or in discrete time. The former is called a flow, the latter a mapping. Apparently, the dynamic in design is a mapping.

Any system that come into stable motion with the passage of time can be characterized by an attractor in state space, in which rest is an extreme case. Roughly speaking, an attractor is what the behavior of a system settles down to, or is attracted to. *A system may have several attractors, different initial conditions may evolve to different attractors.* Chaos is an attractor which corresponds to unpredictable motions and have a complicated geometric form. The most fundamental characteristic of chaos is its sensitive dependence on the initial conditions. A small fluctuations can be amplified in its time evolution, in which the qualitative change occurs to the considered system. The fact can be clearly explained by considering the map

$$x_{n+1} = g(x_n) \tag{1}$$

which leads to chaotic motion. The initial difference ε between states is amplified to the separation $\varepsilon e^{N\lambda(x_0)}$, as shown in Fig.2.

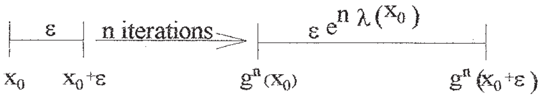

Fig.2 Chaotic Process

However, not all nonlinear dynamical equations will bring about the chaotic motion. An important element in chaotic dynamics is the existence of a simple *stretching* and *folding* operation in the state space. The stretching operation makes a orbit in state space diverge exponentially whereas the folding operation makes the orbit pass close to one another. The orbits on a chaotic attractor are shuffled by this process. The randomness of the chaotic orbits is the result of the shuffling process.

2.3 Dynamic for design system

The purpose of design is to make an artifact that satisfies the prescribed design requirements. Cross has shown that in solving a design problem the various design methods shared a common view of design as a cyclic process which contains an analytical phrase of problem definition and formulation, a synthesis phrase of design solution and an analytical phrase of evaluation[1]. In the problem definition phrase, a set of initial *design requirements*, $\mathbf{f}$, is formulated, thereupon some potential design candidates are suggested from *synthesis knowledge*, $\mathbf{k_s}$, in the synthesis phrase. In design practice, the design candidate is usually described by its *structure* $\mathbf{s}$. The process can be represented as

$$s = k_s(f) \tag{2}$$

Here, the structure $\mathbf{s}$ is not merely determined and the synthesis is accomplished in many ways in which the synthesis knowledge may be generic design knowledge or the past design cases. Correspondingly, we have many synthesis models such as decomposition, transformation or case based reasoning[12]. Anyway, in a given design domain the synthesis knowledge, no matter generic or specific, is implicitly determined though the amount may be very enormous. The basic form of this type of knowledge assumes the following form

$$K_s : F \to S \tag{3}$$

where $\mathbf{K_s}$, $\mathbf{F}$, $\mathbf{S}$ represent the synthesis knowledge set, the requirements set and the structure set, respectively. They are basic elements of a design domain, varying from one designer to another. The requirement and structure may be very generic or very specific. The former comes from the generalization of many design cases whereas the latter is just one of past design cases. Part of the goals of synthesis process is to search for some synthesis knowledge $\mathbf{k_s}$ from the known synthesis knowledge set $\mathbf{K_s}$ in terms of the given specification of design requirements.

$$k_s = [f, K_s]_{\approx} \tag{4}$$

where the symbol '$\approx$' denotes a *relevance* relation on a set, $[\mathrm{f}, \mathrm{K_s}]_{\approx}$ represents the subset of $\mathbf{K_s}$ which is relevant to $\mathbf{f}$.

Following the synthesis process, the proposed design candidate should be subjected to further justification. If the design candidate satisfies the specified design requirements then it might be accepted as a design solution. Otherwise the design candidate must be modified or some new design candidate should be recommended or the whole design problem should be reformulated. This evaluation process can be represented as

$$f' = k_e(s) \tag{5}$$

where the evaluation knowledge $\mathbf{k_e}$ is the natural laws and human value judgments. It may assume the following form:

$$K_e : S \to F \tag{6}$$

where $\mathbf{K_e}$ is the evaluation knowledge set. It is another basic element for a given design domain. In the evaluation stage, the relevant evaluation knowledge is retrieved from the set $\mathbf{K_e}$ through the expected structure and requirement to be tested. Thus

$$k_e = [\langle s, f \rangle, K_e]_{\approx} \tag{7}$$

By integrating the Formulae (2) and (5), we get the representation of design problem as follows:

$$\begin{gathered} k_d = k_s(k_e(\bullet)) \\ s = k_d(s) \end{gathered} \tag{8}$$

