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Research Report

Modularization Method of Framed Structure in Conceptual Design Stage

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ABSTRACT This paper describes a modularization method based on topology optimization using beam elements and cluster analysis for a conceptual design stage. Topology optimization using beam elements is performed to create a framed structure of a new layout as a collection of fine members. For each fine member, the connection and characteristics are expressed as a design structure matrix (DSM). Hierarchical clustering is performed on this DSM, which yields clusters of fine members that become parts and modules. This is obtained hierarchically as a tree diagram called a dendrogram, so that it is possible to obtain an assembly process with less reworking by tracing each fine cluster toward the root of the trunk on the dendrogram. We consider the influence of the cluster analysis method and dissimilarity, and the weighting of physical properties of structural members on the DSM. The proposed method was applied to an example structure, whereby the division of modules and the order of assembly were obtained in a state of complete symmetry, which confirmed the effectiveness of this method.

KEYWORDS Topology Optimization, Cluster Analysis, Modular Design, Process Planning, Design Structure Matrix, Finite Element Method, Framed Structure

1. Introduction

Major changes are predicted in our future society,[1] such as energy and environmental problems, aging population, and population concentration in cities. Mobility functions and values will thus be required to respond flexibly and quickly to social change. Therefore, to efficiently conduct detailed specification changes in accordance with usage environments and customer requirements under limited development resources and cost constraints, the standardization, integration, and modularization of structures and parts should be promoted. IT companies are actively working on the development of self-driving cars, such as the established Sidewalk Labs,[2] to improve city life through science in response to increased population concentration in global cities. Another group has also reported urban systems[3] that include mobility and services for people. Therefore, further promotion of differentiation strategies that make use of the strengths of manufacturing companies is required. Optimization that includes conceptual design contrivance and processes of optimal multi-variety design that flexibly adapt to changes in social values and customer values can be considered as one method to address such requirements. It is effective to use explicit hierarchical notation of compositional relationships based on principles that can easily obtain consensus among stakeholders.

To realize low-volume production of a wide variety of products, it is considered effective to increase productivity by dividing the structure into modules of functional units and combine them to a certain degree of freedom with assembly in small blocks. This division is analogous to forming the trunk of a tree into branches and leaves, thereby enabling simultaneous assembly at each branch and leaf. The loss of assembly time will be reduced, and it will be possible to take measures only near this block, even if reworking occurs.

The design structure matrix (DSM) is one of the effective methods used to organize and systematically analyze the composition of complexly related products.[4] DSM clustering is used as a method to extract modules so as to reduce the relevancy to other modules and to maintain relevance in internal clusters. At this time, numerous studies have also been performed to use the DSM for the system optimization of product design because it is possible to explicitly understand the connection between modules. Those design processing systems using DSM were built as system design methods capable of optimizing the entire product system. The extraction of design tasks without dependency between parameters with the DSM to minimize reworking, as well as the explicit modeling of product information and comprehensive evaluation of design proposals,[5,6] has been reported to allow for overall optimization that is not individual matching. In addition, research is conducted to utilize the function of extracting modules and divide the automotive body structure.[7] The relationship between pressed parts of a car body is described in the DSM, and this DSM is rearranged to find modular divisions using a self-organizing neural network method. Application of this method to a car body composed of 38 pressed parts resulted in a five-module configuration: "front structure", "floor structure", "rear structure", "lower frame of cabin", and "upper frame of cabin". As a result, an effective body divided region can be obtained when changing the design according to the preference of the customer. These components are intended for components, of which the functions and boundaries are predetermined, such as pressed products.

No prior research had proposed a method for determining which areas should be defined as modules and assembled in order of least amount of rework for a new layout structure of an unprecedented part configuration. Therefore, to comprehensively evaluate the design plan of this new layout structure, we previously[8-10] proposed a method that utilizes topology optimization and cluster analysis using beam elements. In this method, structural members are provided in units smaller than parts, and topology optimization using beam elements is performed to create a framed structure of a new layout as a collection of fine members. For each fine member, the connection and characteristics are expressed as the DSM, as a composition in the whole of the framed structure.

By performing hierarchical clustering on this DSM, clusters of fine members are formed and become parts, and modules are configured as sets of these parts. This clustering is obtained hierarchically as a dendrogram; therefore, it is possible to determine the number of divisions of the module of the structure by selecting the granularity of the cluster into modules. Tracing each fine cluster toward the root of the trunk on a dendrogram provides an assembly process with less rework. Clusters collected at a certain granularity can be regarded as modules that are not related to one another. Furthermore, we comprehensively consider the influence of the cluster analysis method and dissimilarity (indicators having higher similarity with smaller values, such as distance), and the weighting of physical properties of structural members to the DSM in dividing a group of fine members into modules based on functions.

2. Basic Principles of Creation of New Layout Structure and Division into Modules

2. 1 Basic Configuration and Flow of Design System

At the stage of planning a new layout structure where the structure is not defined, the basic configuration of a design system for the creation of new beam structures and division into modules is explained in **Fig. 1**. The feature of this configuration is that a structure is created by topology optimization, in which members are provided in units smaller than parts, and this is expressed in the form of the DSM. Hierarchical clustering is applied to this DSM, whereby members with similar properties gather as a tuft, and these become parts and further become modules.

The procedure is roughly divided into three steps, as shown in Fig. 1, and using Microsoft Excel, it is systematized from construction of the analysis model to visualization with a dendrogram, assuming use in the conceptual design stage.

(1) Create a ground structure using beam elements, and find the optimal framed structure by topology optimization using the diameter of the cross-section as a design variable.
(2) The beam element is regarded as a part, and the dependency between the beam elements obtained by optimization and the weighting of the member properties are expressed by the DSM.
(3) Perform hierarchical clustering on the DSM to obtain a dendrogram. Tufts represent each module, and the assembly process is determined and visualized from the tuft connection order.

