Simulation of Developmental Process of Organism and Application to Structural Design

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Abstract— **In the early process of design referred to as conceptual design, many diverse design ideas must be obtained under the constraint of a few design conditions. This paper describes a method for obtaining diverse design solutions without a specific design objective, in a self-organizing manner. In this case, we note the developmental process of an organism that forms diverse individuals by repeated multiplication of cells from a one seed cell. We propose a system for obtaining diverse design solutions by simulating the developmental process of an organism and apply the system to the structural design of chairs. Comparing with the conventional structural optimization method, the proposed system produces design solutions of adequate diversity.**

I. INTRODUCTION

Conventional structural optimization methods have contributed greatly to accurate and efficient structural design in the late processes of design, referred to as basic design and detail design, in which the design conditions are definite. These methods are difficult to apply in the early process of design, referred to as conceptual design. In this early process, many design conditions are not completely defined. A design objective gradually becomes clearer as the process advances from the early process of design to the late process of design. In such a design process, many diverse design ideas must be obtained under the constraint of a few design conditions by globally searching within the solution space. At present, in this design process designers depend on either their intuition or their experience.

In order to globally search for a design solution within the solution space, many topological optimization methods [1, 2, 3] have been proposed, and these typically employ the homogenization method [4, 5] or a method using the genetic algorithm [6, 7, 8, 9]. These methods have demonstrated that optimal topology can be obtained by changing the density of structures or the combinations of the components. However, these methods have difficulty in obtaining diverse design solutions under a design situation in which other design conditions are added because objective functions and design constraints imposed as initial conditions need to be set in detail. In contrast, the present study proposes a system for obtaining diverse design solutions under such a design situation by globally searching within the solution space. The proposed system is applied to the structural design of chairs, and the diversity of solutions is analyzed. The objective of this study is to evaluate the effectiveness of the system for obtaining diverse design solutions.

II. FORM GENERATION

A. Application of Cellular Automata

In order to generate diverse forms without a specified design objective, the proposed form-generation method utilizes the 3 dimensional cellular automata (CA). In this method, the states of cells in the lattice are updated in accordance with a local rule [10]. More specifically, when at time t the state of a cell is S_t and the state of the neighborhood cell is N_t, the state of the cell S_{t+1} at time t+1 is described as shown by Eq. (1).

$$S_{t+1} = f\left(S_t, N_t\right) \tag{1}$$

where, f is referred to as the state transition function. This function defines the behaviors of the cells. In this study, the state of a cell is 0 or 1. A cell in state 1 is called an element, and form consists of the elements. Many form-generation methods using CA have been proposed [11-14]. Forms generated by CA have been previously reported yet all of them depend on starting from an initial form. In contrast, our method does not rely on an initial form and sets an initial state as one seed element without setting an initial form. Forms are generated from one seed element. In order to determine the information about input-output to the CA state transition function, we note the developmental process of an organism that forms diverse individuals by repeated multiplication of cells from a one seed cell.

B. Simulation of the Developmental Process of an Organism

In developmental biology, the phenomenon where the form of an organism emerges by repeated multiplication of cells is called morphgenesis. In a past study, we structured the properties concerned with morphogenesis of the organism by using the graph theory in collaboration with developmental biologists and then sorted out the properties concerned with diverse morphogenesis of the organism. As a result, 'induction' and 'apical dominance' are extracted as significant properties concerned with diverse morphogenesis of the

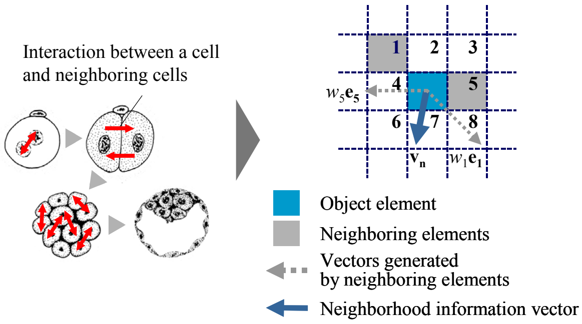

Fig. 1. Induction and neighborhood information vector.