It must be noted that in designing, on one hand the structure $\mathbf{s}$ is accepted as a solution only if the requirements $\mathbf{f}$ are satisfied, which means that the artifact structure $\mathbf{s}$ relies on the requirements $\mathbf{f}$ and in turn on the evaluation knowledge $\mathbf{k_e}$. On the other hand, however, to test whether the design requirements $\mathbf{f}$ are satisfied, the specification of structure $\mathbf{s}$ is necessary to retrieve the relevant evaluation knowledge $\mathbf{k_e}$ from the evaluation knowledge set $\mathbf{K_e}$ as is shown in Formula (7). These mean that the design requirements $\mathbf{f}$ and the relevant evaluation knowledge $\mathbf{k_e}$ alike rely on the structure $\mathbf{s}$. Consequently, it can be concluded that designing is manifested by the *mutual dependence* between the artifact structure and the design requirements as well as the synthesis knowledge and evaluation knowledge. The fact makes designing self-referential and holistic. Here the mutual interaction and dependence causes designing to be an nonlinear dynamic process where the intermediate design proposals and requirements are states and the design knowledge $\mathbf{k_d}$ is the dynamic.

In the above process, the synthesis knowledge is *plausible* which may lead to many probable results. It acts like a stretching operation which 'stretches' the state of the design. In contrast, the evaluation knowledge is *deterministic* which will lead to inevitable results. It plays the role of folding operation which 'folds' the state of the design. The 'shuffling' process made up of these two elements will bring the designing into some 'stable state' which is the last design description. Hence *the goal of design is to search for an attractor, i.e., a design proposal, under the dynamic made up of synthesis knowledge with evaluation knowledge.*

Generally speaking, every design problem has many and even infinite design proposals which satisfy the design requirements. Therefore, for a dynamical system of designing there may be many or infinite 'attractors', some of which are creative whereas others are routine. The final 'attractor' depends upon the initial conditions of the design problem.

In design process, the definition of design requirements $\mathbf{f}$ is the initial condition which varies in two ways. First, different people or one people in different time may specify the design requirements in different manner. Second, as design problem is ill structured, design requirements keep on change according to the intermediate solution as the designing proceeds. Hence the initial conditions for design is apt to change. Naturally, the final design proposals may be greatly different when different peoples perform the same design task or does the same people in different time or situation. Creative design occurs when some *special conditions* appears, which is largely counted on the design context. Also the randomness of design creativity is evident in the framework. Then how to get such kind of '*novel attractors*' becomes the key in the so called creative design.

3. SYMBOL STRUCTURE OF DESIGN CREATIVITY

Although designing implies a dynamical process in itself, as is argued in the above section, not all designs are creative. The *special conditions* are the driving forces to motivate a creative design. The recognition of such conditions should be the initial attempt to study creative design. To do so we will concisely show the process solving the equation (8) in the first place. Then the possible ways of initial condition alteration are investigated.

3.1 Design process

We have assumed the existence of some basic elements in a design domain. They are the synthesis and evaluation knowledge, a requirement set and a structure set. Generally speaking, for each design task despite of the difference among individual design problems, the availability of a set of primitive components can always be assumed. An architect, for example, might assume the availability of walls, doors, windows, floors, rooms and other architectural components when accomplishing a floor planning task. Based on these primitive components, we may have the primitive design requirements and the synthesis as well as evaluation knowledge. Then any artifact can be studied by describing it as a global set of components related to each other. Denote the set of corresponding *primitive structure* as $\mathbf{S^a}$, the set of *primitive design requirements* as $\mathbf{F^a}$, then we have

$$\begin{aligned} S^a &= \{s_i^a \mid i = 1,2,\cdots,n\} \\ F^a &= \{f_j^a \mid j = 1,2,\cdots,m\} \\ K_s &\subseteq F^a \times S^a \\ K_e &\subseteq S^a \times F^a \end{aligned} \tag{9}$$

Having these basic elements at hand, a design problem with the requirements set $\mathbf{f}$ can be recursively defined as

$$\begin{aligned} f^1 &= f \\ f^j &= U(f_j^a, f^{j+1}) \end{aligned} \tag{10}$$

where $\mathbf{f}^j$ is also a requirements set. **U** is the *requirement decomposition operator*. Corresponding to each primitive requirement $\mathbf{f}_j^a$,there is a set of synthesis knowledge $\mathbf{k}_s^j$ to generate a set of primitive structures

$$\begin{aligned} k_s^j &= \left[f_j^a, K_s\right]_\approx \\ s^j &= k_s^j(f_j^a) \\ s^j &\subseteq S^a \end{aligned} \tag{11}$$

