DESIGN FAMILIES AND DESIGN INDIVIDUALS

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Abstract: This paper discusses design families and design individuals. Phase space is introduced to complement state space. Phase transition as a generic method of generating design families is proposed and then demonstrated through an example of simple designs with one component. Based on phase transition in the biological world, a development model for complex designs (with multi-components) is established, by which different phase transitions for changing complex design families are analyzed and simulated. Two concepts are drawn from the biological analogy: through gene mutation and regulation the individuals of complex design systems can be varied and searched within their state space; and by changing the interpretation process of genes the families of such systems can be explored within their phase space.

Keywords: design families; design individuals; design diversity; phase transition; phase bifurcation; developmental biology; design phase space; exploration.

1 INTRODUCTION

1.1 Motivation and background

Both design optimization and design variation are important in design development. Design diversity is a key factor in creating new markets of products. Like biological diversity, design diversity has two modes: diversity of individuals and diversity of families. Without the diversity of families, the diversity in both nature and design is incomplete. Families and individuals are two ways to characterize objects. A *family* is a group of objects or beings related by common characteristics, which demonstrate a kind of commonality of the group. On the other hand, an *individual* is a particular object or being distinguished from others in a family. One family differs from another in ways that could be either qualitative or quantitative. Qualitatively different families show disjoint distinctions, while the quantitatively different families show continuous differences. Thus, the individuals in quantitatively different families demonstrate less of a difference than those in qualitatively different ones.

Earlier research on families of natural form has been conducted by Thompson (1942). He examined a vast spectrum of life forms, such as leaf, crab, and fish families, and families of mammalian skulls. By comparison of correlated forms, he proposed a theory of transformation, and then developed a method of coordinates to explain the transition of natural forms in families. he also demonstrated the use of t parameter variation in determining the families' deformation of natural forms. Drawing an analogy with the mechanisms and concepts from nature for design research and application was the initial motivation for this research.

There is a number of well-known computation methods for the generation of individuals in design. These include such methods as optimization, genetic or evolutionary algorithms, and standard shape grammars. However, fewer computation methods exist for the exploration of design families. Two major computation methods for the generation of design families exist. The first approach is the generic product structuring (GPS) method. As a modular design method it is used to describe product families with well-defined interfaces between modules of these families (Erens and Breuls, 1995), which implements design families by applying different module variants hierarchically. This is a feasible approach for industries that compose their product families by selecting and assembling module variants rather than designing diverse module variants. The second approach is based on parametric shape grammars, which are an extension of standard shape grammars in which shape rules are defined by filling in the open terms in a general schema (Stiny, 1980). Standard shape grammars are used to generate individuals for a specific family, while parametric shape grammars are able to create families of shapes. The difference is that each rule in standard grammars is defined explicitly; the rules in parametric grammars are not fully fixed.

This paper proposes a method for the generation of design individuals and design families from the perspective of state and phase spaces. It explicitly demonstrates the dependent mechanism between individuals and families. It also proposes an analogy from developmental biology that enriches design by inheriting a number of concepts and mechanisms for design exploration and design diversity, using concepts such as phase transition, bifurcation, transformation, gene mutation, phenocopies, and the process of development and evolution.

Thompson (1942) claimed that from the standpoints of mathematics and biology, that besides gene mutation, natural forces and the environment influence the families of natural forms and their growth. Morphogenesis was proposed by Thom (1983). Orders of form were explained and illustrated by Kauffman (1993) and Goodwin and Webster (1996). They established the connection among genes, phase transition, the environment and forms that reveals the relationship of form and its generation. Those researches form the basis of this paper.

The paper is organized in four major sections. In Section 1, the motivation and background for this research is briefly introduced. Secondly, a simple mathematical example is given to illustrate phase space and phase transition. Thirdly, the relationship between state and phase space is explained and that is used to demonstrate that phase transition changes the design family. In Section 2, a generic method for creating families is introduced followed by a simple example of one component design families and individuals. In the third section on development model for complex design families, the relationship between design variables and designs is modeled by an analogy with the relationship between genotype and phenotype in developmental biology. In the final section on design families for complex systems, complex design families and individuals are generated by the development model.

1.2 Phase transition

Phase transition is illustrated by the following five contour families in Figure 1. The contours are created by the equation $\lambda_a \times x^2 + \lambda_b \times y^2 = C$, where C is a constant, in which the variables {x, y}, and parameters {λ_a, λ_b} (or coefficients), determine the families of contours. Parameters are as important as variables in determining the families of contours. Table 1 describes the relationships between the parametric variation and contour families in Figure 1, by which some concepts are shown.

