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APPLICATION TO A CAR BODY FRAME BASED ON PARAMETER GUIDELINES FOR DERIVING DIVERSE SOLUTIONS USING EMERGENT DESIGN SYSTEM

Koichiro Sato[1], Yoshiyuki Matsuoka[1]
(1) Keio University

ABSTRACT

In the early design process, diverse design ideas are generated from a global solution search under unclear design conditions. Because it is difficult to apply conventional engineering design in the early design process, the emergent design system capable of generating various three- dimensional forms is proposed. Although this system appropriately set the parameters in every application cases, the system cannot determine whether the values of the obtained parameters are the best because the parameters are selected by trial and error. The research herein extracted the parameters that influence the diversity of form with the goal of devising the emergent design system that uses these extracted parameters to generate forms. Then these guidelines in this emergent design system were applied to a car body frame design. The results demonstrate that diverse solutions satisfying the mechanical properties can be derived, and thus confirm the usefulness of the guidelines.

Keywords: Diverse solutions, Experimental design, Early process of design

1 INTRODUCTION

If a design process can be roughly divided into the early process of design and the late process of design, then engineering design methods are often used in the latter process. Like mathematical programming [1], solutions in engineering design are parametrically derived by setting the form dimensions or positions of the design object as design variables. Through such a method where a designer searches for a local solution based on set conditions only the optimum solution is derived. Hence, this strategy is effective for design problems with clear design conditions, e.g., design objective and variables, as well as parameters. However, for the early process of design where the design conditions are often unclear, the aforementioned engineering method is not feasible. Additionally, in the early process of design, designers often derive diverse solution candidates with different topologies based on trial and error. Because the early process of design often depends on the experience and knowledge of the designer, often a local solution, but not the optimal solution, is found. For these reasons, it is necessary to develop a method, which is applicable to the upstream process and is capable of deriving diverse solutions via a global solution search under unclear design conditions [2-3]. Because a method capable of deriving diverse design solutions (candidates) is expected to assist designers in the early process of design, we have been studying a design method and system based on the concept of emergence, which we call emergent design [4].

In previous studies, we have proposed the emergent design system, which allows a global solution search under limited design conditions to generate diverse three-dimensional structures on a computer. In executing this system, it is necessary to properly set the parameter value characteristics of the system to the application cases to efficiently generate diverse forms. However, because the values are set on a trial and error basis, the obtained values may not be the optimal values. Additionally, the influence of the parameters on diversity or the efficiency in form generation is unclear. Accordingly, further knowledge about the system parameters and diversity of the generated forms in the emergent design system is necessary.

The purposes of this study are: to extract the emergent design system parameters that influence the diversity of generated forms, to obtain knowledge about the diversity of the generated forms and the form generation efficiency of the extracted parameters, and to provide the guidelines to set these parameters. The first step in this procedure is to analyze the variance using the parameters of this system as factors to extract the parameters that influence the diversity of generated forms. Then to determine the guidelines for setting the parameters, an analysis is performed to clarify the correlation between the extracted parameters and the diversity of generated forms as well as the form generation efficiency. Finally, the system is applied to an actual design case to confirm the usefulness of the system parameter guidelines.

2 EMERGENT DESIGN SYSTEM

This chapter gives outlines the emergent design system capable of generating diverse forms.

2.1 Concept of Emergence and Emergent Design

In nature, various organisms coexist in the same environment. In the fields of biology and ecology, scientists have hypothesized that various species have been created through the process of emergence. According to Kitamura [5], emergence is defined as a new function, character, or action acquired by an interactive dynamic process where global order appears by local interactions between individuals, which behave autonomously, with the environment. On the other hand, this order restrains the behavior of an individual. Thus, the appearance of global order is a bottom-up process, whereas the process of restraining individual behavior is a top-down process.

By comparing the design process proposed herein to the emergence process, the following similarities are observed. First, a process to generate a design proposal through evaluation using certain standards is similar to a bottom-up process to generate the entire feature by the interaction of the autonomous components in emergence. Second, the process to optimize details in a design proposal is similar to a top-down process, which binds the components by the overall features in emergence. Thus, the concept of emergence may be applicable to design, and diverse novel design solution candidates can be derived by "emergent design" where bottom-up and top-down processes interact.

2.2 Outline of the Emergent Design System

The emergent design system proposed herein is based on the concept of emergent design described above. The emergent design system is composed of two processes: a bottom-up process to generate diverse three-dimensional forms and a top-down process to optimize the forms obtained in the bottom-up process. Figure 1 is a flowchart of the emergent design system. In the bottom-up process, diverse forms are generated by cellular automata (CA) [6]. The element of CA is expressed by the voxel in this system. Moreover, induction and apical dominance, which are generation characteristics originating in biodiversity as state transition rules in CA, are introduced.

Induction is a generation characteristic that changes a neighboring cell into a specific character. It influences the activation of cell proliferation by the action of a cell on neighboring cells (Fig. 2). Thus, a certain element provides a stimulus, which then influences the generation of an element in a neighboring element. Thus, induction can be modelled as a neighboring information vector, and is expressed as

$$\boldsymbol{v_n} = \sum_{i=1}^{26} b_i w_i \boldsymbol{e_i} \tag{1}$$

where n is the number of maximum surrounding elements and i is the surrounding element number. b_i indicates the existence or non-existence of an element (1 or 0, respectively), w_i is the action size of the induction recorded in a one-dimensional arrangement when each form is generated and has a value from 0 to 8, and $\boldsymbol{e_i}$ is the unit vector of the direction to the object element.