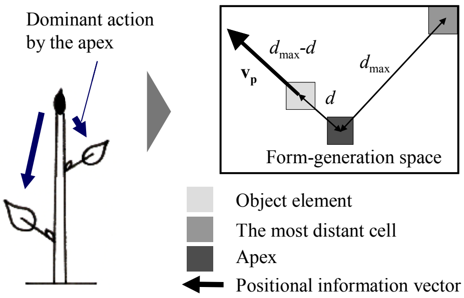

Fig. 2. Apical dominance and positional information vector.

organism [15]. In this study, rules referring to two properties in the developmental process of the organism, 'induction' and 'apical dominance,' are input to the CA state transition function.

Firstly, the form-generation method is referred to as induction. An organism forms by interaction between a cell and neighboring cells. Neighboring cells affect a cell and change it into a cell exhibiting different features. This property is called induction. Induction is the characteristic which prompts active multiplication of cells. All elements affect 26 cells surrounding an element. This action is represented as a vector with a direction and a magnitude. In this study, the elements which judge element generation are called object elements. When multiple elements exist in the neighborhood of an object element; the vector to the object element is the sum of the vectors to those neighboring elements that affect the object element (Fig.1). The first input is defined as a neighborhood information vector $\mathbf{v_n}$, which is expressed by Eq. (2).

$$\mathbf{v_n} = \sum_{i=1}^{26} b_i w_i \mathbf{e_i} \tag{2}$$

where, i is the neighboring element number, b_i indicates the existence or non-existence of element (1 or 0), w_i is the scalar part of the vector, and $\mathbf{e_i}$ is the unit vector of the direction to the object element.

Secondly, the form-generation method is referred to as apical dominance. In the developmental process certain tissue dominates; for example, the buds of plants and heads of animals. Such tissue is called an apex, and dominant action by the apex is called apical dominance. Apical dominance is the characteristic that inhibits the multiplication of cells. In this study, the apex is the one initial seed element. The second input is defined as a positional information vector $\mathbf{v_p}$, which is expressed by Eq. (3) (Fig. 2).

$$\mathbf{v_p} = (d_{\max} - d)\mathbf{e_d} \tag{3}$$

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 $\mathbf{e_d}$ is the unit vector of the direction to the object element. When the distance between the apex and elements is short, the elements are influenced from the apex.

Moreover, the composite ratio k is set, and input vector $\mathbf{v_{in}}$ is defined by Eq. (4).

$$\mathbf{v_{in}} = k\,\mathbf{v_n} + (1-k)\mathbf{v_p} \qquad (0 \le k \le 1) \tag{4}$$

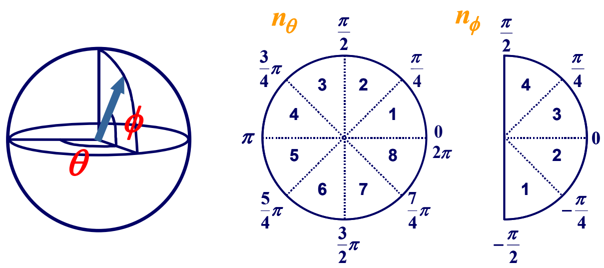

Fig. 3. Input vector to the CA state transition function.

This input vector is input to the CA state transition function, and the direction of generation is determined. The forms are generated by repetition of generation starting with a seed element, and the forms consist of elements.

C. Process of Element Generation

In this section we explain the process wherein the direction of generation is determined by the CA state transition function. In this study, the direction of generation is described in the state transition table.

Firstly, the input vectors are represented as θ and ϕ and is classified as the angle region number, which is set in the angle region (Fig. 3). The input vector is classified as the state number n_{state} ($1 \le n_{state} \le 32$), which is calculated from Eq. (5).

$$n_{state} = n_\theta + 8(n_\phi - 1) \tag{5}$$

where, n_θ and n_ϕ are the angle region number of θ and ϕ. The state number is 33 when the input vector is $\mathbf{0}$.

Secondly, the output vector is calculated from the state number and the state transition table. The relationships between the state number and output are described in the state transition table (Table 1). The output in the state transition table is $\Delta\theta$ and $\Delta\phi$ which are increments of θ and ϕ. The output vector θ_{out} and ϕ_{out} are calculated from Eq. (6).