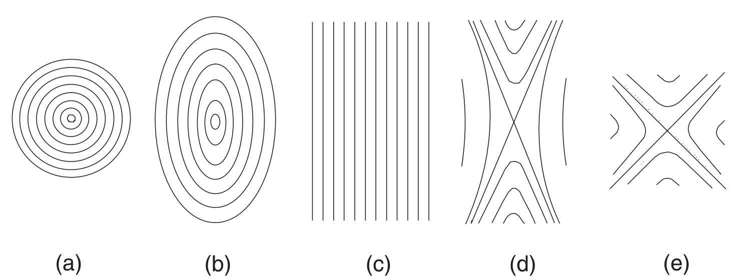


Figure 1. Families of contours (Potson and Stewart, 1978)

	Contour (a)	*Contour (b)*	*Contour (c)*	*Contour (d)*	*Contour (e)*
λ_a/λ_b	=1	>1	∞	<-1	=-1

Table 1. Phase transition for the contours

Firstly, two spaces may be conceived of: a *state space*, expressed as all possible values for a set of variables $\{x, y\}$, and a *phase space* that is established by all the possible values for a set of parameters $\{\lambda_a, \lambda_b\}$. A specific set of parameters denotes a point in phase space, which defines a *family*. The variation of this phase point is called a *phase transition*. Secondly, each point in a specific state space indicates an individual, while all the points in this state space demonstrate a commonality that is determined by its phase point. Thirdly, two basic phase transitions exist. By changing the value of ratio λ_a / λ_b from *1* to larger than *1*, the contour changes from a circle, Figure 1 (a), to an ellipse, Figure 1 (b), or to an asymptote, Figure 1 (d), when the ratio changes to be less than *-1*. Another change is more dramatic, for instance, when the value of ratio λ_a / λ_b changes from plus to minus, or from limited to unlimited, the contour changes from an ellipse, Figure 1 (b), to an asymptote, Figure 1 (d), or from an ellipse, Figure 1 (b), to a line, Figure 1 (c). The former phase transition is called a *smooth phase transition*, while the latter phase transition is called *phase bifurcation*. Fourthly, the families between circles and ellipses, or two kinds of asymptote are *quantitative*, but the families between lines and ellipses, or circles and asymptotes are *qualitative*. In other words, phase transition changes families in quantitative terms, but phase bifurcation shifts families qualitatively. By changing the phase space the state space is transformed or moved correspondingly.

1.3 State space of design: search and exploration

In design, the state space is a representation of all the possible states that could exist if all the design processes are legally operated on all the variables (Gero, 1990). Search is the process of navigation within a fixed, predefined state space of possible designs. To locate an appropriate or the most appropriate solution, a number of methods for design searching are employed to traverse this state space. Exploration is the process by which state spaces are produced. Such processes include: expanding a design state space through the addition of design variables (Gero and Kumar, 1993) and adaptive enlargement of state space in evolutionary designing (Gero and Kazakov, 2000).

Other than these manipulations of the design state space itself, what are the means to change the state space and what determines the state space? The phase space, as a higher-level controller that moves and transforms the state space is explained and demonstrated in the following sections.

1.4 Design phase space determines state spaces

A phase space in design is made up of a number of parameters that could be conceived of a parameter space where each axis represents one parameter. A point in that space indicates a set of parameters that relates to a specific state space by means of an interpretation mechanism. The movement of different points in phase space, in turn, explores different state spaces as illustrated in Figure 2. A design family represents the commonality of a group of design individuals; design phase transition transforms or moves this group of designs rather than a single design. Design individuals are expressed by points in the state space. Without phase transition, no matter what kind of individual searching methods are applied and how well the procedure of optimization is achieved, the commonality of the individuals remains the same. If the phase space as a meta-level controller is changed, the commonality will be broken, and new design families will occur.

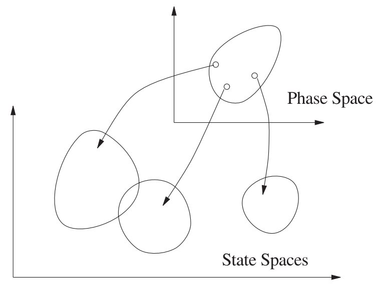


Figure 2. Phase transition exploring state spaces

2 GENERIC METHOD FOR THE CREATION OF DESIGN FAMILIES

To generate design individuals, the common way is to find and establish design variables for its state space. Consequently, the variation of the design variables generates design individuals. As described previously, in order to change design families, besides design variables, design parameters that set up the phase space need to be established as well. The generic way to establish design parameters is to find the relationship among variables of a specific design and the relationship between variables and design. Once the relationships are found, the initial specific parameters for a single case are replaced with generic parameters. By changing the dynamic parameters, the variation of phase space may create design families. When exploring the phase space, the phase bifurcation points determining the qualitative families could be found out by the nature of the relationship of variables and parameters. At the meantime, the smooth phase transition point could be determined or planned for applications, which may cause quantitative families. The key procedure is to find out the design variables and their relationships; this could be simple or complicated depending on the design system. In the following sections an example of simple designs (with one component) is given to demonstrate how to explore design families and search design individuals.