On the other hand, apical dominance is a generation characteristic, which predominately manages the ontogeny, and is also referred to as the apex. It influences morphogenesis and controls cell proliferation (Fig. 3). This predominant action increases closer to the apex. For instance, a plant has an apex in the position shown in Fig. 3, and leaf growth is controlled in the part near the apex. Consequently, light can be efficiently received. Therefore, the positional information vector, which is influenced by the apex to the object element, can be modelled from the aforementioned character as

$$\boldsymbol{v_p} = (d_{\max} - d)\boldsymbol{e_d} \tag{2}$$

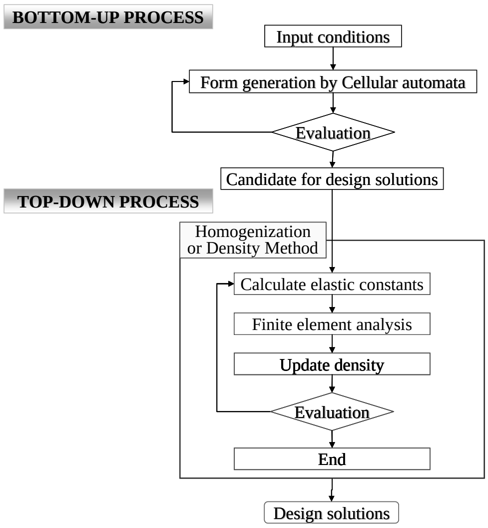


Figure 1. Emergent design system

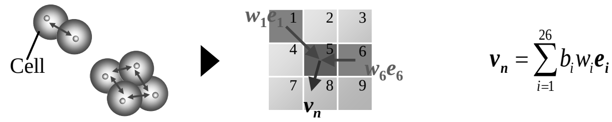


Figure 2. Induction

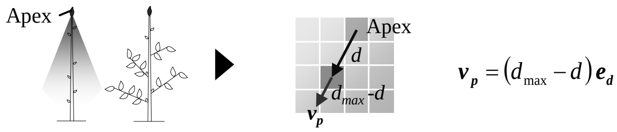


Figure 3. Apical dominance

where $d_{\max}$ is the distance between the apex and the most distant cell from the apex, d is the distance between the apex and the object element, and $\boldsymbol{e_d}$ is the unit vector of the direction to the object element. By uniting these two vectors, the composite ratio can be defined as k, and the input vector of CA becomes

$$\boldsymbol{v_{in}} = k\,\boldsymbol{v_n} + (1-k)\,\boldsymbol{v_p} \tag{3}$$

If the value of k is near unity, then induction tends to strongly influence k. In contrast, if k is near 0, then k is strongly influenced by apical dominance, and a rhabdoid or board form tends to be generated. The input parameters in the bottom-up process are the position of apex, composite ratio k, form generation space, element size, initial element, generation number, and evaluation item. The apex position becomes the center of action for apical dominance, and the form generation space is a space that allows CA to be generated. The element size is a voxel and is composed of form. Thus, reducing the element size causes the output to be in a detailed form. The initial element position is where the form generation of CA begins. Hence, it is possible for an element to have two or more components, and the part where the element definitely exists is assumed to be the initial element. The generation number is the frequency that the form is updated, and this evaluation item must be satisfied in the bottom-up process.

In the top-down process, diverse solutions are derived by optimizing ideas from the design generated during the bottom-up process under conditions determined by the designer. The structure is optimized by the topology optimization method (Density method) [7]. The input parameters in the top-down process are the mechanical conditions, including the loading condition and restraint condition, objective function, and restriction function. Furthermore, the desired condition is inputted using the above parameters, and the forms are optimized.

3. GUIDELINES FOR SETTING THE SYSTEM PARAMETERS BASED ON EXPERIMENTAL DESIGN

In this chapter, parameters that influence the diversity within the emergent design system are extracted, and the guidelines for setting the parameters are discussed.

3.1 Extraction of the Parameters that Influence Diversity

3.1.1 Determination of Analytical Parameters

Table 1 shows the input parameters in the emergent design system. The parameters of Category 1 in Table 1 are unrestrained by the application case when they are set. In contrast, the parameters of Category 2 are restrained by the designable space in the application case, while the parameters of Category 3 are determined by the design conditions, e.g., design objective and mechanical conditions, for each application case. This study is intended to obtain knowledge about the general parameters and diversity; accordingly, the parameters of Categories 1 and 2 are determined as analytical parameters in

Table 1. Parameters of system

	Classification	Parameters
Bottom up process	1	Composite ratio *k*
		Maximum number of element generation
		Size of element in relation to generation space
	2	Aspect ratio of generaiton space
		Connectivity number of generation space
	3	Position of apex
		Number of apex
		Number of initial element
		Number of position of initial element
Top down process		Load condition
		Constraint condition
		Objective function

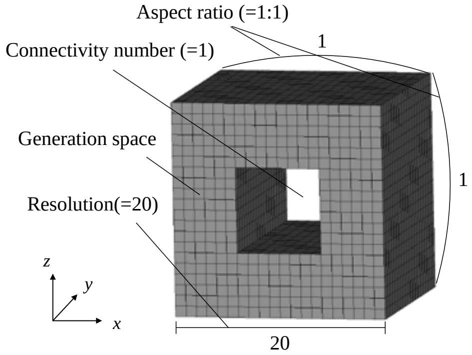


Figure 4. Analytical Parameters

this study. The composite ratio *k* is the ratio of the combination of neighboring information vectors and positional information vectors where the number of element generation denotes the frequency of form updates. The element size in relation to the generation space (resolution) indicates the number of elements on one side (Fig. 4). The aspect ratio of generation space, which is a Category 2 parameter, is the ratio of the *z*-axis side to either the *x*-axis or *y*-axis side as shown in Fig. 4, while the connectivity number indicates the number of holes in the generated space.

3.1.2 Evaluation of Diversity in the Generated Forms

The diversity index *D* proposed by Inoue et al [8]. was adopted to evaluate the diversity of forms generated by changing the analytical parameters. The diversity index *D* is capable of quantitatively expressing the difference of voxel elements according to their coordinate position, and is defined by the expression below with regard to the group of forms generated by the system

$$D = 1 - \frac{\sum_{i=1}^{n-1}\left(\sum_{j=i+1}^{n} S_{ij}\right)}{{}_nC_2} \tag{4}$$

