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SUPPORTING MODULAR DESIGN ON THE CONCEPTUAL DESIGN STAGE

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ABSTRACT
These days, developing various types of products with the short lead-time is needed for diversification of needs of consumers. Moreover, it is quite important to cope with environmental problems. The idea of the modular design is attracts an attention that has the possibility of solving above-mentioned problems. In this paper, the method of supporting modular design on the conceptual design stage is proposed. First, we defined relationship between the function and the arrangement of conceptual parts. Secondary, we proposed modular design process on the conceptual design as five steps; those are "description of function tree structure", "behaviour flow according to functional aspect", "construction of conceptual parts", "synthesis to modular structure", and "verification for modular structure". While first two steps are related mainly to the function of the product, the third one is done by using the information of the product function, qualitative attributes of conceptual entities, and the arrangement rules derived from the functional aspects. On synthesis to modular structure step, combinations of parts are evaluated from various aspects obtained by previous three steps, and the modularization is done according to the result of evaluation. On the last step, whether the modularization result meets the restriction requirement and the satisfaction requirement is evaluated. We also developed the pilot system for supporting the modular design process with proposed approach, and the applicability of the proposal method was examined.

Keywords: Modular design, Conceptual design, Qualitative information, Design process, Functional and spatial relationship

1 INTRODUCTION
These days, the environmental problems have been recognised as serious ones. Therefore, current mass production, mass consumption, and a large amount of waste products manufacturing/usage system have to be reconsidered and be changed in order to reduce materials, energy, and waste [1]. On the other hand, consumer needs are more and more diversified, and the globalization of the market is rapidly advanced today. Therefore, adopting the newly developed materials and/or technologies quickly, and developing various types of products with short lead-time is strongly needed.

The idea of the modular design is attracts an attention that has the possibility of solving many of above-mentioned problems. A lot of researches have been done about modular design. For example, Kusiak proposed a methodology for determining modular products while considering cost and performance [2]. Kimura focused on not only product functionality and product commonality but also product life cycle cost and proposed production modularization strategy [3]. Umeda proposed the life-cycle simulation system that optimizes target life-cycle model and modular structure of the product by using genetic algorithm [4].

Here, most of researches on conceptual design stage are mainly focused on functional aspect, and the arrangement of parts and modules is not handled at the conceptual design stage because product shape is not decided clearly on this stage. However, designer usually thinks/uses about both functional hierarchy and structure hierarchy for cognition process on design [5]. Therefore, it is quite important to consider the space relations among module parts from the conceptual design stage even if it is an abstract level.

This research also pays attention to the modular design on the conceptual design stage. We give priority to the handling of information that is a qualitative level at the conceptual design stage. The objective of this research is to propose the method for supporting the modularization of the product by using qualitative information not only functional aspect but also qualitative spatial and/or structural information.

2 REPRESENTATION OF FUNCTION, ENTITY, AND MODULE

2.1 Conceptual design process on modular design

Generally, the product design is done in the following processes [6]:

1. Clarification of the role and the purpose of the product.
2. Search for functional design solution that satisfies functions while decomposing required function to simpler functions.
3. Deriving of mechanism corresponding to design solution at function level.
4. Making to entity by combining derived mechanisms while keeping correspondence.

It is preferable to take a similar process in the modular design. In addition, the viewpoint how it modularize is needed. That is to say, it is necessary to consider the element that relates to the modularization; those are function, size, weight, longevity, and material, etc. Though many of these information were given only to qualitative level at the conceptual design stage, the modular design can be considered, and be supported by using these information to examine the modularization at the early stage of the design.