2.1 Quantitative shape families

Firstly, in order to generate individual cylinder designs, the state space of the cylinder design is expressed through the variation of its variables $\{r, h\}$, where r is radius, and h is height. A feasible design normally has constraints to satisfy the given requirements, such as the requirements of volume V, and ratio $\{r/h\}$. C is a constant.

$$V = \pi \times r^2 \times h,$$
$$r / h = C$$

By changing the variables of the state space, various individual cylinder designs can be generated for the given requirements.

Secondly, in order to generate a range of families of cylinder designs, new requirements need to be explored. To do this, the requirements of the cylinder design could be dynamically expressed by introducing phase parameters to$\{\lambda_r, \lambda_h\}$ as follows:

$$V = \{\lambda_r \times \lambda_h\} \times \pi \times r^2 \times h,$$
$$\lambda_r / \lambda_h = r / h$$

Through the phase transition parameters $\{\lambda_r / \lambda_h = 1, 0.5, 0.25\}$, and $\{\lambda_r * \lambda_h = 1\}$, the flattened, normal, and slim shape families of the cylinder design are created as shown in Table 2. In this table the parameters $\{\lambda_r / \lambda_h\}$, and $\{\lambda_r * \lambda_h\}$ can take any value within their domains, the above specific values represent three points in the phase space that generate three cylinder shape families.

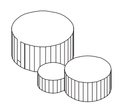
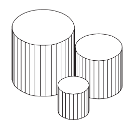
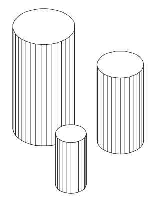
	Quantitative families of cylinder		
Cylinder shape individuals	$\lambda_r/\lambda_h=1$ flattened	$\lambda_r/\lambda_h=0.5$ normal	$\lambda_r/\lambda_h=0.25$ slim
			

Table 2.Families and individuals of cylinder

In this cylinder design example, only three individuals of each family, and three families are shown. Different families can be generated by defining new value ranges for $\{\lambda_r / \lambda_h\}$ and $\{\lambda_r * \lambda_h\}$ in the phase space defined by $\{\lambda_r, \lambda_h\}$. The differences between these families is quantitative and another range of families could have been chosen.

2.2 Qualitative shape families

As we can see from the examples in Table 2 quantitative families produced by phase transitions do not show drastic difference from one family to another. If the expressions of the cylinder design are further generalized and abstracted as follows:

$$V = \frac{n}{2} \times \sin\frac{2 \times \pi}{n} \times \{\lambda_r \times \lambda_h\} \times r^2 \times h,$$
$$\lambda_r / \lambda_h = r / h$$

where n is the number of edges of a prism, its phase transition will cause more dramatic design variations and this is called phase bifurcation.

When the phase space is expressed as $\{\lambda_r, \lambda_h\}$, and $\{\lambda_r * \lambda_h\}=1$, the phase bifurcation $\{n=3, 4, 6, \ldots, \infty\}$ may cause distinguishable qualitative families:

$$V = \frac{3 \times \sqrt{3}}{4} \times r^2 \times h, \quad n = 3, \quad \textit{TRIANGULAR PRISM FAMILY}$$
$$V = 2 \times r^2 \times h, \quad n = 4, \quad \textit{RECTANGULAR PRISM FAMILY}$$
$$V = \frac{3 \times \sqrt{3}}{2} \times r^2 \times h, \quad n = 6, \quad \textit{HEXAGONAL PRISM FAMILY}$$
$$V = \pi \times r^2 \times h, \quad n = \infty, \quad \textit{CYLINDER FAMILY}.$$

This phase bifurcation extends the generation of families beyond the cylinder into triangular, rectangular and hexagonal prism families as shown in Table 3.

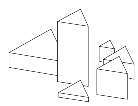
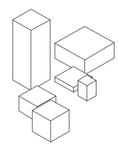
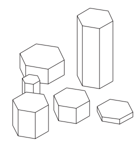
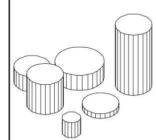
	Qualitative families of prism			
Prism individuals	$n=3$ triangle	$n=4$ rectangle	$n=6$ hexagon	$n=\infty$ circle
				

Table 3. Families and individuals of prism

These examples demonstrate the generation of design individuals and families by using the concept of phase space and the mechanism of phase transition.