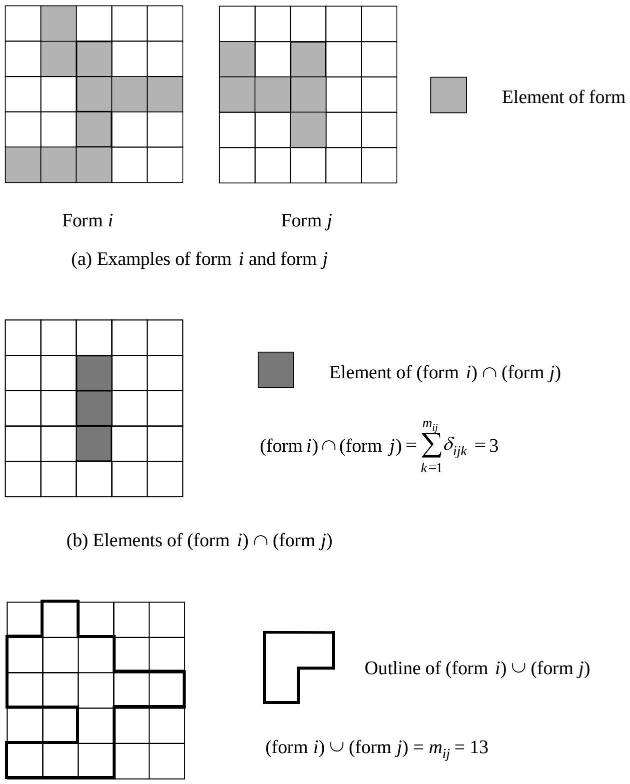
$$S_{ij} = \frac{\sum_{k=1}^{m_{ij}} \delta_{ijk}}{m_{ij}} \qquad \delta_{ijk} = \begin{cases} 1, & for \quad cell[i][k] = cell[j][k] = 1 \\ 0, & for \quad cell[i][k] \neq cell[j][k] = 0 \end{cases}$$

Here *cell*[*p*][*q*] denotes the state of the *q*-th cell of the form *p* (existing element: 1, non-existing element: 0). m_{ij} indicates the number of cells in a union of any pair of forms *i*, *j*, and *n* represents the number of forms（n=50）. To obtain the similarity index S_{ij}, the number of elements duplicated when an arbitrary pair of forms *i*, *j* superimposed is measured first, and then the ratio of the number of the duplicate elements to the number of elements constituting the union of the two forms m_{ij} is calculated.

The diversity index *D* is obtained from the similarity index S_{ij} , i.e., by calculating the mean value of the similarity indices for all the combinations of forms and deducting this value from 1. For example, to calculate the similarity of forms the cell number of the product of form *i* and form *j* present at the same position is measured (Fig. 5(b)), and its ratio to the number of cells m_{ij} that constitute the union of the two forms is obtained (Fig 5(c)). If the two forms are identical, then the similarity of forms calculated by this formula is 1; if all the cells are in different states, then the similarity of forms is 0. In the meantime, the diversity index is based on the idea that form diversity of the group is high for groups with a small number of similar pairs of forms. The mean value of the similarity indices for all combinations within a group is calculated, and the diversity index is obtained by deducting this value from 1. The diversity index *D* has a minimum value of 0 when all the forms in a group are identical, but denotes a maximum value of 1 when all the combinations of two forms in the group do not share the same cell position.

3.1.3 Analysis of variance using Analytical Parameters

To extract the parameters that affect the diversity from the analytical parameters, we performed ANOVA using analytical parameters as factors and the objective characteristics as the diversity index *D*. Analysis of variance (ANOVA) requires an orthogonal experimental design in which factors do not affect each other’s objective characteristics. The orthogonal experiments where the influence of factors



(a) Examples of form *i* and form *j*

(b) Elements of (form *i*) ∩ (form *j*)

(c) Elements of (form *i*) ∪ (form *j*)

Figure 5. Similarity index

Table 2. Orthogonal array $L_{27}(3^{13})$

Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8	Factor 9	Factor 10	Factor 11	Factor 12	Factor 13

is orthogonal include full factorial designs [9, 10]. However, this study employs five factors. Thus, an experiment using a full factorial design at three levels would require 3^5 experimental runs. To reduce the number of experimental runs, we employed orthogonal arrays [11]. An orthogonal array is a table in which the levels are arranged so that respective factors intersect, and experiments are conducted for part of the level combinations, thereby drastically reducing the number of experimental runs.

Orthogonal arrays comprise the power of prime orthogonal arrays and mixed orthogonal arrays [12]. In this study, because we estimate the existence of an effect (interaction) using a combination of respective parameters, we employ the power of prime orthogonal arrays, which is capable of measuring such effects. The power of prime orthogonal arrays can handle five factors and has a number of levels. Table 2 shows the three-level orthogonal array $L_{27}(3^{13})$ employed.

We then set the value of each factor for each level in the orthogonal table (Table 3). The orthogonal array $L_{27}(3^{13})$ can evaluate three or four interactions, and this analysis includes ten interactions between the factors. Accordingly, we prepared four orthogonal arrays to evaluate the interactions among all the factors. Forms are generated in accordance with the four orthogonal arrays. As the analysis conditions, the apex is at the center of the generation space, and the initial element is set to one and placed at the center of the floor surface as shown in figure 6. To determine the evaluation items in the bottom-up process, the number of elements of the generated form is set as 5% or more of the maximum number of elements; 50 forms satisfying this standard are generated to evaluate diversity. Figures 7 and 8 show the response graphs of the analysis result, and Tables 4 and 5 show the ANOVA tables. Factors of less than 2.0% variance ratio to errors are deemed to have an effect equivalent to error, and are included in the errors. These figures and tables demonstrate that the interactions of the respective factors and the contribution rate to error depend on the orthogonal array used.

First, we analyzed the analytical parameters. Because the composite ratio k shows the highest contribution rate in relation to the diversity of generated forms in all the ANOVA tables, it influences the diversity of generated forms. Similarly, in all the ANOVA tables and graphs, the aspect ratio of generation space shows the second highest contribution rate in relation to the diversity of generated forms. Thus, the aspect ratio of generation space also influences the diversity of generated forms. Other analytical parameters exhibit lower contribution rates in the ANOVA tables. These parameters are insignificant compared to the error, which is confirmed by the response graphs. Consequently, these other analytical parameters have a negligible influence on the diversity of generated forms.