Therefore, we propose the modular design processes in the conceptual design as five steps; those are “description of function tree structure”, “behaviour flow according to functional aspect”, “construction of conceptual parts”, “synthesis to modular structure”, and “verification of modular structure”. In “description of function tree structure” step, the function of the product is decomposed to simpler functions, and expressed by a hierarchical tree structure according to the details degree. In “behaviour flow according to functional aspect” step, the relations between functions with the highest details degree obtained as a result of the “description of function tree structure” step, which can be considered to be a behaviour level, are expressed in the directed graph. In “construction of conceptual parts” step, qualitative attributes of the size and the weight etc. of parts are set, and the conceptual shape to express a rough size and weight is made in the hexahedron. In “synthesis to modular structure” step, integration and the modularization are done based on information obtained by previous three processes. “Verification of modular structure” is a process of evaluating and revises the result of modularized plan. Figure 1 shows the flow of proposed modular design processes in the conceptual design. These processes are explained in detail respectively by the following subsections.

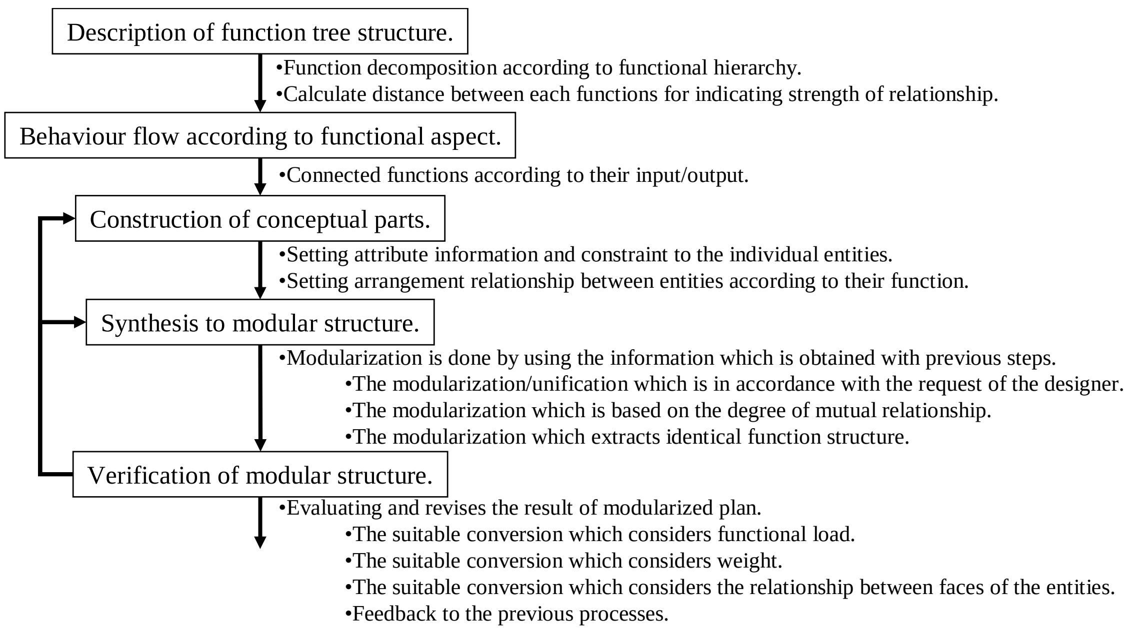

Figure 1. Flow of proposed modular design processes on the conceptual design

2.2 Description of function tree structure

The functions of the product are represented in the "description of function tree structure" and "behaviour flow according to functional aspect" steps.

The method for expressing the function according to the details degree by a hierarchical tree structure is known well in the function decomposition. This research uses a similar function tree expression.

The hierarchy of the function tree is assumed following four levels:

- Level 0: Aim of product
  A level 0 function indicates the main aim of the design object. As a rule, only one level 0 function exists in the product.
- Level 1: Product main functions
  On level 1, functions that become main to realize the aim of the product is described. In other words, level 1 is a result of roughly classification of functions those are required to design object. Level 1 functions are located directly under the level 0.
- Level 2: Subordinate functions
  Level 2 functions are the sub-functions which exist in the process which are decomposed from Level 1 functions to Level 3 functions.
- Level 3: Element level functions
  Level 3 is the element functions which are detailed enough to be able to easily imagine their behaviour. This type functions are generally provided as the fruits of taxonomic methodology of functional vocabulary.