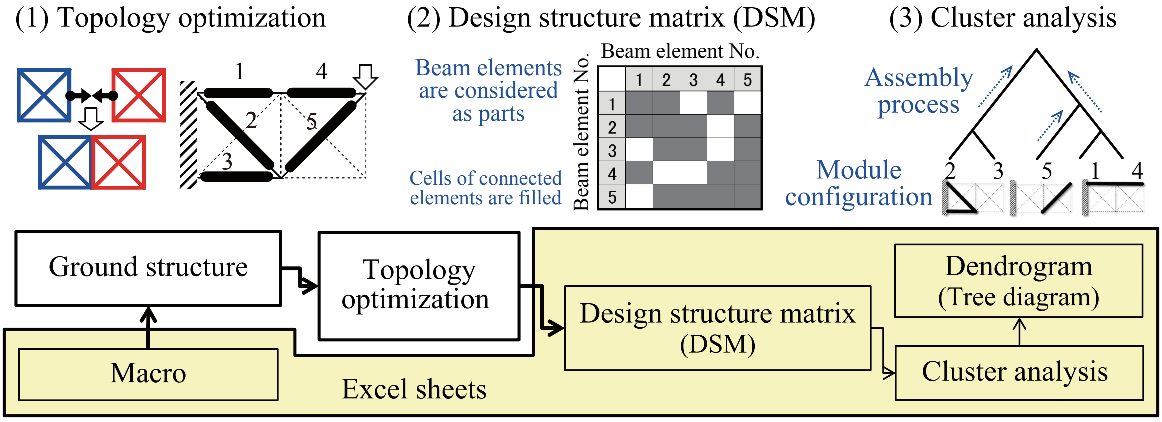


Fig. 1 Procedure of topology optimization and modularization in a system built on Excel.

2. 2 Creation and Evaluation of New Layout Structure

Topology optimization using beam elements(11) is performed to create a new layout structure. A (a) ground structure approach and (b) mean compliance minimization are applied to maximize the stiffness of the structure under the set volume constraints. A min-max approach is used that takes into account the load conditions that receive the maximum damage at each iterative convergence step to handle multi-objective problems under complex loading conditions. In the ground structure approach, as shown in **Fig. 2**, a large number of fixed nodes are preset, and beam elements smaller than parts are arranged for all combinations between these nodes. Here, it is assumed that a three-dimensional elastic body structure is constrained at boundary Γ_d and a load vector $\boldsymbol{f}$ is loaded at boundary Γ_t. The design variables are then updated using the optimization method shown in **Fig. 3**, and unnecessary beam elements are removed to determine the optimal beam structure form. Here, $\boldsymbol{K}$ is a globally assembled stiffness matrix, and $\boldsymbol{u}$ is a displacement vector generated by the load vector, $\boldsymbol{f}$.

A ground structure construction system has been created to easily create a block in this design domain. As shown in **Fig. 4**, the coordinates of the vertices are input in block units, and if vertices are moved to the same coordinates, the block can be degenerated into a triangular pyramid or a rectangle. Nodes and elements that are in the same place where blocks overlap are programmed to be merged and combined. The design variable is the diameter of the thin-walled cylindrical cross-section, and the thickness of the plate is assumed to have a dependency by multiplying the diameter by a constant. In addition, when evaluating the structural mechanical characteristics of the created layout plan, a three-dimensional finite element method program using beam elements(12) is applied.

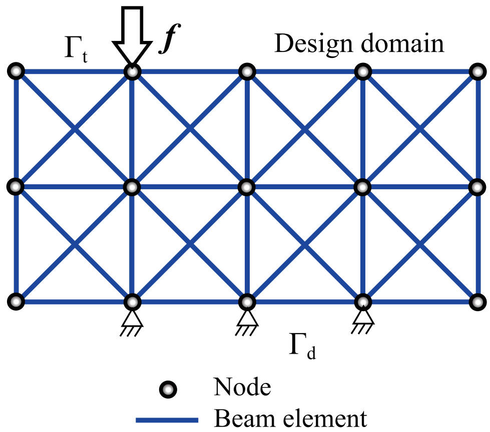


Fig. 2 Ground structure approach.

2. 3 Hierarchical Cluster Analysis Method

Hierarchical clustering is used as a method to visually present the module division and process order. In this section, the specific procedure is shown with an example to demonstrate the effectiveness of this method. In the analysis procedure, a distance matrix that represents the similarity is created from the matrix

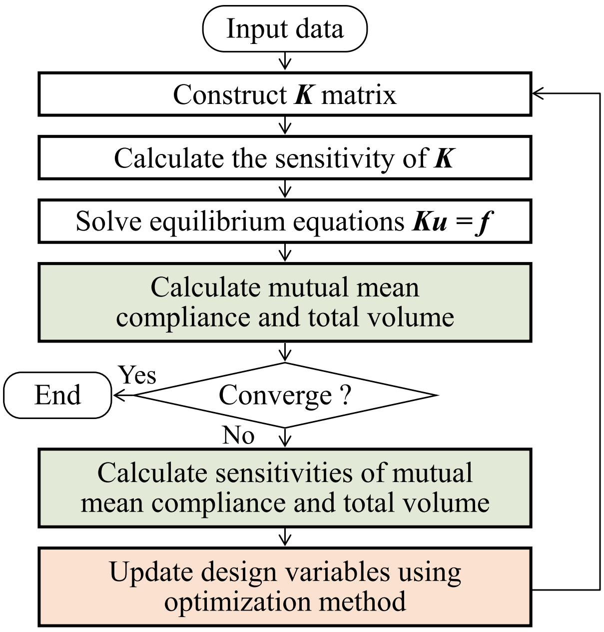


Fig. 3 Flowchart of optimization procedure.