Table 3. Factors and levels of factor

Factors	Level 1	Level 2	Level 3
Composite ratio *k*	0.25	0.5	0.75
Maximum number of element generation	50	250	500
Resolution (Number of element on a side)	20	40	80
Aspect ratio (of side area)	$1/2:\sqrt{2}$	1:1	$2:1/\sqrt{2}$
Connectivity number (Topology)			

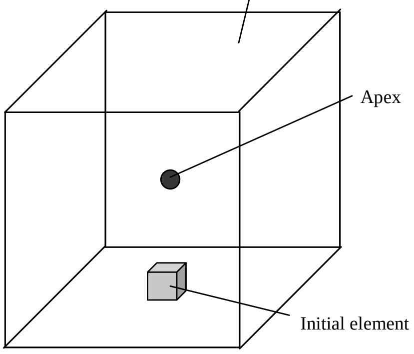
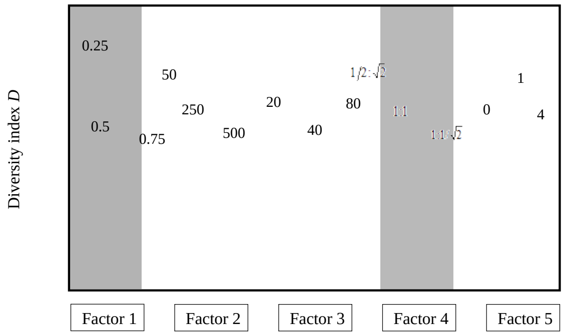


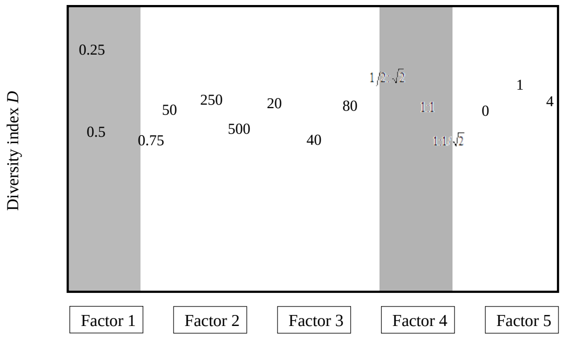
Figure 6. Analysis conditions

Factor 1: Composite ratio *k* Factor 2: Maximum number of element generation

Factor 3: Resolution Factor 4: Aspect ratio Factor 5: Connectivity number

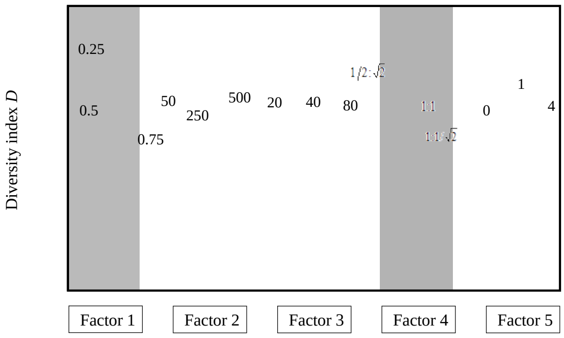


(a) Response graph obtained from orthogonal array 1

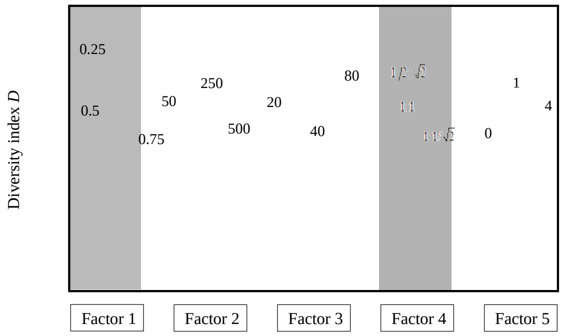


(b) Response graph obtained from orthogonal array 2

Figure 7. Response graph Ⅰ



(a) Response graph obtained from orthogonal array 3



(b) Response graph obtained from orthogonal array 4

Figure 8. Response graph Ⅱ

Second, we examined the interaction between the analytical parameters. The interaction between the composite ratio and the aspect ratio of generation space shows a low contribution rate and is included in the error in three orthogonal arrays. Therefore, the interaction of the two ratios does not influence the diversity of generated forms. The interaction between the composite ratio *k* and the connectivity number, and that of the aspect ratio of generation space and the connectivity number have an effect significant and greater than errors as shown in Table 4(b). However, in view of the fact that these parameters have small contribution rates and that the values of the contribution rate depends on the orthogonal array used in the main analysis, these interactions have a negligible influence on the diversity of generated forms. The other interactions in Table 4(a), e.g., the interaction of the number of element generation and resolution, do not influence the diversity. The existence of factors, which influence the diversity but were not considered in this study, or the interactions among three or more factors that were not evaluated in this analysis are thought to be the reason why the results of the ANOVA depend on the orthogonal array used.

Based on the above examination, the composite ratio *k* and the aspect ratio of generation space are the analytical parameters that influence the diversity of generated forms.

Table 4. Analysis of variance table Ⅰ

(a) ANOVA table obtained from orthogonal array 1

Factor	f	S	V	F_0		S'	ρ (%)
Factor 1	2	0.2711	0.1355	15.80	**	0.2539	38.27
Factor 2	2	0.0663	0.0331	3.86	*	0.0491	7.40
Factor 3	2	0.0120	0.0060	0.70	○	-	-
Factor 4	2	0.1545	0.0773	9.01	**	0.1374	20.70
Factor 5	2	0.0183	0.0091	1.07	○	-	-
Interaction(2*3)	4	0.0306	0.0077	0.89	○	-	-
Interaction(2*5)	4	0.0295	0.0074	0.86	○	-	-
Interaction(3*5)	4	0.0391	0.0098	1.14	○	-	-
Noise	4	0.0421	0.0105				
Total	26	0.6634					100
Noise'	20	0.1716					33.62

(b) ANOVA table obtained from orthogonal array 2

Factor	f	S	V	F_0		S'	ρ (%)
Factor 1	2	0.4306	0.2153	149.11	**	0.4277	57.57
Factor 2	2	0.0005	0.0002	0.16	○	-	-
Factor 3	2	0.0610	0.0305	21.13	**	0.0581	7.82
Factor 4	2	0.0866	0.0433	29.98	**	0.0837	11.26
Factor 5	2	0.0122	0.0061	4.21	*	0.0093	1.25
Interaction(1*4)	4	0.0406	0.0102	7.04	*	0.0349	4.69
Interaction(1*5)	4	0.0449	0.0112	7.77	*	0.0391	5.26
Interaction(4*5)	4	0.0585	0.0146	10.12	*	0.0585	7.87
Noise	4	0.0082	0.0020				
Total	26	0.7429					100
Noise'	6	0.0087					4.28