3 DEVELOPMENT MODEL FOR COMPLEX DESIGN SYSTEMS

In the previous section, the creation of simple design families was demonstrated. This section focuses on families of complex systems with multiple components. The expression for complex systems is established by analogy with developmental biology, in which variables are equivalent to genes, the variation of a gene's interpretation process is expressed as phase transition, and components are generalized from organs. In the following sub-sections, the concepts of phase transition and the nonlinear interpretation between genotype and phenotype are derived from developmental biology, and then is introduced. A development model for complex design systems based on these analogies is used to generate the families and individuals of complex designs.

This model established by the analogy of developmental process of biology also has another advantage, which can bring biology specific mechanisms and concepts into design, such as gene mutation, regulation, evolution, simulation, and crossover, etc. Because the focus of this paper is on design families and individuals, only gene mutation and regulation are used in this paper.

3.1 Unique forms of phase transition in the biological world

In biology, the mapping between genotype and phenotype is not one-to-one. For instance, two identical twins with the same genotype exposed to radically different environments can result in morphological differences. On the other hand, phenocopies are environmentally produced phenotypes that mimic genetically produced phenotypes (Goldschmidt, 1938). The interpretation process is influenced by its environment, which also contributes to the phenotype generation. The same conclusion is proposed by Thompson (1942). One of the consequences of phase transition in biology illustrated by Kauffman (1993) and by Goodwin and Webster (1996) is the generation of families of related forms such as shell patterns whereby the phase space of different developmental mechanisms is changed.

3.2 Development model for complex systems

Genotype definition in design

The genotype is made up of regulatory and structural genes. Regulatory genes as master genes regulate other regulatory and structural genes, and structural genes are coded for physical composition (Jacob and Monod, 1961) This is different to standard evolutionary algorithms since they do not include regulatory genes. The genotype is divided into three parts: regulatory genes, geometrical structural genes, and attribute structural genes.

$$Genotype = \{L, P, A\}$$

where

$L = \{l_{0,1}, ..., l_{0,i}, ...\}$ are regulatory genes

$A = \{a_1, ..., a_i, ...\}$ are attribute structural genes

$P = \{p_{1,1}, ..., p_{i,j}, ...\}$ are geometrical structural genes.

The genes include multiple members related to the components of a complex system. The genes are not linearly mapped into phenotype, but are interpreted into phenotype through a sequence of constraints and structure regulations as described in the next two sub-sections.

Interpretation within constraint fields

The interpretation process from genotype to phenotype is restricted by its environment constraints. The phenotype is not uniquely determined by its genotype; the changing constraints alter the interpretation process and thus change the phenotype. This claim is supported by the theory of constraint fields between genotype and phenotype proposed by Goodwin (1988) and later supported by Rocha (1995), as described below:

$$\{f_L(\lambda_{CL} \times \lambda_{SL} \times L), f_P(\lambda_{CP} \times \lambda_{SP} \times P), f_A(\lambda_{CA} \times \lambda_{SA} \times A)\}$$

where

f_L, f_P, f_A are constraints functions for the genes in the domains of topology, geometry, and attribute

$\lambda_{CL}, \lambda_{CP}, \lambda_{CA}$ are matrices of components-relevant constraint parameters in topology, geometry, and attribute

$\lambda_{SL}, \lambda_{SP}, \lambda_{SA}$ are matrices of component-self-relevant parameters in topology, geometry, and attribute.

Interpretation of complex systems

A complex system comprises a number of components. The overall relationship of the components in topology, geometry, and attribute is expressed as the following equation that describes the structure development, of which hierarchy is the fundamental structure characteristic (Simon, 1996)

$$\{\tilde{L}, \tilde{P}, \tilde{A}\} = \{F_L(\lambda_H \times L), F_P(\lambda_H \times P), F_A(\lambda_H \times \lambda_U \times A)\}$$

where

F_L, F_P, F_A are structure functions in topology, geometry, and attribute (see Gero and Shi, 1999)

λ_H is environment parameter matrix that influences the topological hierarchy

λ_U is matrix of unity attribute parameters

$\{\tilde{L}, \tilde{P}, \tilde{A}\}$ are interpretations of all regulatory, geometrical structural, and attribute structural genes.

Synthesis into phenotype
As previously mentioned, the genotype {*L, P, A*} is interpreted as $\{\tilde{L}, \tilde{P}, \tilde{A}\}$ through the pressure of constraints f_L, f_P, f_A and the component structure equations $C_i = \tilde{L}_{ii} \times \{\tilde{P}_{ii}, \tilde{A}_{ii}\}$, which is finally synthesized as a phenotype comprising the components of a complex system as shown below

$$Phenotype = \{C_1, ..., C_i, ..., C_n\}$$

C_i is component *i* of a complex design system

$\tilde{L}_{ii}, \tilde{P}_{ii}, \tilde{A}_{ii}$ are interpretations of regulatory, geometrical structural, and attribute structural genes of component *i*.