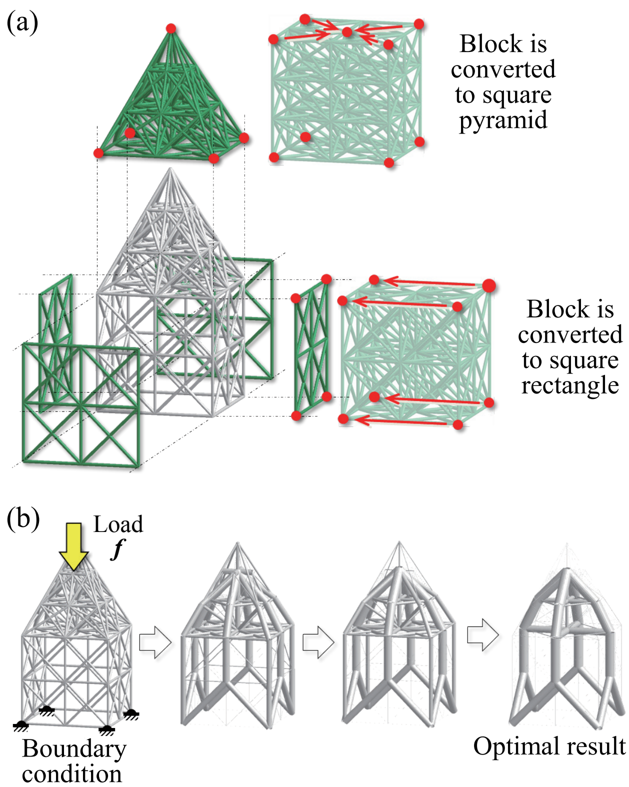


Fig. 4 (a) Procedure of modeling of ground structure. (b) Optimization process of example.

that describes the features of the element, and the procedure is repeated in which the closest elements (the strong relationship) are classified into the same group. The relationship of the connection of clusters is shown by a tree-like diagram called a dendrogram, by which the configuration and hierarchical structure of the clusters are visually grasped, and modules can be identified. The divided modules have a small number of interfaces, and the modules are rearranged in accordance with the related dendrogram, which makes it possible to determine a process with less rework. The clustering method that divides the data set into subsets is applied to the problem of dividing structural elements into parts and dividing them into modules, and the algorithm used here follows the general method of collecting data in the order of close characteristics. Therefore, we compare the typical problem of organizing data in order of closeness of characteristics (**Fig. 5**(a)) and the module division of parts proposed in this paper (Fig. 5(b)) is addressed through a specific process.

The target issue is defined by (l) in Fig. 5. Six data have W and L coordinates as characteristic values, as shown in Fig. 5(a). Figure 5(b) shows the configuration of a seven-piece ballpoint pen.[13] The connections are shown by arrows, where an arrow pointing in one direction shows the assembly direction, and arrows pointing in both directions show the fixation process.

These problems are expressed in the matrix of (2) of Fig. 5. The items in rows represent the characteristic values; Fig. 5(a) represents a data number, and Fig. 5(b) represents a part number. The items in columns represent the characteristic values; Fig. 5(a) represents the coordinates (W, L) of each data item, and Fig. 5(b) represents the same part number as the rows, and the link between the parts indicated by the arrow is described.

In (3) of Fig. 5, the Euclidean distance is calculated from each matrix defined in (2) of Fig. 5 as an evaluation value of the closeness of the characteristics of the data. A matrix of distances is obtained by determining the square root of the sum of squares of the differences of the components of the column vector between the items in each row.

The group average method,[14] which is generally used as a clustering method that sequentially combines things with similar properties, was employed. In the process of collecting data, the definition of the distance between clusters is taken as the average of the distances of all combinations between each cluster.

Hierarchical clustering used in this study is a method to arrange in order from the most similar combination, and the intermediate process can be expressed as a hierarchy that is finally expressed as a dendrogram ((4) in Fig. 5). In addition to classification, by tracing the dendrogram, it is possible to confirm how clusters are combined in the process of classification. In the grouping of data in (4) of Fig. 5(a), the process of collecting data with close coordinates corresponds well to the dendrogram connection.

The ballpoint pen problem in (4) of Fig. 5(b) shows the procedure for the assembly of parts. It can be understood that the lower part group (2, 3, 4, and 5)