Here, from level 0 to level 2, the designer can describe freely because descriptions on these level are depend on current design object. Level 3 makes selective from the functional vocabulary which is prepared beforehand based on the functional basis [7] and ontological approach [8].

Function can also classify into the following three types with the type of role which is carried out with the product.

- Basic function: Necessary function for the product.
- Special function: Optional function. Extended function.
- Subsidiary function: The function which becomes necessary with mutual relationship between functions.

Category of this classification is also indicated in each function. This is utilized for decision of combination of functions on "synthesis to modular structure" step.

Generally speaking, functional parts with the same purpose are modularized. In other words, functions whose distance is close in the function tree structure are easy to make identical module. Therefore, the method of deciding the distance between the functions which are described with function tree structure is introduced. Calculation method of distance is explained using Figure 2 as an example. Combination of two functions which contains level 0 function in their trace route does not deal with to become same module because these two functions' principal aims are different. For example, function A and function C does not modularized. Distance between functions is calculated between up to level 1 from level 3. Here, in many cases, level 2 is designed to be multilevel structure. Therefore, at first, the branch where the number of stages is largest is selected, and distance in each inter-stage is designated as one. In case in Figure 2, the branch of function C is selected, and the distance from level 1 to level 3 is decided three. This becomes standard distance between level 1 and level 3. As for function A, because they are two stages from level 1 up to level 3, distance in each inter-stage becomes with 1.5. In addition, when the designer judges that the stage of decomposition was clearly skipped, he/she can adjust distance by inserting dummy function in route such as the branch of function B. This calculated distance indicates the strength of relationship between the functions.

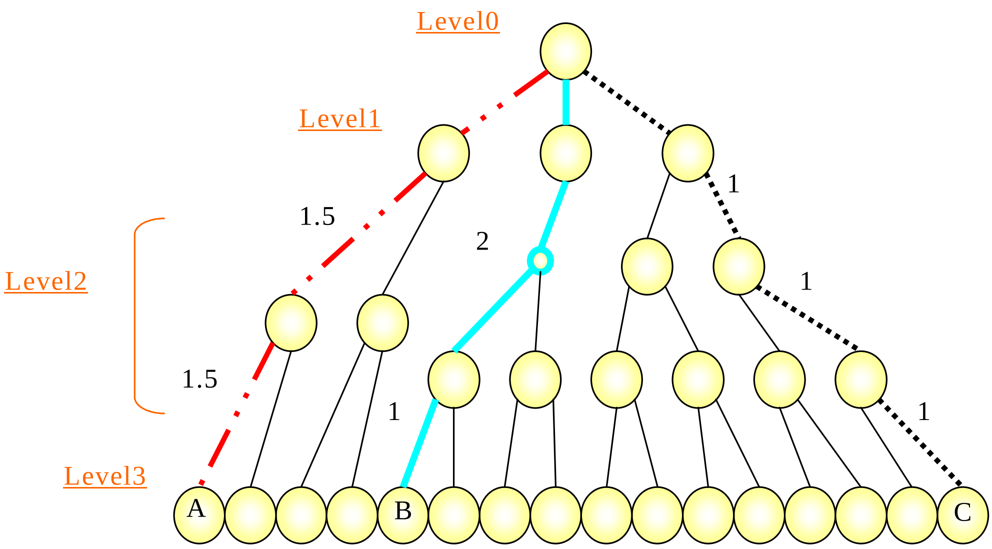

Figure 2. Distance calculation of function tree

2.3 Behaviour flow according to functional aspect

In this step, connection between the element functions are represented in a directed graph based on each functions' input/output. This kind of function structure description method is known well [6, 9], and in many cases, agrees with the structure of real mechanism well. Therefore, we also use this kind of function structure to represent behaviour flow like Figure 3. Due to connections between element functions have to be done by the designer, typical combination of element functions are provided as the template in order to assist him/her. Distance between functions calculated on previous step also supports the designer to construct behaviour flow because element functions pair whose distance is close has related to similar to main function. The behaviour flow which was drawn up with this step decides the arrangement of each functional part roughly, and is used as the fundamental data of modularization.