Table 5. Analysis of variance table Ⅱ

(a) ANOVA table obtained from orthogonal array 3

Factor	f	S	V	F_0		S'	ρ (%)
Factor 1	2	0.3776	0.1888	28.52	**	0.3643	54.66
Factor 2	2	0.0101	0.0051	0.76	○	-	-
Factor 3	2	0.0200	0.0100	1.51	○	-	-
Factor 4	2	0.1150	0.0575	8.69	**	0.1018	15.27
Factor 5	2	0.0416	0.0208	3.14		0.0284	4.26
Interaction(1*3)	4	0.0255	0.0064	0.96	○	-	-
Interaction(1*4)	4	0.0171	0.0043	0.65	○	-	-
Interaction(3*4)	4	0.0338	0.0085	1.28	○	-	-
Noise	4	0.0259	0.0065				
Total	26	0.6666					100
Noise'	20	0.1324					25.82

(b) ANOVA table obtained from orthogonal array 4

Factor	f	S	V	F_0		S'	ρ (%)
Factor 1	2	0.2804	0.1402	16.37	**	0.2632	35.66
Factor 2	2	0.0057	0.0028	0.33	○	-	-
Factor 3	2	0.0944	0.0472	5.51	*	0.0772	10.46
Factor 4	2	0.1389	0.0695	8.11	**	0.1218	16.50
Factor 5	2	0.0703	0.0352	4.11	*	0.0532	7.21
Interaction(1*2)	4	0.0430	0.0108	1.26	○	-	-
Interaction(1*4)	4	0.0176	0.0044	0.51	○	-	-
Interaction(2*4)	4	0.0209	0.0052	0.61	○	-	-
Noise	4	0.0669	0.0167				
Total	26	0.7381					100
Noise'	18	0.1541					30.16

Factor 1: Composite ratio *k* Factor 2: Maximum number of element generation

Factor 3: Resolution Factor 4: Aspect ratio Factor 5: Connectivity number

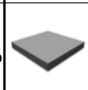
f : Degree of freedom S : Sum of squares V : Variance

F_0 : Variance ratio S': Net sum of squares ρ : Contribution rate

* : Significance level 5%
** : Significance level 1%

○ : Factor of less than 2% in variance ratio

Table 6. Factors and levels of factor

	Levels				
Composite ratio *k*	0.1〜0.9 count by 0.1				
Aspect ratio	 $1/4:2$	 $1/2:\sqrt{2}$	 $1:1$	 $2:1/\sqrt{2}$	 $4:1/2$

3.2 Analysis of Influence of Extracted Parameters on the Diversity of Generated Forms and Form Generation Efficiency

3.2.1 Setting the Levels of the Respective Parameters and Execution of Analysis

To evaluate the influences of the extracted composite ratio *k* and the aspect ratio on the diversity of generated forms and the form generation efficiency in more detail, we set the levels of respective factors and analyzed all the combinations of the respective factors. Table 6 shows that the levels are set to nine for the composite ratio and five for the aspect ratio of generation space.

In the main analysis, the diversity index *D* is used to evaluate diversity. Additionally, to consider the calculation efficiency in practical applications, the number of trial forms required is evaluated. The number of trial forms is the number of trials required until forms that fulfill a certain evaluation standard in the bottom-up process are generated. The evaluation standard in this study is the generation of 50 forms, which consists of 5% or more of the maximum number of elements. The fewer the number of trial forms, the higher the efficiency of form generation. Herein the evaluation values varied every time forms are generated even under the same system conditions. Hence, the aforementioned analysis is repeated ten times.

3.2.2 Results of the Analysis

Figure 9 shows the analysis results of the diversity indices, and demonstrates that more diverse forms are generated when the composite ratio is smaller. The results confirm that diverse forms tend to be generated when the composite ratio *k* is set at lower values. Similarly, with regard to the aspect ratio, the diversity of generated forms increases more in board form generation space than in rhabdoid form generation space. Therefore, in rhabdoid generation space, the composite ratio *k* should be set at a low value.

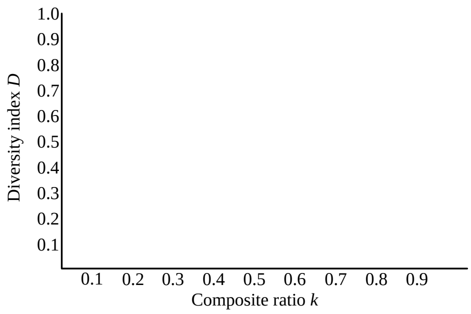
Figure 10 shows the experimental result on the form generation efficiency. The form generation efficiency remarkably decreases as the composite ratio *k* becomes smaller. In cases where forms are generated with small composite ratios, the influence of the apical dominance increases, making it difficult to satisfy the form output condition of 5% or more of the maximum number of elements.

Consequently, form generation requires more time. Additionally, the efficiency is lower in board form generation space than in rhabdoid form generation space. These results demonstrate that diverse forms are generated with small composite ratios *k* and that the diversity of generated forms increases but the form generation efficiency decreases more in board form generation space compared to rhabdoid form generation space.

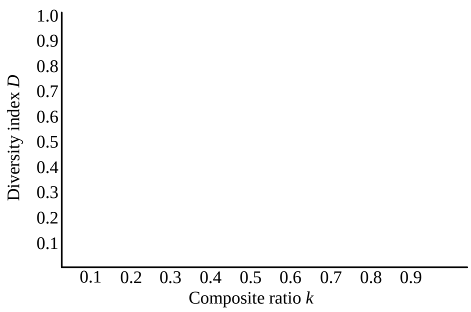
3.3 Guidelines for Setting the Parameters to Generate Diverse Forms

The analysis indicates the following three points. First, the value of the diversity index of the generated forms increases as the composite ratio *k* decreases. Second, the value of the diversity index of generated form increases more for board form generation space than for rhabdoid form generation space. Third, although decreasing the value of the composite ratio *k* increases the diversity, it decreases the form generation efficiency. These findings demonstrate that there is a trade-off between the diversity of forms and form generation efficiency. Thus, to efficiently generate diverse forms, the composite ratio *k* must be adjusted in accordance with the characteristics of the generation space. In a generation space where a rhabdoid space and board form space coexist, generation of diverse forms may be possible by setting the composite ratio *k* at the minimum value within the permissible form generation efficiency.