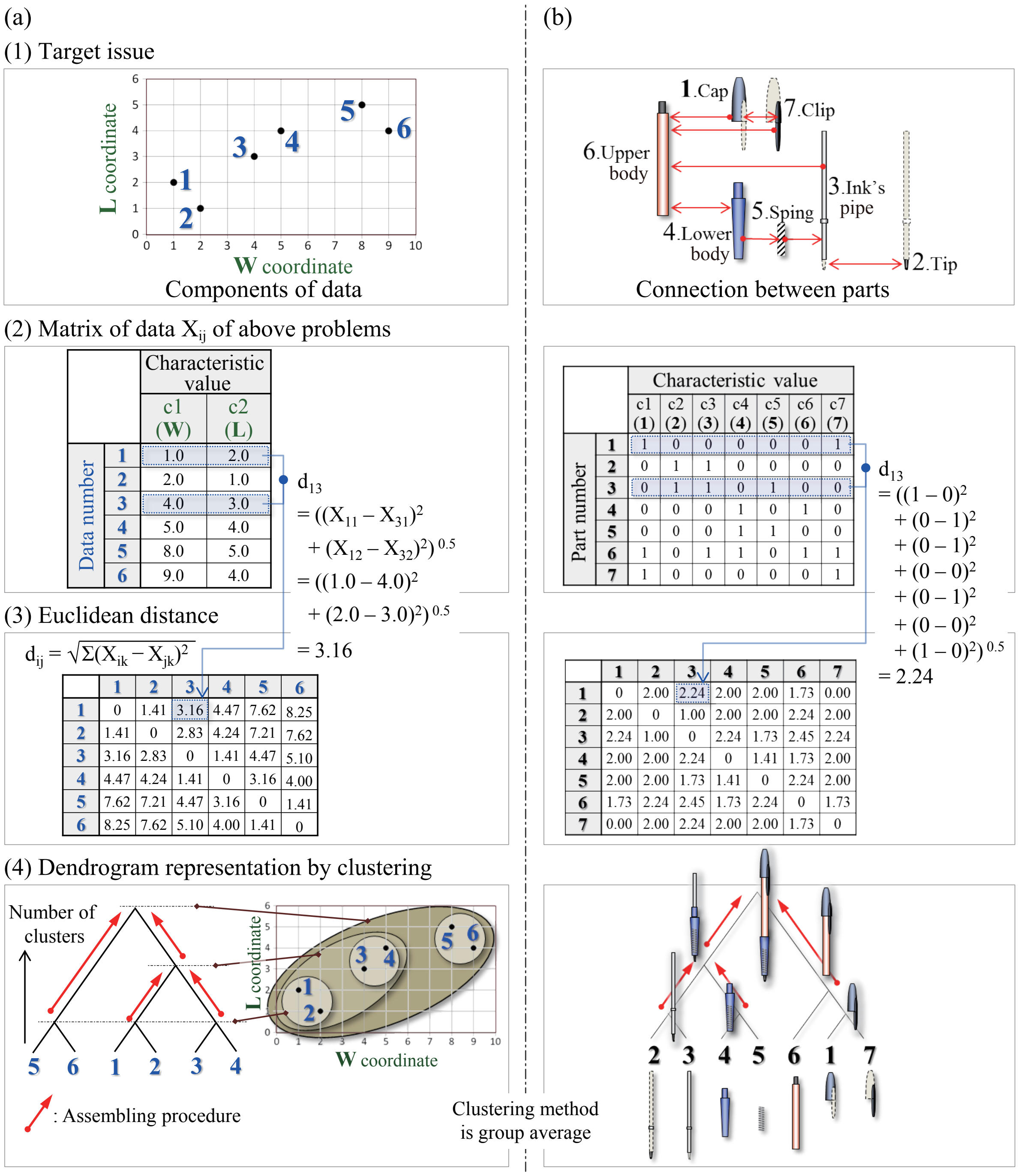


Fig. 5 (a) Grouping by closeness of data. (b) Modularization from connection of parts.

and the upper part group (6, 1, and 7) independently construct modules and are assembled separately.

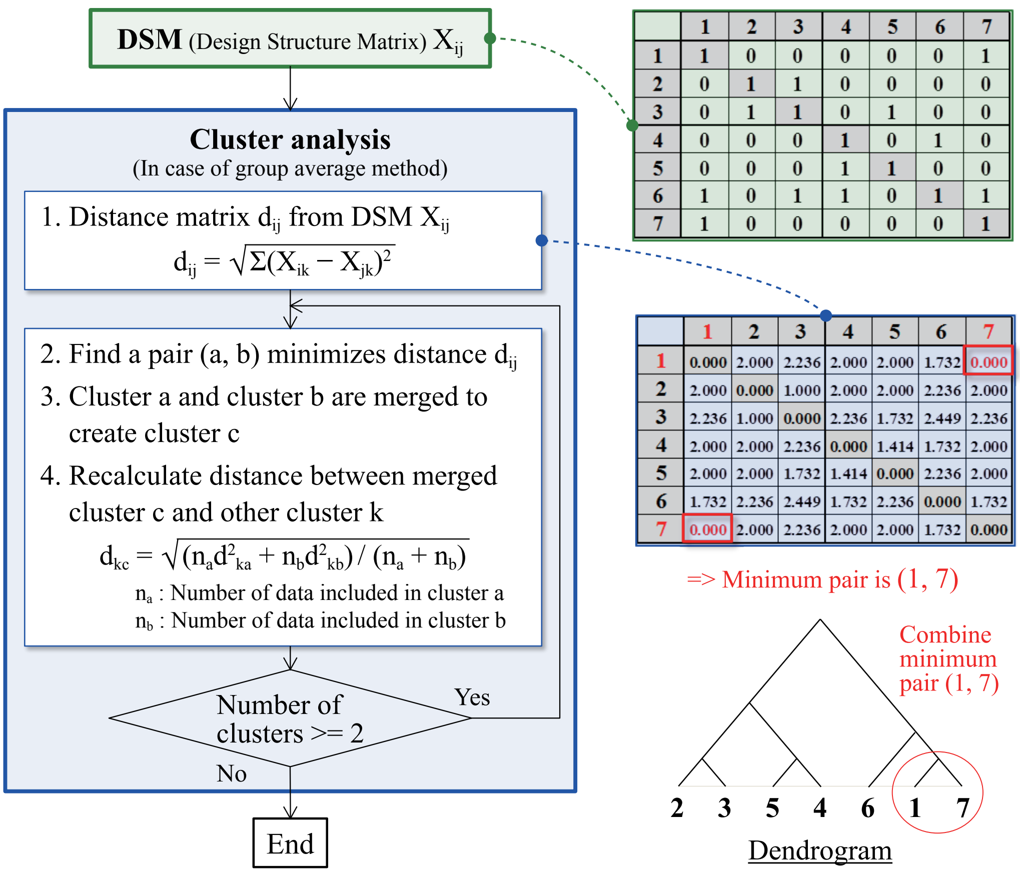
Figure 6 shows a flowchart that includes a specific arithmetic expression for the clustering method using the example of a knock-type ballpoint pen. Cluster analysis is performed using the DSM. The Euclidean distance d_{ij} is used as the dissimilarity of cluster X_{ij}, and the pair with the minimum d_{ij} is integrated as a new cluster. In the example, d_{17} and d_{71} are minimum values of 0; therefore, element 1 and element 7 are merged into one new cluster as having the closest properties. The distance to other clusters is determined again for the new cluster, and the cluster analysis procedure is repeated until the number of clusters is integrated into one. This process of cluster integration is visually represented as a dendrogram, and the figure at the bottom right of Fig. 6 shows how element 1 and element 7 are integrated.

Figure 7 shows a summary of this series of flows. The configuration (1) of parts is described in the DSM (2). This DSM is rearranged by cluster analysis (3) and a dendrogram is obtained (4). This dendrogram represents how the ballpoint pens are divided into modules at the top and bottom, and they are assembled independently and become the final product.

3. Analysis Result and Consideration of Box Structure

3. 1 Creation of New Layout Structure

The effectiveness of the proposed method is confirmed through analysis using the box structure shown in **Fig. 8**. First, topology optimization using beam elements is performed to determine the optimal framed structure layout along the load path. We define a ground structure that places beam elements in a designable space (Fig. 8(a)). The cross-sectional shape of the beam element is cylindrical, and the design variable is the diameter *d* of the cross-section of each beam element. The maximum diameter of the beam element is set to 200 mm, the volume constraint (final volume/volume when all beam elements have the



	1	2	3	4	5	6	7
1	1	0	0	0	0	0	1
2	0	1	1	0	0	0	0
3	0	1	1	0	1	0	0
4	0	0	0	1	0	1	0
5	0	0	0	1	1	0	0
6	1	0	1	1	0	1	1
7	1	0	0	0	0	0	1

	1	2	3	4	5	6	7
1	0.000	2.000	2.236	2.000	2.000	1.732	0.000
2	2.000	0.000	1.000	2.000	2.000	2.236	2.000
3	2.236	1.000	0.000	2.236	1.732	2.449	2.236
4	2.000	2.000	2.236	0.000	1.414	1.732	2.000
5	2.000	2.000	1.732	1.414	0.000	2.236	2.000
6	1.732	2.236	2.449	1.732	2.236	0.000	1.732
7	0.000	2.000	2.236	2.000	2.000	1.732	0.000

Fig. 6 Flowchart of hierarchical cluster analysis and example of knock-type ballpoint pen method.