Table 1. Example of CA state transition function.

n_{state}	$\Delta\theta\,(\pi/4)$	$\Delta\phi\,(\pi/8)$
1	4	2
⋮	⋮	⋮
32	6	5
33	1	7

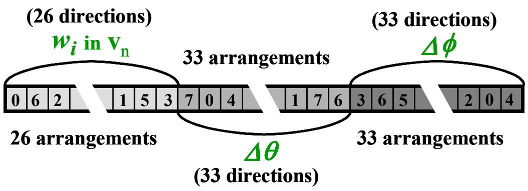

Fig. 4. One-dimensional arrangement.

$$\theta_{out} = \theta + \Delta\theta$$
$$\phi_{out} = \phi + \Delta\phi \tag{6}$$

The scalar of a vector w_i (26 directions) in the neighborhood vector $\mathbf{v}_\mathrm{n}$, $\Delta\theta$, and $\Delta\phi$ are described in the one-dimensional arrangement (Fig. 4). Elements are generated according to the generation rule described by this one-dimensional arrangement.

D. Execution of Form Generation

The form-generation is repeated until ten forms composed of one hundred elements are obtained. Figure 5 and Figure 6 show that neighborhood information vector $\mathbf{v}_\mathrm{n}$ tends to generate massive forms and positional information vector $\mathbf{v}_\mathrm{p}$ tends to generate flat forms. Moreover, Figure 7 shows change of forms followed by composite ratio *k*. It was indicated that frame forms tended to be generated by combining two vectors.

III. APPLICATION TO STRUCTURAL DESIGN OF CHAIRS

A. Form Evaluation

The proposed form-generation method is applied to structural design and extended to the system by addition of the evaluation process (Fig. 8). Then, the form-generation system is applied to the structural design of chairs. In the proposed system, a restriction is imposed on the space occupied by a human, and the one initial seed element is set on the seating face (Fig. 9).

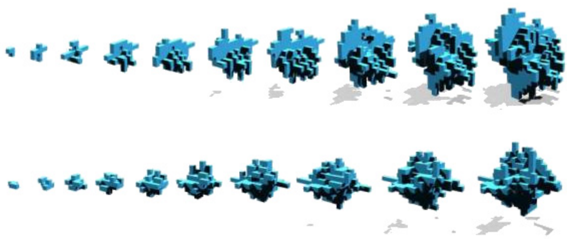

Fig. 5. Process of form generation using $\mathbf{v}_\mathrm{n}$.

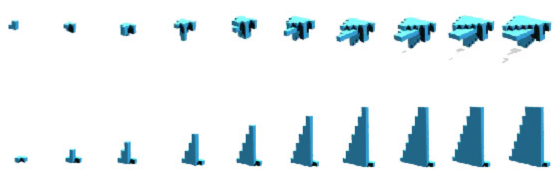

Fig. 6. Process of form generation using $\mathbf{v}_\mathrm{p}$.

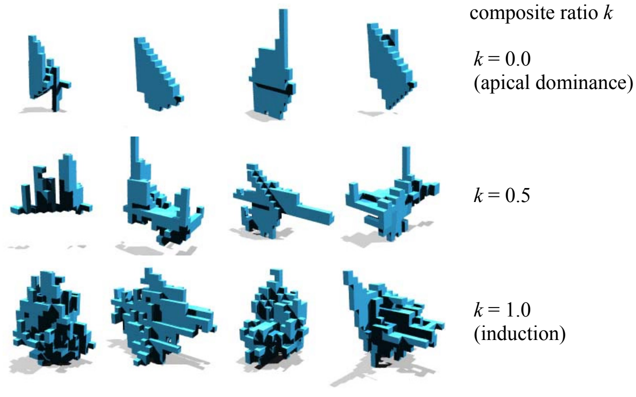

Fig. 7. Change of forms followed by composite ratio *k*.

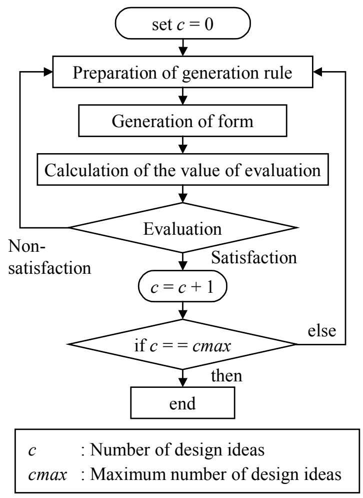

Fig. 8. Addition of the evaluation process.

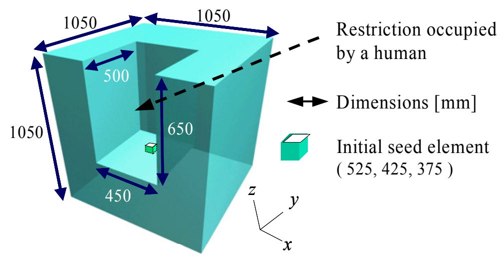

Fig. 9. Form-generation space.