This development model differs in two ways from other evolution computing models in that it includes a development process in addition to the evolution process implying that the interpretation process is not linear and regulatory genes are utilized as a means of controlling structure.

4 PHASE TRANSITION FOR THE EXPLORATION OF DESIGN FAMILIES

In the biological world, each individual has its own uniqueness because of its gene drift (micro-mutation) and the specific environment during its development. The commonality among individuals which may be noticed through the observation of groups of individuals is created more often by phase transition than gene drift, while the uniqueness of an individual is generated by gene drift rather than by phase transition. The following section discusses the way of manipulating complex design families with the development model.

4.1 Design families for complex systems

Design families of complex systems with multiple components are examined in this section. The development model for complex systems is used to generate both design families and individuals.

The interpretation from genotype to phenotype by the development model passes through a longer journey and exposes to more complicated pressure from constraints and structure than the linear mapping of the standard evolutionary algorithms, as demonstrated by the interpretation of the attribute gene.

$$a_i \rightarrow \lambda_{SA} = \{\lambda_{SA_{Whole}}, \lambda_{SA_{Part}}\} \rightarrow \lambda_{CA_{ij}} \rightarrow \lambda_{U_i} \rightarrow \lambda_H \rightarrow \tilde{A}_i$$

The attribute gene a_i of the genotype is interpreted as $\tilde{A}_i$ under the control of a set of parameters involving constraints and structure { λ_{SA} , $\lambda_{CA_{ij}}$, $\lambda_{U_{ij}}$, λ_H } (λ_{SA} is divided into two $\lambda_{SA_{Whole}}$, $\lambda_{SA_{Part}}$), which could be conceived as a phase space. A phase point in this phase space corresponds to an interpretation that is like a canal, under which all the possible mutations of attribute gene a_i are interpreted and then synthesized. The mutation of genes supplies the uniqueness of individuals, while the specific phase point canalizes the commonality of individuals.

4.2 Prototype of a multiple-component system

To discuss design families, A prototype of a multiple-component system is defined in Figure 3 as the basis for the discussion on design families. This prototype has nine components. The components are able to be varied through mutations of their regulatory and structural genes {*L*, *P*, *A*}.

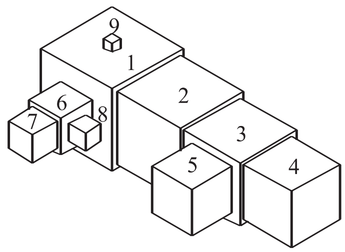


Figure 3. Prototype of a complex design system

The variation of the nine components are connected by a specific hierarchy structure F_L, F_P, F_A and also constrained by a specific boundary and relevant relations f_L, f_P, f_A. All the possible states of structure λ_H and constraints $\{\lambda_{SA_{Whole}}, \lambda_{SA_{Part}}, \lambda_{CA_{ij}}, \lambda_{U_i}\}$ are conceived as a phase space. The initial phase point for this prototype is defined as value *1* (either logic value or geometrical and attribute values). In the following sub-sections a number of means of phase transition for the generation of complex design families is introduced and illustrated by examples, which simulate the phase transition and genes mutation.

4.3 Whole and part related families

4.3.1 Whole-related families

A whole-related family is generated by a phase transition from a common environment that influences all the components of a complex design system homogeneously. As shown in Table 4, two kinds of design variations are implemented by phase transition to produce two quantitatively different families of designs. Within these two families six gene mutations are used to produce specific individuals.

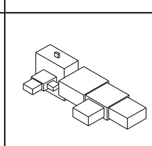
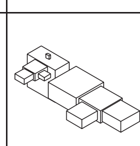
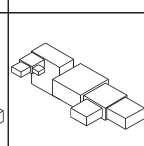
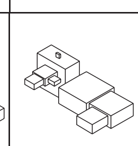
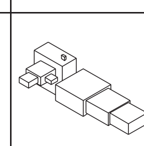
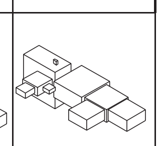
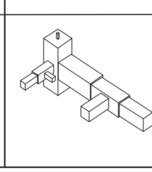
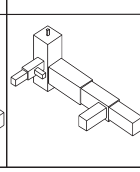
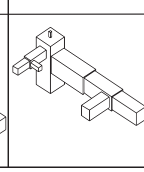
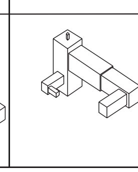
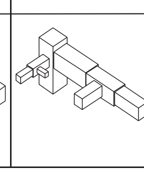
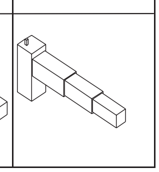
		Individuals by mutation of regulatory and structural genes {L,P,A}					
		1	2	3	4	5	6
Families by phase transition	B						
	A						