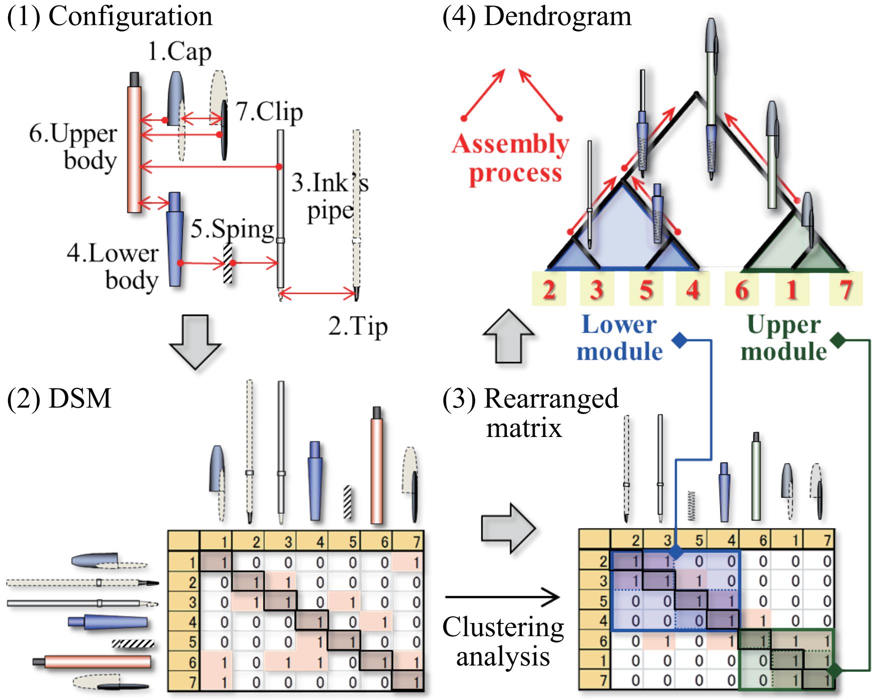


Fig. 7 Example of cluster analysis using knock-type ballpoint pen.

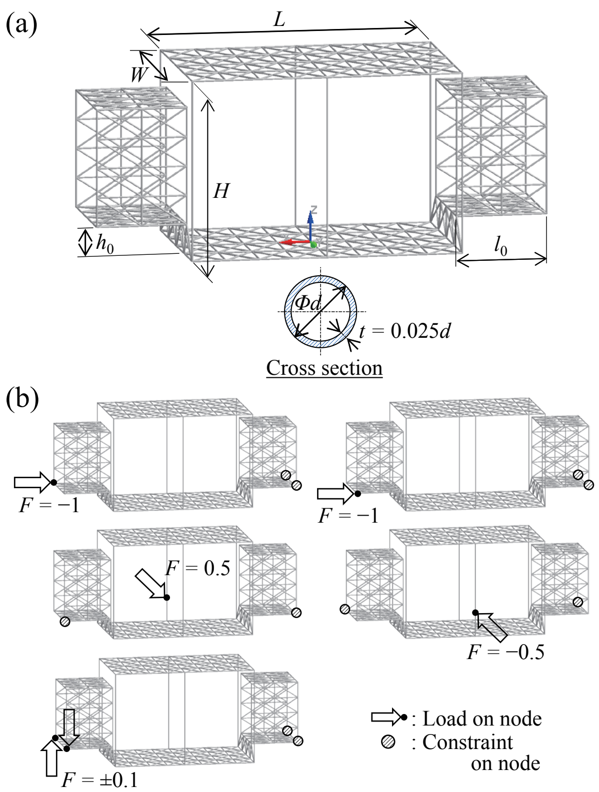


Fig. 8 (a) Grand structure for topology optimization. (b) Boundary conditions for five loading cases.

maximum diameter) is set to 10%, and the thickness t is set to 0.025 times the beam element diameter. The analysis was performed with L = 3000 mm, W = 2000 mm, H = 2000 mm, l_0 = 1000 mm, and h_0 = 350 mm, which simultaneously satisfy the five boundary conditions shown in Fig. 8(b). **Figure 9** shows the topology optimization results. Unnecessary elements that do not contribute to the load path are deleted, and the necessary elements can be confirmed to become thicker, depending on the role of the transmission of force.

3. 2 Replacement of Standard Members in Consideration of Manufacturing Requirements

The layout of the framed structure obtained by topology optimization is replaced with standard components that are available for purchasing. During the topology optimization process, thin beam elements are deleted at the threshold 0.3 (30% or less of the diameter for the maximum diameter). Under the loading condition with consideration of safety factors, the lightest standard member is selected without the maximum generated stress of the beam element exceeding the yield stress. Fully stressed design is performed on discrete values. In fully stressed design, the maximum stress is required to be equal to the allowable stress; however, in the case of standard members, it is generally not in the ideal fully stressed state. Therefore, the standard members are arranged in descending order of rigidity, and the algorithm reduces the rigidity one step at a time if the maximum generated stress does not exceed the allowable stress for each beam element, and the diameter *d* of the cross-section of each beam element and the thickness *t* are determined.

According to this method, under stress conditions where the unit of load is newtons and the load scale is 4.0×10^5, the results for full stressed design on standard members of diameter *d*, thickness *t*, and yield stress σ_y are given in **Table 1** and shown in **Fig. 10**. Although there is no significant difference in appearance with the topology optimization result (Fig. 9), a structure consisting of standardized members not exceeding the yield stress under the assumed load is obtained.