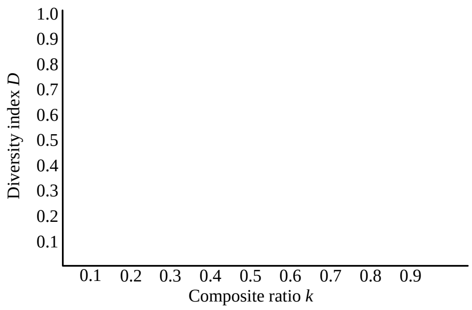
Based on the above knowledge, Fig. 11 shows the basic concept for the guidelines to set the parameters, and suggests that the composite ratio *k* be set to the minimum value within the constraints



(a) Aspect ratio = 1/4:2

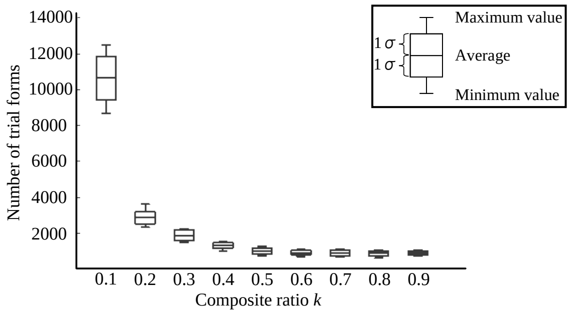


(b) Aspect ratio = 1:1

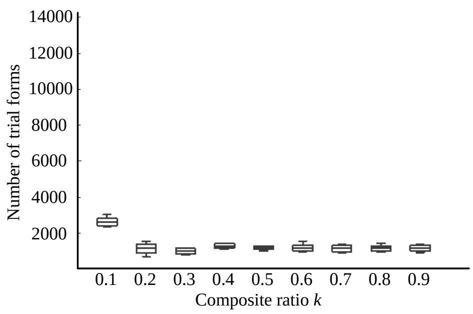


(c) Aspect ratio = 4:1/2

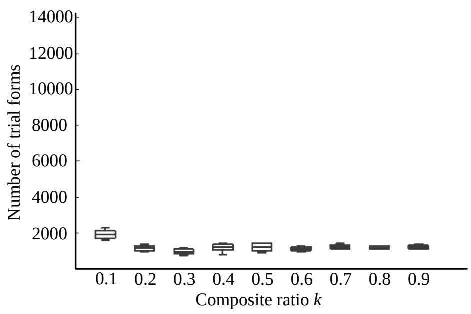
Figure 9. Relationship between composite ratio k and D



(a) Aspect ratio = 1/4:2



(b) Aspect ratio = 1:1



(c) Aspect ratio = 4:1/2

Figure 10. Relationship between composite ratio k and number of trial forms

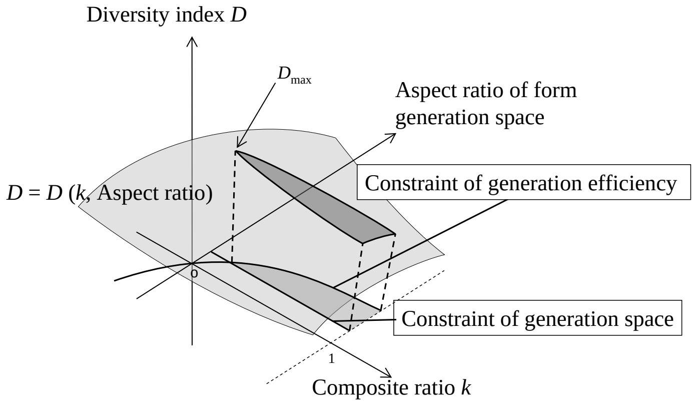


Figure 11. Basic concept of parameter determination

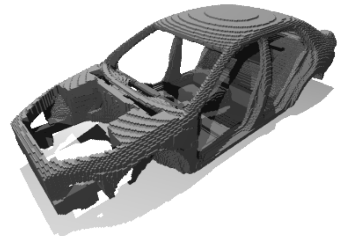


Figure 12. Form generation space

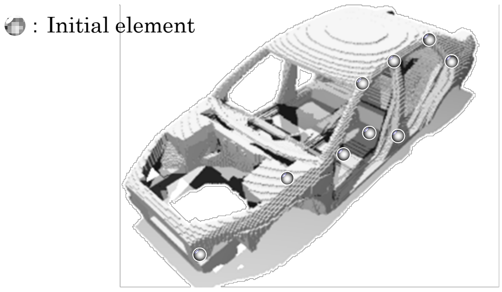


Figure 13. Initial elements

of the aspect ratio of generation space and of the form generation efficiency, but varies depending on the generation space. For example, the form generation efficiency is high when forms are generated in rhabdoid space; thus, diverse forms can be efficiently generated by setting the composite ratio k to the minimum possible value within the range of form generation.

4. APPLICATION TO CAR BODY FRAME

This chapter explains the application of the emergent design system to a car body frame based on the aforementioned guidelines for setting parameters.

4.1 Setting the Input Parameters Based on the Guidelines

Figure 12 shows the form generation space of the body frame. The generation space in this case is a complex space where rhabdoid and board form spaces coexist. Based on the parameter guidelines, the composite ratio k is set at 0.6 within the form generation efficiency constraint. The element size is set to a length of 15 mm on a side. Figure 13 shows the initial elements. Elements are set in the joint part of each pillar, the roof, which requires a constructional element, and part of the load point input in the top-down process. The apexes are set to the hip, head, and ankle points for the back and front passengers (Fig. 14).