Table 4. Whole-related families

Design families by phase transition: Compared with the prototype, Table 4 demonstrates that two phase transitions with $\lambda_{SA_{Whole}} = \{1.0, \lambda_{SA_{Whole}y} / \lambda_{SA_{Whole}x},\ \lambda_{SA_{Whole}z} / \lambda_{SA_{Whole}x}\} = \{1.0, 0.5, 1.0\}$ and {1.0, 1.0, 2.5} produce two quantitatively different families of designs, where the ratio values of y to x, and z to x are selected to demonstrate two noticeably different families. However this ratio could have a wide range of values and still produce noticeably different families. These two transitions create two different kinds of whole-related shape families, which are labeled slim family *A* and flattened family *B* in Table 4. The whole-related families are controlled by the phase transition $\lambda_{SA_{Whole}}$ in three directions $\{1.0, \lambda_{SA_{Whole}\,y} / \lambda_{SA_{Whole}\,x},\ \lambda_{SA_{Whole}z} / \lambda_{SA_{Whole}x}\}$. If the value of $\lambda_{SA_{Whole}\,z}$ is larger than the standard value *1*, then the design families are characterized by the slim component families. If two phase transitions are close each other, the shape difference between the whole shape families would be slight. The whole phase transitions canalize different kinds of whole shape commonality.

Design individuals by gene mutation: Regulatory, geometrical and size genes {*L, P, A*} are mutated differently from individual to individual, which is its peculiarity. Taking design family *B*, for instance, compared with the prototype, the location of the left branch in individual 2 is moved up by its geometrical gene's mutation. The smallest component in individual 3 is switched off by the mutation of its regulatory gene. The size of component 1 in individual 6 is enlarged by the mutation of its size gene.

The obvious characteristic of these design families is distinguished by the overall changed shape for all the components of the complex design system.

4.3.2 Part-related families

A part-related family is generated by a phase transition from a local environment which influences the partial components of a complex design system separately. As shown in Table 5, there are two kinds of design variations: phase transition for groups of designs and gene mutation for specific individuals.

Design families by phase transition: Compared with the prototype, Table 5 demonstrates that the phase transition $\lambda_{SA_{Part\,1}} = \{1.0, 1.5, 1.5\}$ of component 1 in three directions only influences the shape of component 1 of all individuals in family *B*.

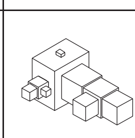
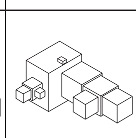
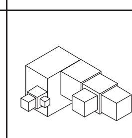
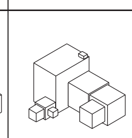
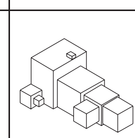
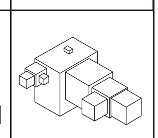
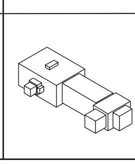
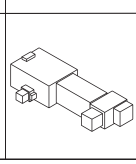
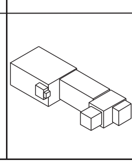
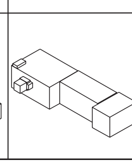
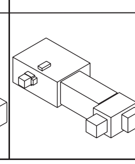
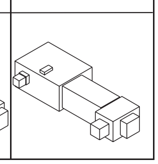
		Individuals by mutation of regulatory and structural genes {L,P,A}					
		1	2	3	4	5	6
Families by phase transition	B						
	A						

Table 5. Part-related families

The phase transition for the nine components in three directions $\{\lambda_{SA_{Part\,1}}, \ldots, \lambda_{SA_{Part\,9}}\}$={ {1.0,0.75,0.5},{1.0,1.0,2.0},{1.0,0.5,0.5},{1.0,1.0,0.3},{1.0,1.0,1.0},{1.0,1.0,0.5},{1.0,1.0,1.0},{ 1.0,1.0,0.4},{1.0,2.0,0.3} } (the numbers are selected randomly) influences the shapes of the components separately in family *A*. The part-related design families are controlled by the phase transition $\lambda_{SA_{Parti}}$ in three directions {1.0, $\lambda_{SA_{Part}y} / \lambda_{SA_{Part}x}$, $\lambda_{SA_{Part}\,z} / \lambda_{SA_{Part}\,x}$}. If the value of $\lambda_{SA_{Parti}\,z}$ is larger than the standard value 1, the design families are characterized by the slim component *I* families. The partial phase transitions canalize different kinds of part-related shape commonality.