3. 3 Modularization and Consideration by Cluster Analysis

At this stage, division of the module is performed with the beam element regarded as a part. The connection between beam elements is described in the DSM for the framed structure, where the members are regarded as components, and cluster analysis is performed by the neighbor-joining method.[15] By displaying the relationships of cluster connections as a dendrogram, it is possible to show modules and their connections, and also to show process connections and order. **Figure 11** shows a dendrogram obtained by the proposed procedure. Each element is assembled as it goes up from the bottom to the upper level. The number of stages represents the number of assemblies. In the dendrogram, the number of members increases as they are integrated from the bottom to the top of the stairs. It can be understood that a small area forms a large area while involving the surroundings, and it also forms an almost symmetrical structure. The result shows that it is possible to achieve module division by the combination of five modules.

4. Analysis Results and Consideration of L-shaped Structure

4. 1 Creation of New Layout Structure

The effects of different clustering methods on module division are examined for simple L-shaped cantilever

Table 1 Specifications of the standardized member.

No	Diameter ϕ *d* [mm]	Thickness *t* [mm]	Yield stress σ_y [N/mm^2]
1	190.7	3.5	685.0
2	165.2	3.5	685.0
3	141.3	2.6	685.0
4	127.0	2.0	685.0
5	101.6	1.8	685.0
6	82.6	1.8	685.0
7	70.0	1.0	685.0
8	60.5	1.0	685.0
9	48.6	1.0	685.0
10	38.1	1.0	685.0
11	25.4	1.0	685.0

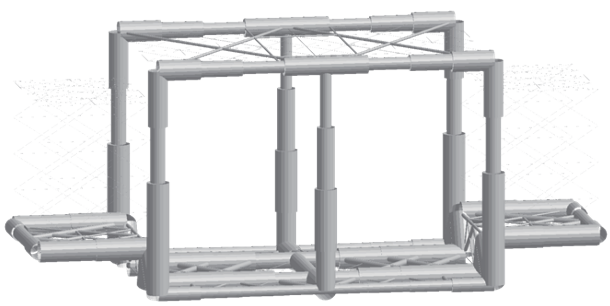


Fig. 9 Optimized shape obtained by the topology optimization.

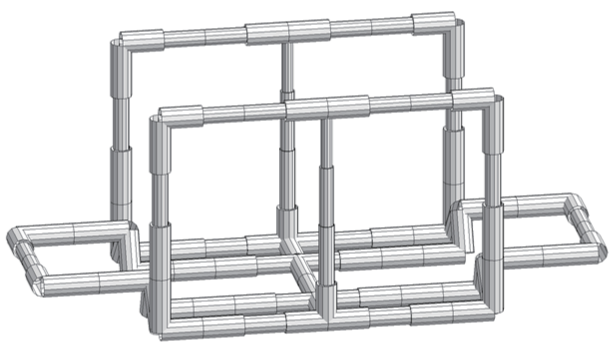


Fig. 10 Results of fully stressed design.

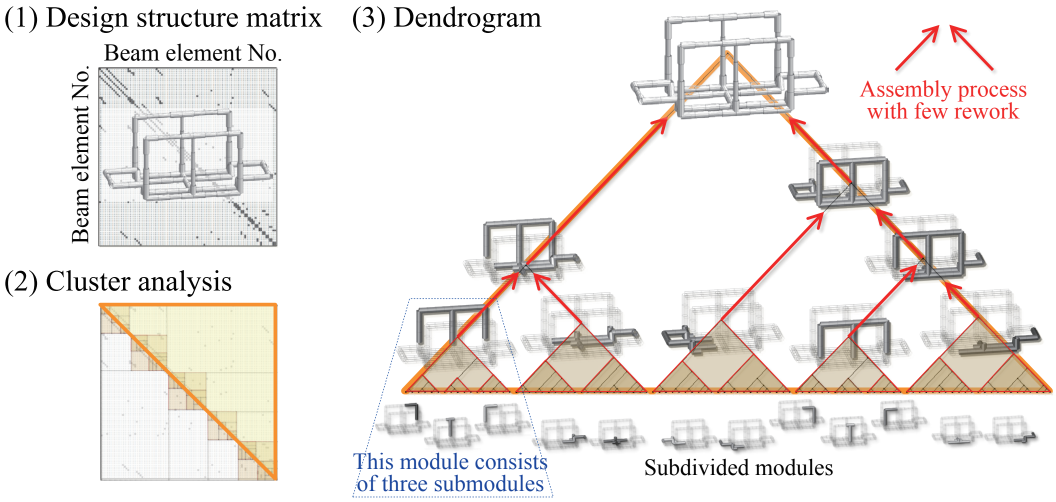


Fig. 11 Visualization of the module configuration and process after clustering.

structures. First, topology optimization using beam elements is performed to determine the optimal framed structure layout along the load path. A ground structure is defined that places beam elements in the designable space. The cross-sectional shape of the beam element is cylindrical, and the design variable is the diameter d of the cross-section of each beam element. The maximum diameter of the beam element is 100 mm, the volume constraint is 10%, and the thickness t is 0.0125 times the beam element diameter. In addition, the dimensions of the structure are set to 1400 mm in width, 800 mm in depth, and 400 mm in height, and topology optimization was performed under boundary conditions where individual loads of 1.0 N (unit load) and 0.2 N were separately loaded (multi-loading) at the upper and lower center points of the front surface (**Fig. 12**). Thin beam elements less than 20% of the maximum diameter were removed.