Next, the input conditions in the top-down process are set. In this study, the loading conditions are set based on the opinion of an expert in car body frame design (Fig. 15). The loading conditions related to four types of stiffness for a body frame (torsional, bending, engine-room, and pillar traverse stiffnesses) are set. The frame is composed of carbon steel, and Young's modulus and Poisson's ratio are set as 210 GPa and 0.3, respectively. In the application to the car body frame design, topology is optimized by the density method assuming the objective function is the mean compliance C and the constraint condition is 10% of the mass for the form derived by the bottom-up process. The topology optimization problem by the density method is formulated using the following expression.

$$\min_{\boldsymbol{\rho}\in L}\left[C(\boldsymbol{\rho})\right],\quad C(\boldsymbol{\rho})=\boldsymbol{d}^T\boldsymbol{K}(\boldsymbol{\rho})\boldsymbol{d}$$
$$L=\left\{\boldsymbol{\rho}\,\middle|\,0\le\rho_i\le 1\ \ (i=1,\cdots,N),\ \sum_{i=1}^{N}\rho_i\le m_s\right\} \tag{7}$$

Here, $\boldsymbol{\rho}$ is the design variable $\{\rho_1, \rho_2, \dots, \rho_N\}$, ρ_i shows the density ratio of element number i, and N is the number of finite elements. In addition, $\boldsymbol{d}$ is the node displacement vector, $\boldsymbol{K}$ is the total stiffness matrix, L is a set of permissible design variables that satisfy the given conditions, and m_s is the restriction value of the density ratio, which is set to 10% assuming the density ratio of all the elements is one [7].

4.2 Execution result of system and consideration

Figures 16 and 17 show the form generation process and examples of design candidates in the bottom-up process, respectively. The connectivity of the elements, which grew from plural initial elements, differs for each form. For example, in one form the front of the roof is open, while the front does not connect in another form. Figure 18 shows examples of the topology optimization results using the density method for the form derived in the bottom-up process. Although each derived form differs around the cabin, the forms are optimized with the desired feature. Hence, the topology around the cabin and diverse design solutions with different load transmissions are generated.

Next, we compared design solutions derived by this system to those derived by the conventional optimization method (Fig. 19). The conventional solution is the design solution where topology optimization is executed using the density method for the form that fills the form generation space with elements. Figure 20 shows the maximum equivalent stress of the conventional design solution and design solutions derived by the emergent design system. Compared to the conventional design solution, the maximum equivalent stress of the solution using the emergent design system is slightly higher with regard to stress for engine-room stiffness, but has a lower value of stress for bending stiffness. As for the design solution of (b), the reinforcement near the dash-panel and the rear side of the cabin is due to the bending stiffness. For solution (I) using the emergent design system (Fig. 20(c)), the mass is 13.5% lighter, but the stiffness is nearly identical to the conventional solution. Lightening the rear and front parts of the body is likely due to the influence of bending stiffness. The same results are obtained for design solution (II). These findings demonstrate the possibility of generating diverse solutions by generating forms based on the guidelines to set parameters proposed herein as well as confirm the effectiveness of the emergent design system.

5. CONCLUSIONS

In this study, we obtained knowledge about the parameters, diversity of form generation, and form generation efficiency of the emergent design system. This information was used to provide guidelines for setting the parameters that influence the diversity of form generation. Additionally, we applied this system to a car body frame design based on the parameter guidelines, to demonstrate the usefulness of the guidelines. The findings of this study are summarized below.