Design individuals by gene mutation: The uniqueness of different individuals in Table 5 is generated by gene mutations. Take design family *A*, the location of components 9 and 6 in individual 2 are moved close to the edge by the mutation of their geometric genes; while components 4 and 5 in individual 4 are turned off by the mutation of their regulatory genes and the size of component 1 in individual 5 is enlarged. This kind of design family is characterized by the phase transition of specific components of a complex design system, which is in contrast with the whole-related families.

4.4 Structure-related families

There are two basic kinds of phase transitions. The first is the phase transition in which parameters change smoothly, and results in the slight variation of state space such as the phase transition of size and shape. The second is phase bifurcation, in which small phase transitions may result in dramatic changes in the state space. For a complex design system, a parameter change, which influences the whole structure of the system is considered as the most dramatic design bifurcation. This parameter is associated with the regulatory gene. It has a Boolean value of either 1 or 0, but its influence is dramatic and may destroy the whole component or a group of relevant components. Table 6 demonstrates two groups of structure-related families that are qualitative families (group *A* and *B* and group *C* and *D*) caused by phase bifurcation.

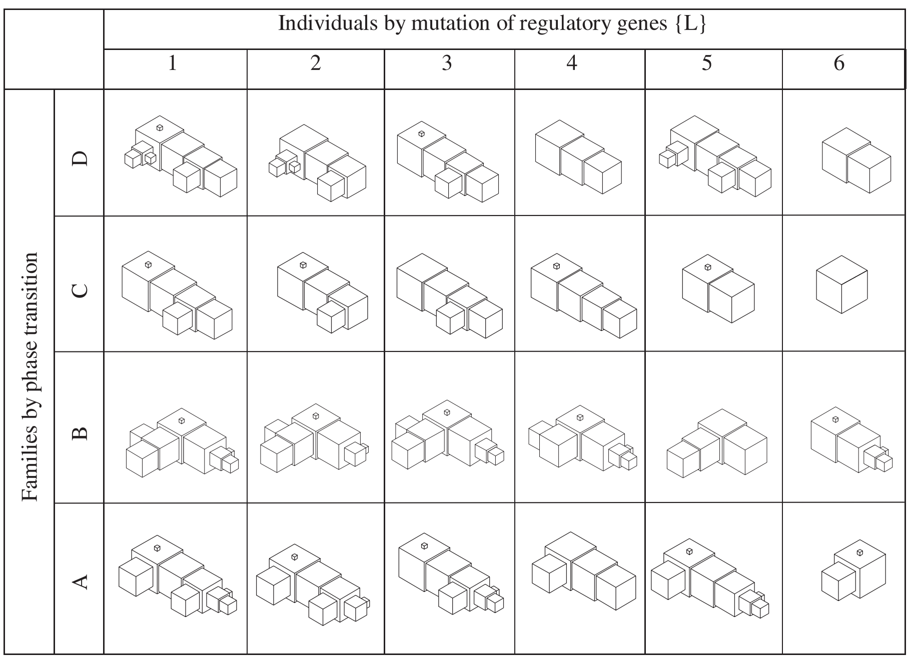


Table 6. Structure-related families

4.4.1 Structure elimination families

Design families by phase bifurcation: By changing the value of the element of parameter matrix associated with component 6 from *1* to *0*, the structure of the complex design system is changed from family *D* to family *C*. There is no smooth variation for this kind of value.

Design individuals by gene mutation: No matter how the regulatory genes and other genes may change individually, the whole structure is forced or canalized as an eliminated branch family by phase bifurcation. Take family *C*, components 3, 4 and 5 in individual 5 are destroyed by turning off their regulatory genes, but they are still the individuals within family *C*. The interesting point is that individual 3 in family *D* is exactly the same as individual *1* in family *C*. This phenomenon is called phenocopies in biology, which are environmentally produced phenotypes that mimic the genetically produced phenotypes (Goldschmidt, 1938).

4.4.2 Structure swapping families

Design families by phase bifurcation: Compared with family *D*, family *B* is a structure swapping family, which is generated by swapping two elements of the parameter matrix associated with both components 3 and 6. As a result, the left branch of individual 1 in family *D* is swapped with three components of the right branch. Family *A* is another structure swapping family, in which the relevant elements (associated with both components 4 and 6) of the parameter matrix are changed to *1* and the elements (associated with component 4 or component 6) are changed to *0*. All individuals are generated into two distinguishable canals in family *A* and *B*.

Design individuals by gene mutation: Regulatory genes mutate and create diverse individuals as shown in families *A* and *B*. For example, individual 6 in family *B* is caused by the mutation of regulatory gene 6, which results in the disappearance of its left branch components.

Structure elimination and swapping by phase bifurcation and mutation of regulatory genes are based on a hierarchy. This means that the upper components determine their downstream components, which are guaranteed by the second interpretation of the genotype (Gero and Shi, 1999).