4. 2 Modularization and Consideration by Cluster Analysis

A DSM is created from the optimized framed structure and cluster analysis is performed. In the creation of the DSM, the beam elements of the framed structure obtained by the topology optimization in Fig. 12 are regarded as parts, and the dependencies between the elements are expressed in a matrix (**Fig. 13**). Rows and columns are set as the same beam element number, and each element of the matrix is set to 0 if there is no connection between elements,

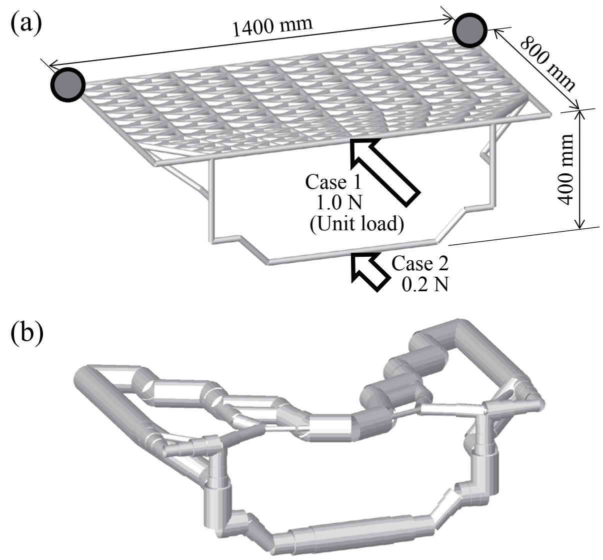


Fig. 12 (a) Ground structure and multi-loading condition. (b) Topology optimization result.

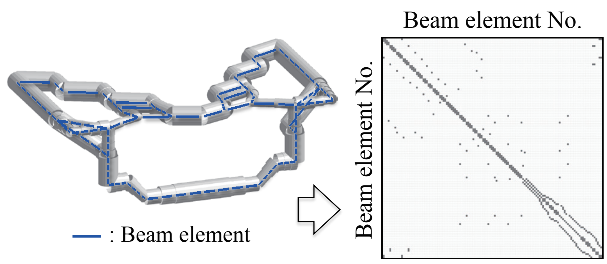


Fig. 13 Construction of design structure matrix from newly created layout structure.

whereas if there is a connection, then weight is added by a number. Furthermore, the polar moment of inertia of area J is added as a weight, considering that the diameter of the framed structure obtained by optimization represents the importance in the structure. Cluster analysis was applied to the obtained DSM (**Fig. 14**).

The results of the three clustering methods (Ward's method, group average method, and neighbor-joining method) are considered below. In the Euclidean distance shown in Fig. 14, the dendrograms obtained by Ward's method and the group average method are similar. However, the results of Ward's method are not only complicated, but also have a nested structure. Compared with Ward's method, which uses the square sum of the deviation of a cluster as a distance between clusters, the group average method, which uses the average of the distance of all the combinations of a cluster element as a distance between clusters, the absorption of a cluster becomes clear and the relation of the dendrogram does not easily become complicated. In the following discussion, we will consider the remaining group average method[14] and neighbor-joining method.[15]

In the cluster analysis results using Euclidean distance, it is difficult for the module assembly order to be divided symmetrically in both the group average and neighbor-joining methods. In the Euclidean distance, without consideration of the large number of dimensions of the vector component, the result is simplified to the scalar quantity represented by the root of the square sum of the difference of the distance. It is difficult to obtain suitable symmetrical results, which then requires consideration of the connection characteristics of the entire structure. On the other hand, the cosine distance measures the closeness at the angle between two vectors, where the n-dimensional vectors need to be in the same direction and the values for each dimension will be close to each other. As a result, even if the model has a large number of components, it can be considered that clustering can be performed with high accuracy.

Therefore, clustering was performed by the group average method and the neighbor-joining method using the cosine distance as an evaluation value of the closeness of the data characteristics (Fig. 14,

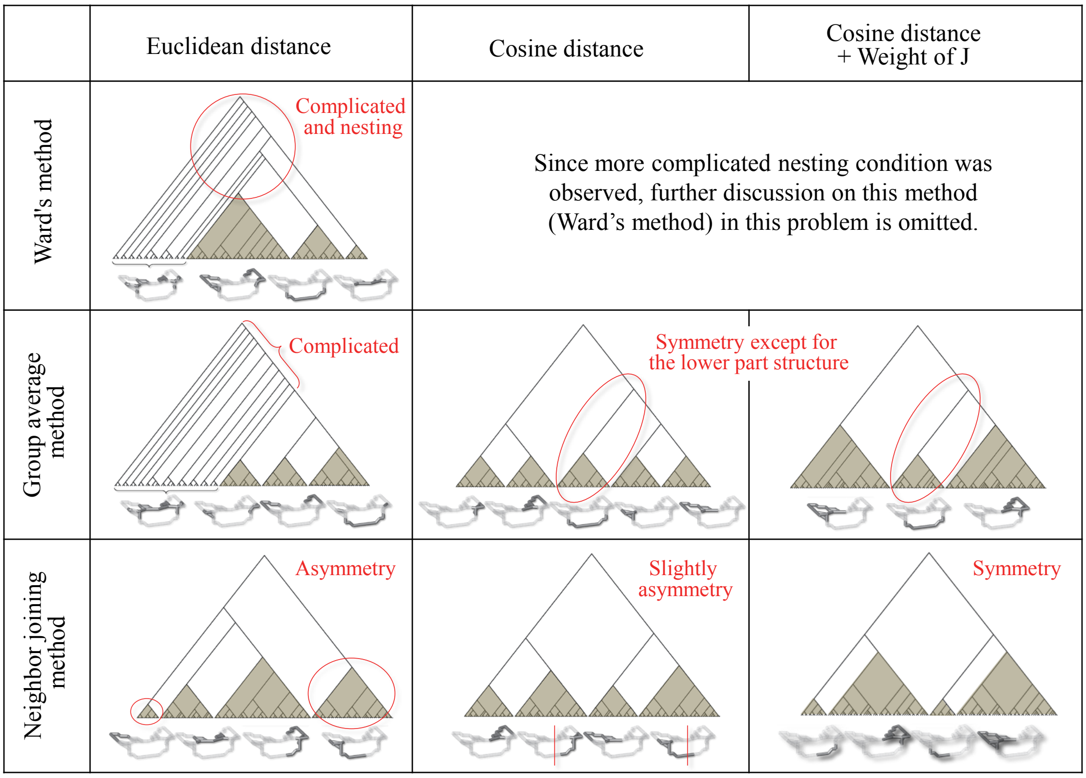


Fig. 14 Results of dendrogram after cluster analysis using some dissimilarity.

middle column). As a result, it was confirmed that it is effective to use cosine distance as a dissimilarity in the problem targeted in this research because modules are divided into meaningful functional units. In particular, the group average method shows improvement effects, such as the similarity of the module assembly order of modules in the upper hierarchy, and the almost symmetric assembly order of modules. However, in both methods, symmetry is not satisfied. In the group average method, the entire structure is assembled after the front lower structure belongs to one side, even though the upper structure is obtained symmetrically as the configuration of the dendrogram. In the neighbor-joining method, an almost symmetrical structure is obtained; however, the front lower structure is divided in a state shifted by one element from the plane of symmetry.