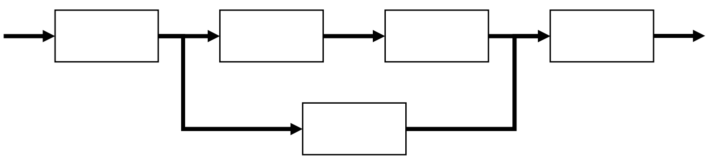

Figure 3. Structure of functions according to behavior flow

2.4 Construction of conceptual parts

In this step, the information of the entity is set to conceptual shape. Here, because the product shape has not been decided at the early stage of design, hexahedron and/or hollow hexahedron as conceptual entity is used. The constraint which decides product shape is various. We prepared size, weight, module life, and the number of approved modules as the attribute regarding the product, and also prepared size, weight, weight resistance, material, life, possible part removal direction, amount of heat generation, heat resistance, optical occurrence, light resistance, ventilation, electrification, and resistance electric characteristic as the attribute regarding each entities. Attributes regarding heat, light, ventilation and electricity are optional item, and used by positive/negative or several grade evaluation according to the designer's need. Size, weight, and weight resistance uses qualitative and/or relative gradual indication because usually quantitative value is not decided at early stage of design. When there are decisive, the material, life, and possible part removal direction indicate because there are important items in regard to product life cycle. These attributes are utilized as a condition for deciding the arrangement of the entities, and also utilized as the considerable information in "synthesis to modular structure", and "verification of modular structure" steps.

After setting attribute to the individual entities, connection and arrangement relationship between the entities are considered. With connection relationship, the designer can describe indication of modularity; those are modularization, unification, not modularize, or not unify. Because this description shows designer's intention about modularity, this is handled preferentially in "synthesis to modular structure" step.

Arrangement relationship of the entities is derived from restriction that accompanies element function and arrangement pattern based on behaviour flow. Some aspects of geometrical form can be derived from required functions [10, 11]. Therefore, the combination data related to each function and their arrangement are provided to the designer. An example of relationship between function and arrangement is shown in Table 1. This table shows the relationship between two parts. Number of module displays the presence of existence of the other parts which becomes the same arrangement relations as the target part. Face relation displays evaluation value of the status of contact face. Arrangement shows the face where is possible to arrange the target part. Contact ratio indicates the contact ratio of the surface which excludes the arrangement face. These information are prepared in database, and the designer decides arrangement of parts under these restrictions. After arrangement of parts is decided, it is checked whether it does not conflict with qualitative attribute information.

Table 1. Relationship between function and arrangement

Function	Behaviour	Number of module	Conceptual Shape	Contact ratio	Face relation	Arrangement
Support	Pile up	-	Hexahedron	0		Upper
	Adjust	-	Hexahedron	0		Side, lower
	Support	-	Hexahedron	0		-
	Enclose	-	Hollow Hexahedron	-	-	-

2.5 Synthesis to modular structure

In this step, modularization is done by using the information which is obtained with previous three steps.

First, conversion of the behaviour flow structure which is the same function, and unification of connected/fixed function are done. "Conversion of the behaviour flow structure which is the same function" makes plural functional conceptual entities replaced to one when the target functions for a certain function exists plural in the behaviour flow directed graph and those target functions' functional types are same. On "unification of connected/fixed function" phase, a part that has connection/fixed function is unified the function that is connected before connected/fixed function in behaviour flow because these functions consist with the existence of target part. Through these phases, the number of function is decreased and as a result function structure can more simplified.

Then, in order to use decision criterion of modularization, the degrees of mutual relationship between functions are calculated. This value is weighted sum of value of each item which is used for evaluation. On this research, function pattern, function type, distance between functions, arrangement relations between function, type of the input/output which connects between functions, material, and life of an entity were adopted as evaluation items. Here, the item where method of giving the value is not decided such as function pattern or function type, the ratio which is modularized with the past design case is adopted as item value. The weight factors are decided by the designer. The guide that shows whether each item corresponds to purposes of product is prepared. The designer's intention becomes easy to reflect on weight factors by displaying the guide to the designer.