In this paper, basic properties for chairs; existence of the grounded surface, existence of the seating face, and stability, are accounted for in the form evaluation. The calculation method for each evaluation item is shown below.

First, existence of the grounded surface f_{gr} is calculated from Eq. (7).

$$f_{gr} = \frac{d_{elem}}{d_{cell}} \tag{7}$$

where, d_{elem} is the distance between the seating face and the undermost element, and d_{cell} is the distance between the seating face and the grounded surface.

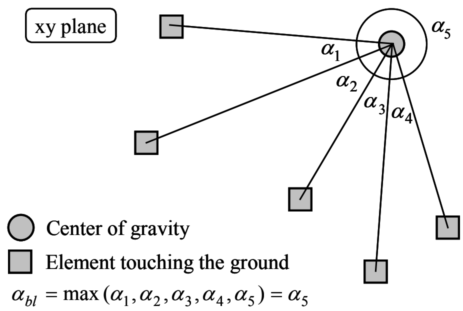

Fig. 10. Angle for judging stability.

Second, existence of the seating face f_{sf} is calculated from Eq. (8).

$$f_{sf} = \frac{n_{elem}}{n_{cell}} \tag{8}$$

where, n_{elem} is the number of the elements that are generated in the seating face, and n_{cell} is the number of cells which exist in the seating face.

Finally, the stability f_{st} as expressed by Eq. (9) is calculated by reference to the angle for judging stability (α_{st}). α_{st} is defined in Fig. 10.

$$\begin{aligned} &if \quad \alpha_{st} < \pi \quad then \quad f_{st} = 1.0 \\ &else \quad f_{st} = 1 - \frac{\alpha_{st} - \pi}{\pi} \end{aligned} \tag{9}$$

The ranges for these evaluations were set to 0 or 1 respectively. When all evaluation items calculated by the following equations are satisfied (Eq. (10)), a form is sampled as a design idea.

$$f_{gr} = f_{sf} = f_{st} = 1.0 \tag{10}$$

B. Execution of Form-Generation System

The form-generation system was executed under the design conditions described above. Figure 11 shows examples of generated forms. As shown by the figure, diverse chair forms were obtained. Specifically, the results indicate diverse chair forms were obtained; for example, massive chairs, flat chairs, chairs with frames, etc.

IV. FORM OPTIMIZATION

A. Form-Optimization System

A design objective gradually becomes clearer as the process advances. In this paper, we propose the form-optimization system for optimizing the diverse forms obtained by the form-generation system. Many optimization methods have been proposed and can be applied to the structural design. The proposed system can use the existence of elements as the design variables, because forms are composed of a cluster of elements. The proposed system uses the optimality criteria method, which can be applied to a design problem involving many design variables. This method can optimize diverse design ideas obtained in the generation system.

The basic structure of the form-optimization system consists of form modification and form evaluation. Forms

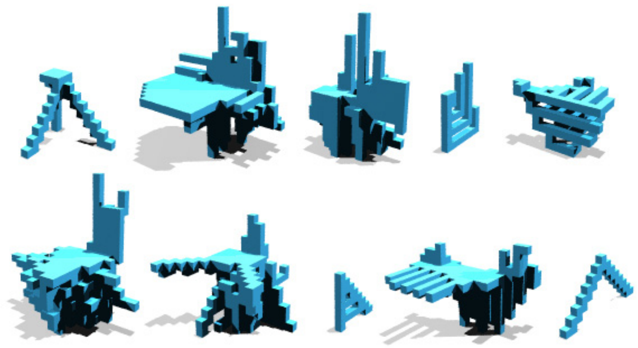

Fig. 11. Examples of generated chair forms.

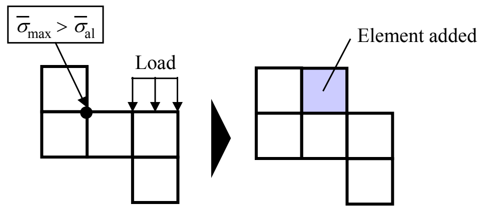

Fig. 12. Modification for increasing strength.