As the next consideration, each component of the DSM matrix is weighted according to the number of connections, and the polar moment of inertia of area J for each beam element is further added as a weighting based on physical characteristics. It can be expected that modules are divided based on the characteristics that not only provide connections but also functions for the entire structure. As a result, although a slight disturbance of the symmetry of the assembly order with the group average method could not be eliminated, the problem of the one-element shift with the neighbor-joining method of the cosine distance with weight as J was solved. The following discussion is based on the result of this condition shown in the lower right panel of Fig. 14.

In the modularization of an L-shaped structure (**Fig. 15**(a)), the DSM after cluster analysis (Fig. 15(b)), with respect to the initial DSM (Fig. 13), shows that the non-zero component of the place away from the diagonal line is aggregated to the diagonal line. The connections between modules in the DSM can be regarded as the order of processes;(4) therefore, it can be confirmed that the reworking of the assembly process is reduced. Furthermore, if the module units obtained are assembled independently in parallel, then the dependency between modules in the process is reduced. From that point of view, the result of the cosine distance and the neighbor-joining method (Fig. 15) is composed of six modules (L_1, L_2, L_3, R_1, R_2, R_3), and the modules are joined at eight places (J_1, J_2, J_3, J_1', J_2', J_3', J_4, J_5). The relationship between these modules and connection joints can be represented by the DSM in Fig. 15(b), and as shown by the dendrogram in Fig. 15(c). In the dendrogram, the hierarchical structure of modules is visually illustrated, so that it is possible to easily perform the following considerations. First, between L_2 and L_3, and between R_2 and R_3, module coupling occurs at two places each (J_1, J_2, J_1', J_2'). Furthermore, between L_1 and integrated L_2 and L_3, and between R_1 and integrated R_2 and R_3, there are two more module coupling places (J_3, J_3'). Finally, the L side of the module (L_1, L_2, L_3) and the R side of the module (R_1, R_2, R_3) are assembled in two places, J_4 and J_5. The state of such simultaneous parallel assembly is shown by the block diagram in **Fig. 16**.

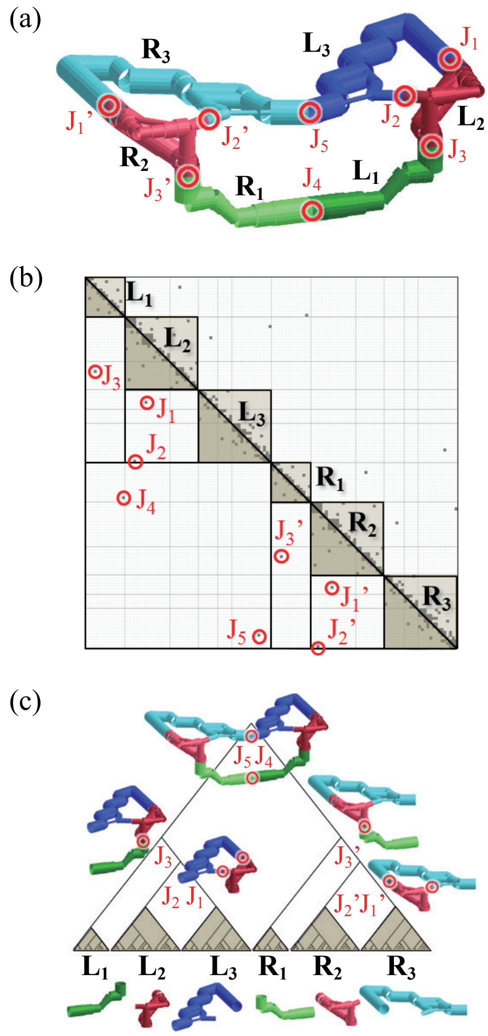


Fig. 15 (a) Module candidates and joint positions.
(b) Notation by design structure matrix.
(c) Notation by dendrogram.

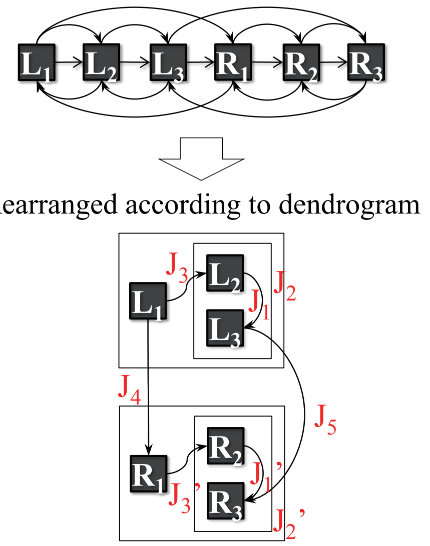


Fig. 16 Block diagram of module configuration.

5. Conclusion

We have proposed a method that utilizes topology optimization and cluster analysis using beam elements to comprehensively evaluate the design plan for a new layout structure. Topology optimization using beam elements is performed to create a framed structure for a new layout as a collection of fine members. For each fine member, the connection and characteristics are expressed as a DSM. Hierarchical clustering is performed on the DSM to form clusters of fine members that become parts and modules. This is obtained hierarchically as a dendrogram, so that it is possible to obtain an assembly process with less rework by tracing each fine cluster toward the root of the trunk on a dendrogram.

Furthermore, we comprehensively consider the influence of the cluster analysis method and dissimilarity, and the weighting of physical properties of structural members on the DSM in dividing a group of fine members into modules based on functions. The proposed method was applied to an example structure, whereby the division of modules and the order of assembly were obtained in a state of physically continuous connections with no significant difference in the number of components of each module, and maintaining complete symmetry, which confirmed the effectiveness of this method.

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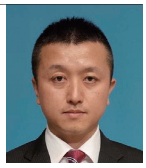

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