Modularization is done from following three viewpoints.

- The modularization/unification which is in accordance with the request of the designer.
- The modularization which is based on the degree of mutual relationship.
- The modularization which extracts identical function structure.

Since the designer's request has already described in "construction of conceptual parts" process, first viewpoint of modularization/unification is automatically done. In regard to second viewpoint, due to the degree of mutual relationship is calculated in advance, modularization is done automatically when the designer sets threshold. As a result, functions where the degree of mutual relationship is high are modularized. From last point of view, when more than two same functions structural groups exist in behaviour flow, the functions structural group is modularized. The module generated with this viewpoint is expected that it can utilize wide-ranging as a common module.

2.6 Verification of modular structure

The result of modularization, plural modules are proposed. In this step, propriety of the proposed modules is verified, and united plural modules or divided one module into two or more if necessary. For that purpose, four activities are provided. Those are:

- The suitable conversion which considers functional load.
- The suitable conversion which considers weight.
- The suitable conversion which considers the relationship of the face.
- Feedback to the previous process.

In "the suitable conversion which considers functional loads" activity, when a number of functions which is included in one module are too large, the module is divided. A number of functions can obtain by counting level 1 and level 2 functions. If more than two level 1 functions are contained in one module, or if a number of level 2 functions exceeds a number the designer set, module is divided. With module dividing, while keeping the connection relationship which the designer describes, it divides at the place where the degree of mutual relationship is low.

In "the suitable conversion which considers weight" activity, when the weight of a module exceeds a weight the designer sets, or when the weight of a module exceeds the resistance weight of another module which is arranged under it, the module is divided. In this case, in order to solve the problem of weight, it is necessary to modify the relationship of arrangement after the dividing. Rearrangement is done in order to satisfy the arrangement relationship between the conceptual entities. If appropriate arrangement relationship does not exist, retrial of module division or feedback to previous process is executed.

In "the suitable conversion which considers the relationship of the face" activity, the restriction regarding the surface is checked, and if restriction has not been satisfied, unifying modules or dividing module is executed. Procedure of module division is similar to the other case. When module unification is needed, aforementioned verification process and the restrictions regarding the face are considered at first, then, only when contradiction does not occur, target modules are united.

If adjustment of modular structure are not well in spite of these three suitable conversion activities are executed, the designer returns "construction of conceptual parts", "synthesis to modular structure", or "verification of modular structure" step and doing modularization again. Ahead of feedback is selected by the designer.

The modular design on the conceptual design stage is executed by doing the steps above.

3 SUPPORTING MOLULAR DESIGN SYSTEM

3.1 Architecture of the system

The pilot system which realizes supporting the modular design process proposed above was developed. The architecture of the system is shown in Figure 4.

The module generation database has stored the several kinds of data such as element function template and the data regarding the relationship of arrangement, those becomes necessary for constructing function tree, behaviour flow, conceptual entities, and modularization. The modular information management system pulls out various kinds of information from this database in order to provide various kinds of template and/or initial setting of relationship of arrangement to the designer.

The modular product database has stored data regarding the product such as function tree, behaviour flow, information regarding entities, nodular structure, etc. These data are bound in every product in order to be able to utilize as the design case. Though current design data is also recorded into this database, it is distinguished from data of the design case, and is handled in the current product folder. After finishing the design, information of the current design is stored in the design case folder.

The modular information management system connects two databases and the designer, and handles the both database.
Figure 5 displays examples of proposed five steps.