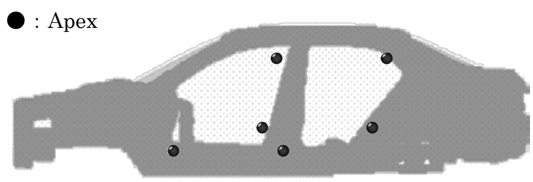


Figure 14. Position of apexes

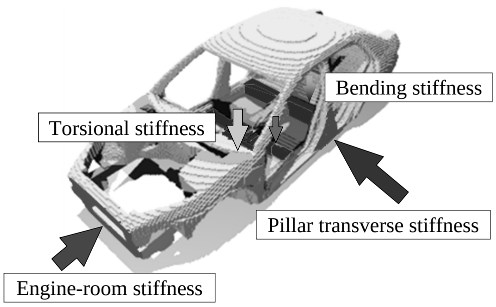


Figure 15. Loading conditions

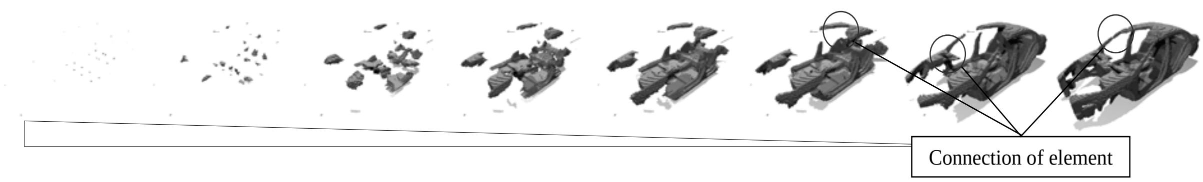


Figure 16. Form generation process

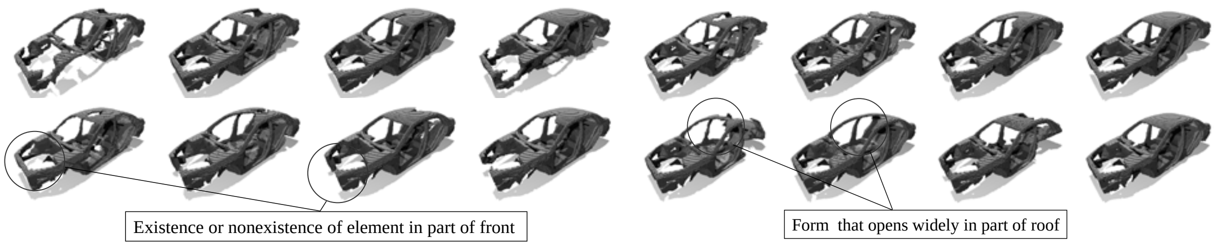


Figure 17. Examples of design solution candidates by bottom-up process

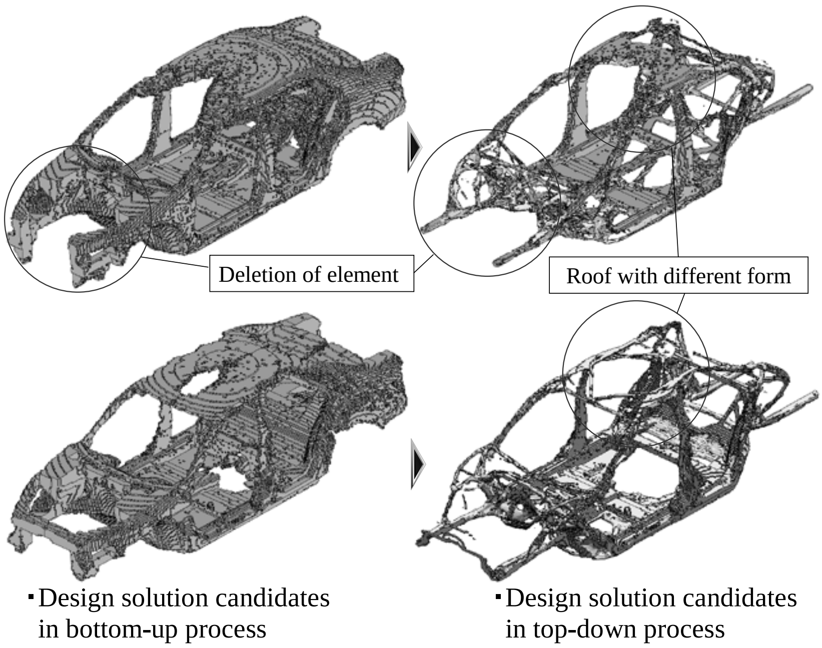


Figure 18. Design solutions by Emergent design system

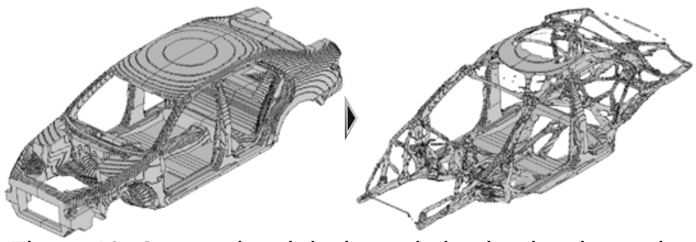
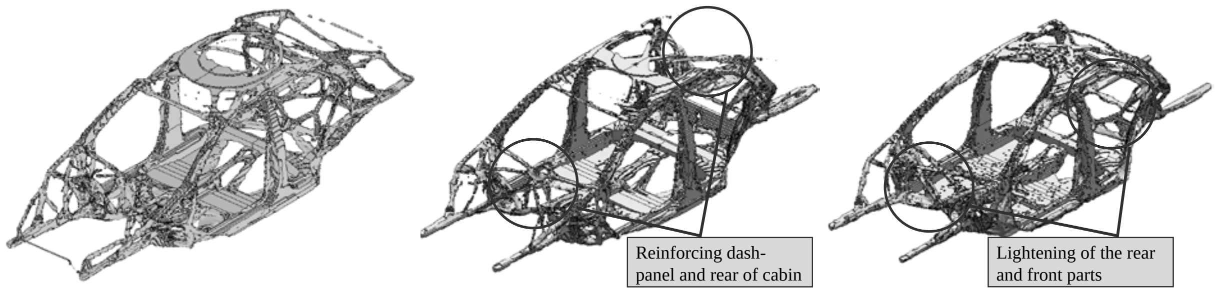


Figure 19. Conventional design solution by density method



Mass	574 kg
Torsional stiffness	4.07 MPa
Bending stiffness	4.79 MPa
Engine-room stiffness	15.9 MPa
Pillar transverse stiffness	67.5 MPa

(a) Conventional design solution

Mass	496 kg
Torsional stiffness	5.26 MPa
Bending stiffness	4.55 MPa
Engine-room stiffness	23.6 MPa
Pillar transverse stiffness	67.9 MPa

(b) Design solution obtained by the form generation system（Ⅰ）

Mass	499 kg
Torsional stiffness	5.29 MPa
Bending stiffness	5.61 MPa
Engine-room stiffness	16.4 MPa
Pillar transverse stiffness	68 MPa

(c) Design solution obtained by the form generation system（Ⅱ）

Figure 20. Comparison between mass and maximum equivalent stress

(1) ANOVA was performed using orthogonal arrays and setting the five parameters of the emergent design system as analytical parameters. Consequently, the composite ratio *k* and aspect ratio of generation space were extracted as significant parameters for diversity of generated forms.

(2) The following three points were derived from the analysis results on the effect of diversity and form generation efficiency using the extracted parameters.

・The diversity of form generation increases by setting the composite ratio *k* to a low value.

・More diverse forms are generated in board form space than in rhabdoid space.

・The increase in diversity of the generated forms and the decrease in form generation efficiency are greater in board form space than rhabdoid space.

(3) Based on the conclusions in (2), the composite ratio k can be set as the minimum value within the constraints of the aspect ratio of generation space and of the form generation efficiency, which depend on the generation space.
(4) The results of the emergent design system on a car body frame design based on the system parameter guidelines confirmed diverse solutions that satisfy the mechanical properties were derived and consequently, the usefulness of the parameter guidelines.

In the future works, to confirm the usefulness of the emergent design system based on these parameter guidelines, we intend to employ this system to other cases.

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Contact: Koichiro Sato
Keio University
Keio Advanced Research Centers
3-14-1 Hiyoshi, Kohoku-ku, Yokohama
JAPAN
Tel: Int +81-(0)45-563-1141
Fax: Int +81-(0)45-566-1495
Email: koichiro_sato@2006.jukuin.keio.ac.jp

Dr. Koichiro Sato is has held the Assistant Professor of the Global COE Program 'Symbiotic, Safe and Secure System Design' at Keio University (Japan) since 2008. His research interests are emergence, bio-inspired design, computer aided design, and soft computing. He has published in scientific journals and presented at academic conferences including international conferences.

Prof. Dr. Yoshiyuki Matsuoka is currently a Professor of the Department of Mechanical Engineering and the School of Integrated Design Engineering at Keio University. His major research interests are design science, design theory and methodology, industrial design, design engineering. Based on the design theory and methodology he proposes, he has designed and created various products and system.