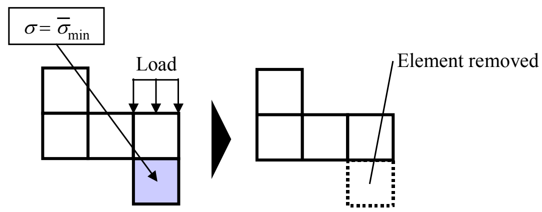

Fig. 13. Modification for reducing weight.

modified in form modification are evaluated in form evaluation. The result of the evaluation is fed back to form modification, and the forms are modified again. This cycle is repeated until convergence is attained.

The proposed system is assumed to be applied to structural design. Forms are optimized, provided that the design objective is weight reduction, and the design conditions of constraints are satisfaction of strength requirements and basic items for chairs evaluated in the generation process; existence of the grounded surface, existence of the seating face, and stability.

B. Form Modification

In form modification, forms are modified by equivalent stress distribution, which is calculated by the finite element method (FEM).

Form modification consists of modification for increasing strength and modification for reducing weight. In modification for increasing strength, maximum equivalent stress is calculated by use of the FEM, and then elements are added around a node where allowable stress has been exceeded (Fig. 12). Similarly, in modification for reducing weight, the element with minimum equivalent stress is deleted (Fig. 13).

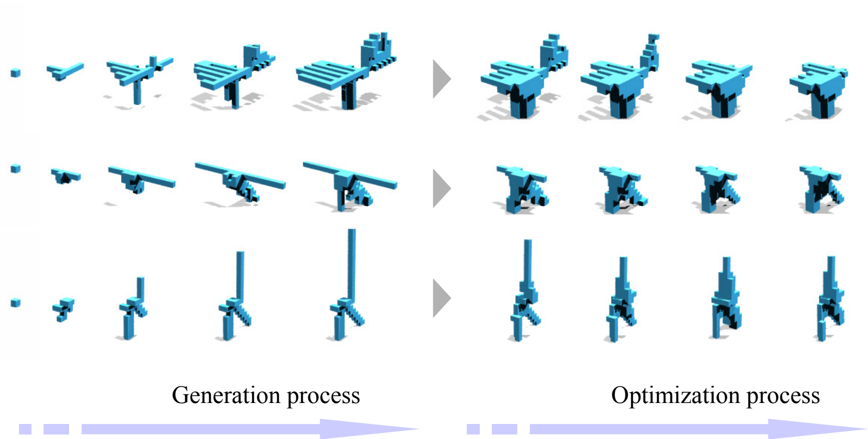

Fig. 14. Generation process and optimization process.

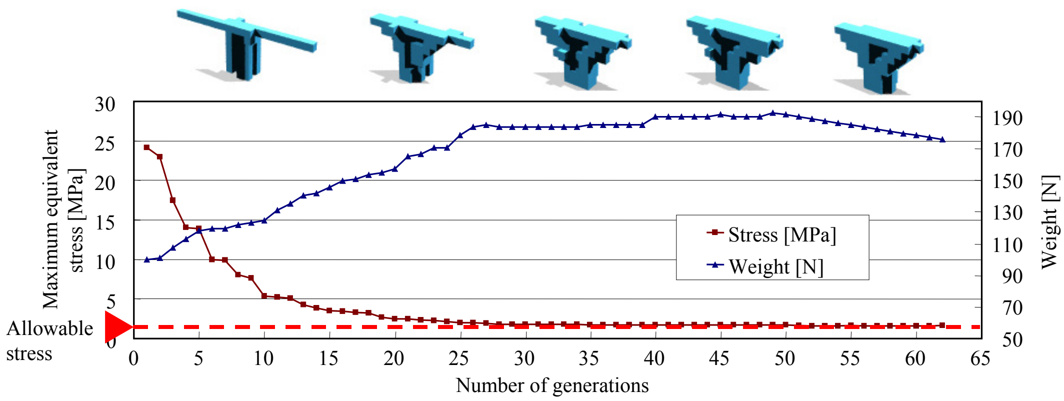

Fig. 15. Effect of number of generation on maximum equivalent stress and weight.

C. Form Evaluation

The objective function $\phi^{(n)}$ is defined. This function involves evaluation of weight and strength. The optimization problem of the proposed system is written as shown in Eq.(11).