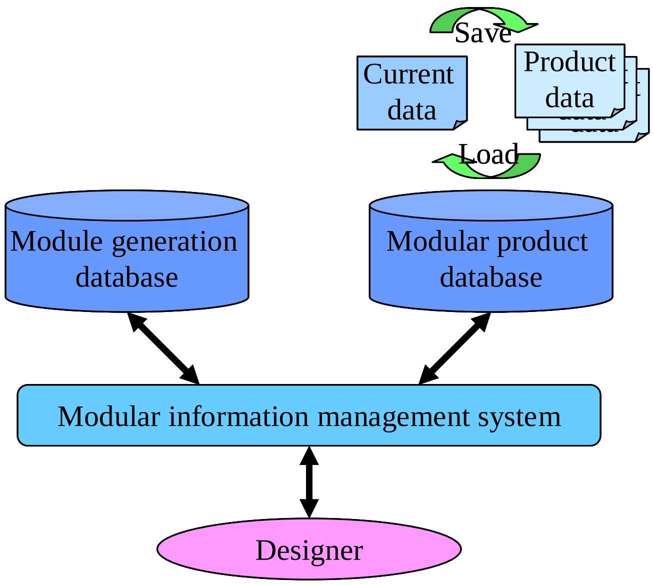

Figure 4. The architecture of the system

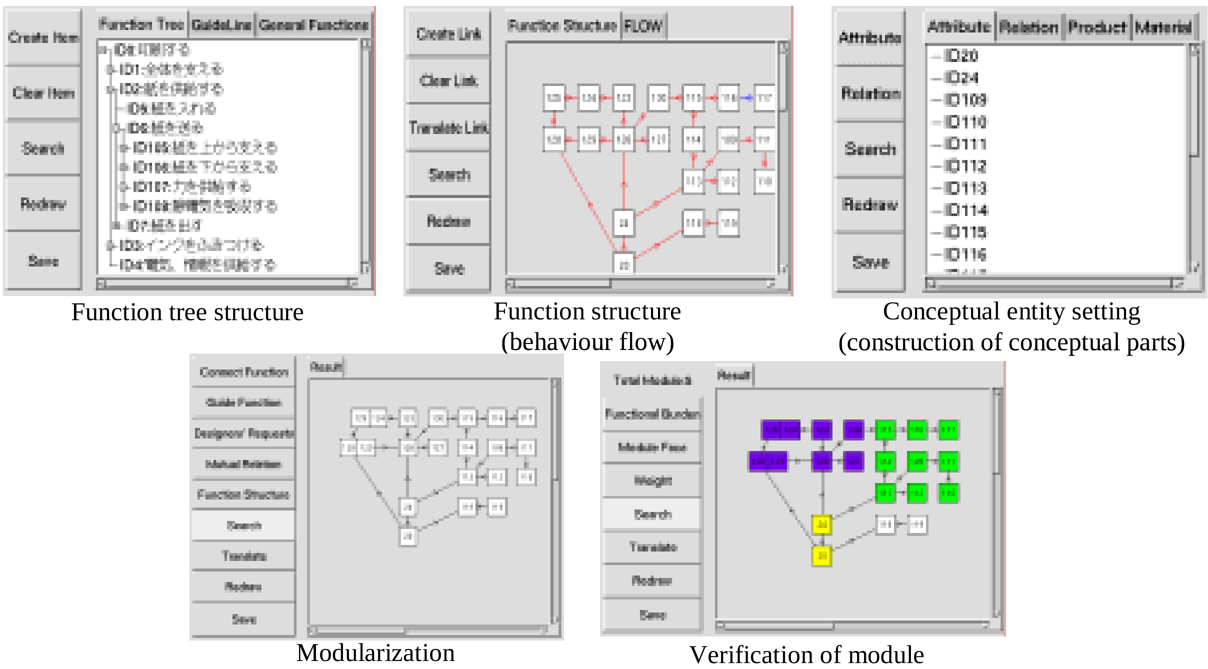

Figure 5. Snapshot of the system

3.2 Case study

Using the developed pilot system, the conceptual modular design of the ink jet printer was executed and compared with the actual product.
Figure 6 shows an example of the modularization processes. On this case, first, when the designer selects the degree of mutual relationship for modularization method, the system pop up the windows those support the designer to setting the strength degree of mutual relationship, weight factors of importance for current modularization, and threshold value to be same module. The system

automatically set average value of the past design cases as initial value. The system also displays guideline of setting weight factors. The designer can modifies the value of degrees of mutual relationship and weight factor of each item if he/she wants. Then when the designer sets threshold and push “OK” button, the system presents the module plan which is distinguished with colour.