Naturally, following requirement decomposition is the *structure recomposition* which incrementally combines a generated primitive structure $\mathbf{s}_i^j$ in $\mathbf{s}^j$ into the completed partial structure:

$$s_p^j = V(s_i^j, s_p^{j-1}), s_i^j \in s^j \tag{12}$$

where **V** is the *structure recomposition operator*. $\mathbf{s}_p^j$ is a partial structure which represent the intermediate solution of design process. But it has to be pointed out that, in general, design requirement as a whole is not easy to be broken down into independent parts and the primitive structure cannot be simply added up to an integral structure. *The primitive structures, when combined together, may give rises to some conflicts with each other which may make the recomposition fail.* To solve the problem, the interaction among subrequirements must be taken into account through reformulating the problem by adding some new constraints to the completed partial design. This is termed as goal-constraints propagation[8].

$$\begin{aligned} k_e^j &= \left[< f_j, s_i^j >, K_e\right]_\approx \\ f_j' &= k_e^j(s_i^j) \\ f_j^n &= R_d(f_j, f_j') \\ f^{j+1} &= f^j \cup f_j^n \end{aligned} \tag{13}$$

where $\mathbf{R}_d$ is the problem redefinition operator.

Based on the Formulae (9), (10), (11), (12) and (13), a design task is accomplished in the following steps:

1. picks up a design requirement $\mathbf{f}_j$, which is primitive, from the design requirements set $\mathbf{f}$;
2. in terms of picked requirements $\mathbf{f}_j$, retrieves the relevant synthesis knowledge $\mathbf{k}_e^j \mathbf{k}_e^j$ from the synthesis knowledge set $\mathbf{K}_e$ and generate a set of primitive structures $\mathbf{s}^j$ which correspond to the picked primitive design requirement $\mathbf{f}_j$;
3. selects one, $\mathbf{s}_i^j$, from the generated primitive structure set $\mathbf{s}^j$, if there exists no completed partial structure then takes this one as the partial structure $\mathbf{s}_p^0$ else adds this one to the existing partial structure $\mathbf{s}_p^{j-1}$;
4. detects new constraints from the addition of the primitive structure $\mathbf{s}_i^j$ and adds them to the original design requirements set;
5. repeats the above steps until all the elements of the design requirements set, original or added, are satisfied.

The above process is shown in Fig.3.

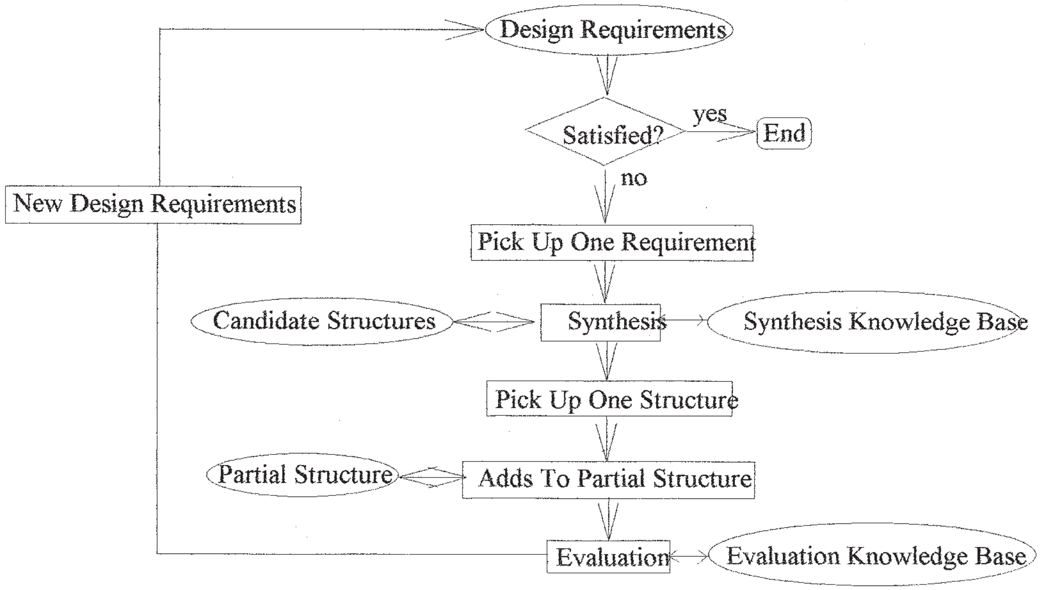

Fig.3 Dynamic design process

3.2 Routes to creative design

As the initial condition for a design problem is the corresponding design requirements set, thus the ways to change the design requirements are essential to get different design proposals. As design problem is itself ill structured, the design requirements keep on changing in design process. From the discussion made in the section 3.1 it can be seen that the ill structured nature of design manifests itself in three basic aspects: extension of primitive knowledge set, order of requirements decomposition and the redefinition operators. They provide potentials to give a creative design by leading to different design attractors.