Maximize $\phi^{(n)}$

$$\phi^{(n)} = \frac{W^{(n-1)} - W^{(n)}}{W^{(n-1)}} + \zeta\left(1 - \frac{\bar{\sigma}_{\max}^{(n)}}{\bar{\sigma}_{\mathrm{al}}}\right) \tag{11}$$

$$\zeta = \begin{cases} 1, & for \quad \bar{\sigma}_{\max}^{(n)} > \bar{\sigma}_{\mathrm{al}} \\ 0, & for \quad \bar{\sigma}_{\max}^{(n)} \le \bar{\sigma}_{\mathrm{al}} \end{cases}$$

where, $W^{(n)}$ is the total weight at state n, $\bar{\sigma}_{\max}^{(n)}$ is maximum equivalent stress at state n, and $\bar{\sigma}_{\mathrm{al}}$ is allowable stress.

D. Execution of Form-Optimization System

In the forms, distributed load was applied in the directions of the seating face (Total load: 2.5×10^4 N) and the seat back rest (Total load: 1.5×10^4 N). The material is polystyrene exhibiting the following properties: Young's modulus is 3.3 GPa, Poisson's ratio is 0.33, mass density is 1.05×10^3 kg/m^3, and allowable stress is 1.7 MPa. Figure 14 shows the process of optimization. The result indicates that diverse chair forms are generated without employment of an initial form in the generation process, and then in the optimization process forms are optimized while maintaining the diversity and the features of forms obtained by the generation process.

Figures 15 shows changes in weight and maximum equivalent stress in the optimization process. The results indicate that form of reduced weight is obtained while strength requirements is satisfied.

V. ANALYSIS OF EFFECTIVENESS OF PROPOSED SYSTEM

In order to analyze the effectiveness of the proposed system, solutions obtained by the proposed system are compared with solutions obtained by the conventional structural optimization method, which is the optimality criteria method mentioned in Chapter 4.

The conventional structural optimization method was executed under the conditions described in Chapter 4. As a result, a unique design solution was obtained under initial conditions, as shown in Fig. 16, whereas the proposed system yielded diverse design solutions. Figure 17 compares, in terms of weight, the solutions obtained by the proposed system and those obtained by the conventional structural optimization method. Specifically, the figure shows that the weights of the solutions obtained by the proposed system exhibit a lower average value and higher scatter. This result indicates that the proposed system produces diverse design solutions of reduced weight.

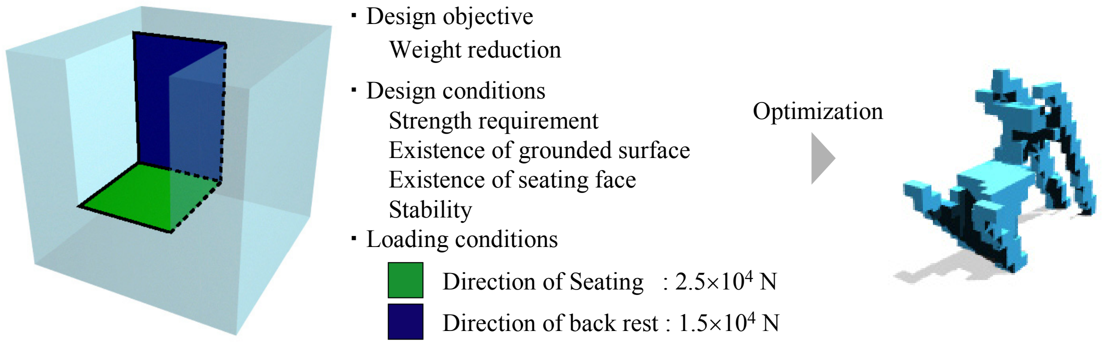

Fig. 16. A unique design solution obtained by the conventional structural optimization method.

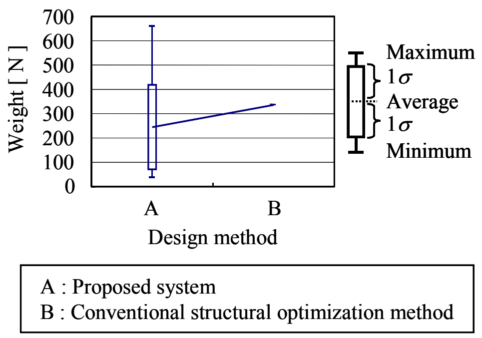

Fig. 17. Analysis of the weight of solutions.

VI. CONCLUSIONS

A system for producing diverse design solutions under the constraint of a few design conditions was achieved by simulating the developmental process of an organism and then using optimality criteria method. In order to evaluate the effectiveness of the proposed system, we applied the proposed system to the structural design of chairs and compared with the conventional structural optimization method. The proposed system produced design solutions of adequate diversity.

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