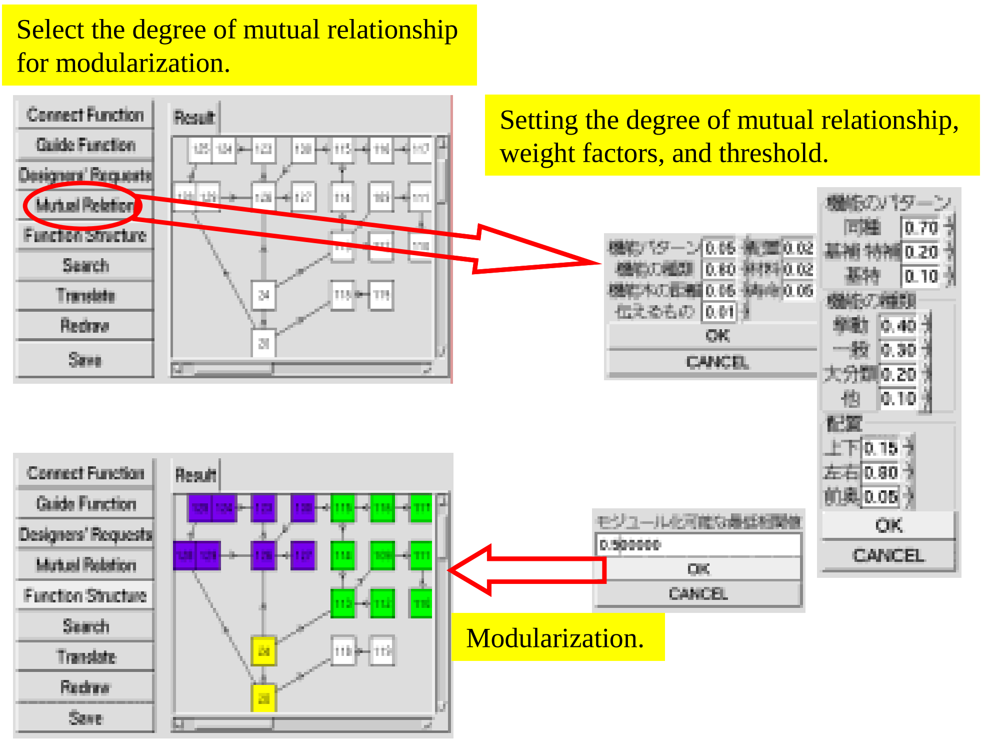

Figure 6. Case study (modularization step)

Figure 7 shows an example of verification of modular structure processes. In this case, when the designer selects the suitable conversion which considers the relationship of the face, the system checks the restriction regarding the surfaces of all entities and displays the candidates of unifying modules/entities or dividing module. This time, the system suggests one candidate group (ID118 and ID119) both of those on the same face of ID20 can be modularized/unified. The designer can get detailed information of each entity from the system. On this example, the designer found that ID118 and ID119 are connecting directly on behaviour flow and their parent function is same (Level 1: supplying sheet - Level 2: forwarding sheet – Level 2: eliminate static electricity). When the designer decide to adopt the system’s suggestion and push “OK” button, the system revises modular plan and displays the result of the revision.