3.2.1 extension of primitive design knowledge set

If the primitive knowledge set is extended, then according to the Formula (11), for a picked design requirement some larger set of primitive knowledge may be generated. As a result, in the light of Formulae (12) and (13) a different set of novel constraints are possibly to be emergent. The design may go into a branch which is different from the original one, and new structure may be generated. Naturally in this way different novel design proposals may be gotten. Hence the definition as well as the amount of primitive design knowledge embedded in designer's mind directly controls the quality and efficacy of the final design through redefining the design requirements in dynamic design process.

It can be seen from the Formula (9) that there are three basic ways to extend the primitive knowledge set. The first is to extend the primitive structure set. For example, the appearance of computer has significantly changed the modern industrial design. Denote the *primitive structure set extension operator* as O_s^e, we have

$$O_s^e : S^a \rightarrow (S^a)^e \tag{14}$$

where $(\mathbf{S^a})^\mathbf{e}$ is the extended primitive structure set.

The second way is to extend the primitive design requirements set. For example, after computer is in wide use the long distance data exchange become required. Denote the *primitive design requirements set extension operator* as $\mathbf{O}_f^e$, we have

$$O_f^e : F^a \rightarrow (F^a)^e \tag{15}$$

where $(\mathbf{F^a})^\mathbf{e}$ is the extended primitive design requirements set.

The third way is to detect more relations between the existing primitive structures and primitive design requirements. For example, the marriage of communication requirement with computer technology has brought us into a completely new world. Denote the *primitive design knowledge set extension operator* as $\mathbf{O}_k^e$, we have

$$O_k^e : K_s \to (K_s)^e$$
$$O_k^e : K_e \to (K_e)^e \tag{16}$$

where $(\mathbf{K}_\mathbf{s})^\mathbf{e}$ and $(\mathbf{K}_\mathbf{e})^\mathbf{e}$ are the extended primitive design knowledge set.

3.2.2 order of requirement decomposition

Different order of requirement decomposition will select different primitive knowledge subset which results in different partial design and in turn give different redefinition of design requirements of the succeeding design problem. As such, the final design solution may be quite different. This serves the same purpose with the restructuring of the problem in Akin[6]; and coincides with an often recommended technique that changing the angle of seeing a problem may lead to an unusual solution which might be very difficult to get. For example, in architectural design, we can arrange the floor planning according to function division, communication sequence or spatial form. Hence, the aforementioned requirement decomposition operator **U** can be further formalized as

$$U = \{u_i \,|\, i = 1, 2, \cdots, l\} \tag{17}$$

where u_i is a viewpoint to decompose the design requirement.

3.2.3 redefinition operator

As is described in section 3.1, in adding a primitive structure to the previously finished partial structure, conflicts may emerge. Besides, the primitive structure itself may bring some new design requirements into the original design problem. The process is represented by the redefinition operator $\mathbf{R}_\mathbf{d}$ in Formula (13). Hence, in each run of requirement decomposition and structure recomposition, different consideration of the redefinition operator will give rises to different new design requirements for the repeated designing. Generally, there are three approaches to redefining the requirements. First, to remove the conflicts, the primitive structure can be modified so that it conforms with the partial structure. Second, an alternative primitive structure may be picked up from the candidate structures. Third, the finished partial structure may also be redesigned.

$$R_d = \{r_d^i \,|\, i = 1, 2, 3\} \tag{18}$$

where $\mathbf{r}_\mathbf{d}^\mathbf{i}$ denotes the above three approaches, respectively.

4. CONCLUDING REMARKS

The paradox in studying design creativity is expressed by the question: why do human beings create new things merely with the existing deterministic knowledge at their hands? It is similar to an argument in chaotic dynamics: chaos provides a mechanism that allows for free will within a world governed by deterministic laws. This association leads us to count on the theory of dynamical systems to investigate the design creativity.

Our research gives the basic representation of a design problem. This form displays a nonlinear characteristic where the intermediate design requirements and structures in the dynamic process of design are state and the mutual interaction between the synthesis and evaluation knowledge is the dynamic. Based on the framework, the randomness of design creativity is naturally inevitable, which comes from the prone-to-change nature of design requirements in design process. Design creativity is then attributed to the emergence of different attractors in different emergence of design requirements.

Having these conclusions in mind, three potential routes: extension of primitive design knowledge set, order of requirement decomposition and redefinition operator, to creative design are pointed out, which are stemmed from the way to change the design requirement. However, in any sense they are still the necessary conditions for design creativity as the conditions to chaos are far more complex than what we described here.

Further efforts will be focused on the refinement of the conditions to creative design and making them more operational. The conclusions here should be naturally embedded into a formal design theory. The relevance of this work to others in studying design creativity also deserves investigating.

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