4.5 Branch and cross-branch related families

The architecture of complex systems is readily made hierarchical (Simon, 1996). The relationship of those relevant components could be either branch-related or cross-branch-related, for instance, disassembling one storey of a building – the walls constituting the storey will be destroyed, and the windows and doors connected to the walls will be dismantled as well. The relationship of those components is called branch-related. If replacing a kind of window in a building, means that all the same kind of windows in the building will be replaced, then the relationship of those components is cross-branch-related.

4.5.1 Cross-branch-related families

Design families by phase transition: As shown in Table 7, by connecting and changing the elements of the parameter matrix associated with a constraint, relevant attributes of both components 3 and 6 in the *z* direction from *1* to *2*, then family *B* is characterized by components 3 and 6 being extruded twice the length of its prototype. Family *A* is characterized by components 5 and 8 being slimmed and flattened, where the elements of parameter matrix associated with the constraint relevant attributes of both component 5 and 8 in three directions are changed from {1.0,1.0,1.0} to {1.0,2.0,0.4}.

Design individuals by gene mutation: Diverse design variations are also generated by gene mutations, such as the mutation of regulatory genes for individuals 2 and 5 in family *B*, and individuals 2 and 4 in family *A*. The varied size of component 1 of individual 5 and component 2 of individual 6 in family *A* and the great diversity of geometrical variations are caused by the mutation of geometrical genes.

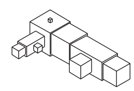
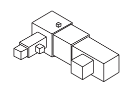
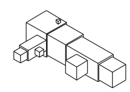
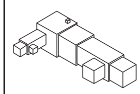
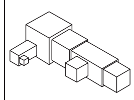
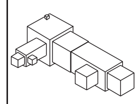
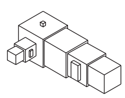
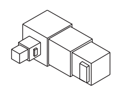
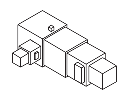
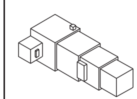
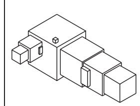
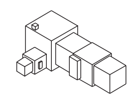
		Individuals by mutation of regulatory and structural genes {L,P,A}					
		1	2	3	4	5	6
Families by phase transition	B						
	A						

Table 7. Cross-branch-related families

4.5.2 Branch-related families

Design families by phase transition: In Table 8, by changing two parameters separately, two branch-related families are canalized, while the individuals are enriched by the mutation of their genes. Family *B* demonstrates that all the components in the left branch are extruded to an increased length compared to the prototype. This is done by varying the parameter associated with the unity attribute of component 6 in the *z* direction from *1* to *2.5*. Similarly, family *A* shows that three components of the right branch are extruded to two and half times their length by the transition of the parameter associated with the unity attribute of component 3 in the *z* direction from *1* to *2.5*. The phase transition could be chosen between *0* and a limited value. If the value is selected as *0*, then a distinguishable change occurs and the whole branch will disappear. Therefore this case is also called bifurcation.

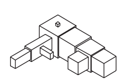
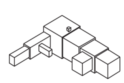
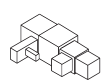
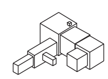
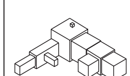
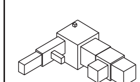
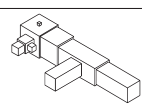
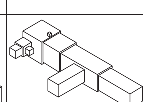
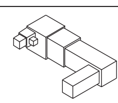
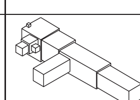
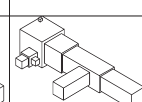
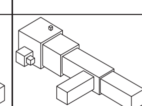
		Individuals by mutation of regulatory and structural genes {L,P,A}					
		1	2	3	4	5	6
Families by phase transition	B						
	A						

Table 8. Branch-related families

Design individuals by gene mutation: The diversity of individuals could be generated by the mutation of regulatory, geometrical and size genes. A typical case of gene mutation is individual *3* in family *B*, which includes the mutation of all the regulatory, geometrical and size genes.

5 DISCUSSION

The introduction of the concept of phase space in design shows that a state space is determined not only by its variables but also by its parameters. The mechanism of phase transition in design demonstrates that a state space is able to be moved and transformed. This is akin to the notion of exploration (Gero, 1994). The phase space is a meta-level controller of the state space. The variation of parameters provides a mechanism for the creation of design state spaces.

The development model for design derived from an analogy with developmental biology inherits many useful ideas and mechanisms from biology. These include gene mutation, phenocopies, and gene regulation and with these the capacity for the generation of diverse design variation could be enhanced.

The concepts and methods of phase transition are applicable to the variation of design families. The development model for complex design systems enables individuals of a complex design to be varied and searched by gene mutation and evolution within the state space, while the families of the complex design can be explored through phase transition within the phase space.

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