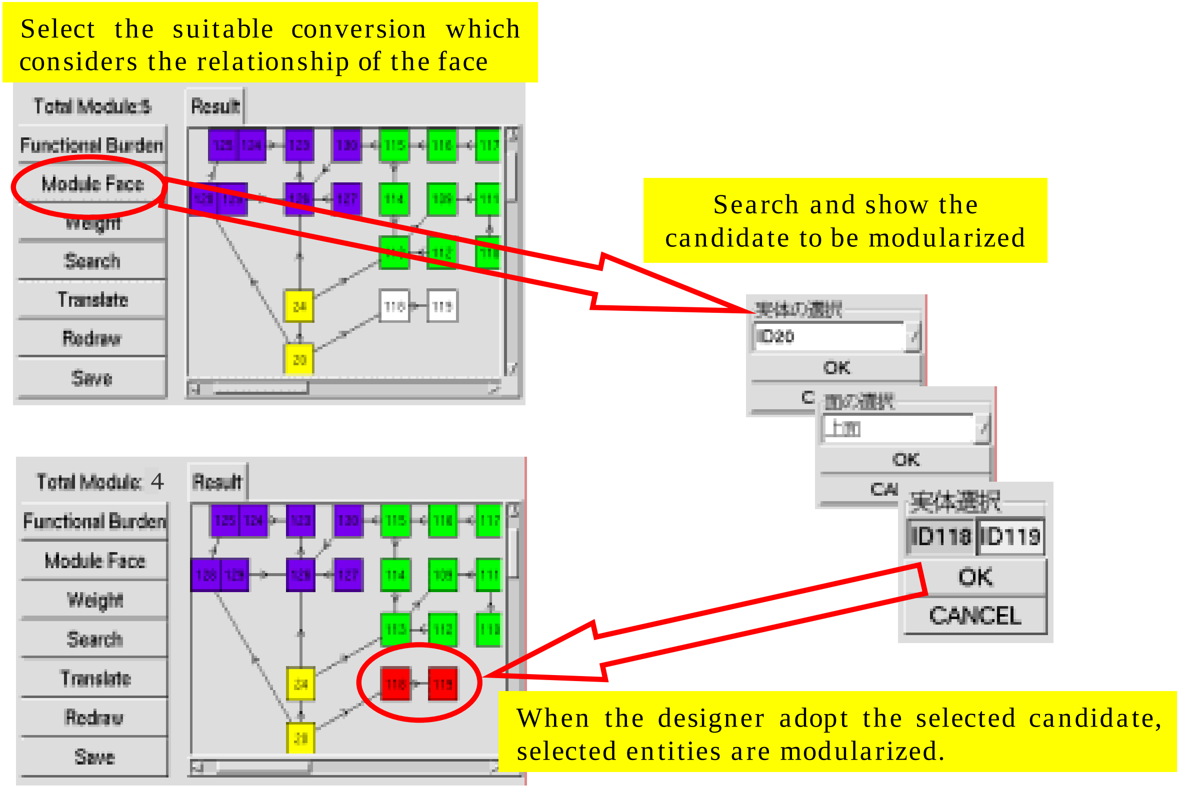

Figure 7. Case study (verification and revision step)

Table 2 shows the number of modules classified by level 1 function. As a result, we found that the modular structure that supporting modular design system derived have been almost similar to the modular structure of actual product. We also found that the modularization result which the system derives have divided a packaged module where many functions are contained with the actual product. This is because the suitable conversion which considers functional load was executed on the verification process. This shows that it is possible to adjust modular structure to the requirement of the designer by modifying the threshold of suitable conversion condition.

Table 2. Comparison with actual modular product (ink jet printer)

Level 1 function	Derived by the system	Actual modular product
Supporting (body)	4	4
Sheet providing	7	8
Ink jet printing	5	3
Electric power providing	6	6

4 CONCLUSION

Conceptual modular design support method by using qualitative information such as functional information and relations among conceptual entities was constructed. We proposed modular design process in the conceptual design as five steps; those are “description of function tree structure”, “behaviour flow according to functional aspect”, “construction of conceptual parts”, “synthesis to modular structure”, and “verification for modular structure”. This method realizes the modular design considering with the structure and attribute of the product at the early stage of design. The result of the case study using the developed system was shown similar to the actual modular design. From these results, it was shown that the proposed model has a feasibility to be an effective method for supporting modular design on the conceptual design stage.

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