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Consistency of the Measure of Modularity for Disassembly Evaluation of Industrial Products

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Improved measures of modularity developed recently for re-designing the module structures are shown. The main point is to keep the consistency of the measure. The latest version is adaptable to the various combinations of components. When new model of product is planned by mechanical design of today, the quantitative assessment of design is very important. The measure of modularity provides us the quantitative indicator to improve their design for keeping good environment by reducing of materials, reusing of used parts and recycling of resources. The calculation of measure is based upon the state of common properties among product components taking numerical weight factors into account. Their common properties can be selected flexibly depending on social demands as well as maker or user demands. The application study to a coffee drip maker has been demonstrated.

Key Words : Mechanical Design, Modular Structure, Measure of Modularity, Disassembly, Reuse,

1. Introduction

Measure of modularity is a useful index of improvement on the way of mechanical design for environmental conscious industrial production. The circulatory society demands the new technologies promoting highly re-usable product design. From the mechanical design point of view, their novel solution respect to the re-usable design is achieved by introduction of the measure of modularity.

The modular structure made up by several mechanical parts, can be handled simply as well as one part in a various kind of production process, i.e. the development of the modular structure is equivalent to the reduction of parts in effect. The effective reduction by the modular structure enables us to have a key solution to build the circulatory society.

Many workers have proposed some modular design concepts based on various viewpoints. The literatures [1] [2] [3], refered the variety of methodologies and limited quantification trials. They showed, however, insufficient information for quantitative studies in practical applications to modular designs. Rational quantification is very difficult in the study because of the diversity of user's sense of value. Survey on the special topic on "measure of modularity" shows a few references. The author has already opened the original idea of measure of modularity to the public [4] [5] [6], and modular structures have been deduced by making use of the design structure matrix to conduct the parts depending on their attributes and functions.

This report shows the latest results on the re-definition of the measure of modularity to have their consistency in practice inspecting various combinations of mechanical parts based on the study that have been performed for last two years by Kato, G. et. al. [7]. Especially, the reference [7] focused on the discussion to get reasonable relation between the value of the measure of modularity and the amount of laborious handling works of disassembly process.

Design of modular structure is dependent on the attributes of mechanical parts composed of the module. The attributes are, for example, function of the parts, kinds of materials, type of mechanical connections, method of post-processing to be expected, level of toxicity, commercial value of the parts, and so forth.

When a very precious reusable module has been plugged in a product, some suitable geometrical design will enable us to take it out without any difficult through some consideration of spatial relations among modular structures. Then, the problem of disassembling a product or extracting a specific part, is the problem of relational settings taking into account the attributes of composed parts. When all the components of a module are same material, there is no need further to disassemble the module for recycling. Our goal is developing the systematic method how to optimize the modular structure in order to be disassembled with the least cost depending on the purpose of post-procession for reuse or recycling.

2. How to make modular structures

The modular structure of every industrial product should works properly without any hindrance in accordance with the product's purpose. Then the first point taking into account is the parts arrangement. The arrangement can be realized under some geometrical restriction in mechanical design practice.

Let's S stands for the set of some constituent parts, $\{x_1, x_2, \cdots, x_m\}$, and the identity among the parts is expressed as $(x_i \sim x_j)_k$ when both the parts x_i and x_j have same attribute value respect to the attribute k. Further, let's $V_k(x)$ stands for partial set of parts belonging to the attribute k. For example, $(x_i \sim x_j)_{mat}$ shows that the material of x_i and x_j are identical, and $V_{mat}(x)$ shows the set of same material parts. The multiple intersections of sets:

$$v_n(x) = V_i(x) \cap V_j(x) \cap V_k(x) \cap \cdots \qquad (1)$$

yields a candidate set for a modular structure. Let's call the candidate set "cluster." It is possible to yield such the cluster from various attribute viewpoints. The available clusters can be selected for modules by making use of Design Structure Matrix (DSM), See Figure 1. Letters A, B, C⋯. in the top row and the left column are the names of parts. Each entry shows coincidence level of the attribute of the pair of parts. If the attributes are perfectly same, then the entry is set 1. Otherwise, the entry is set 2, 3 or 4, depending on the level difference. And rearrangement of rows or columns of the matrix yields some block matrices of all the entries 1 on the diagonal of the DSM as shown the Figure 1. The set of mechanical parts corresponding to the block matrix having entries set 1 is the candidate for a module structure.

3. The Measure of modularity of the First Kind

The cluster is divided to small sets, if necessary, and defined as a module of the product, because the module has to play its role according as some functional requirements of products. Then the clusters are redefined and expressed again by $v_n(x)$. The compatibility rate m_p is introduced as:

$$m_p = \frac{|v_i(x) \cap v_j(x)|}{|v_i(x) \cup v_j(x)|} \quad ; \quad p = 1, 2, \cdots, N \qquad (2)$$

in which the symbol | | shows number of parts belonging to the set of intersection or the union, and p is the serial number on a re-defined cluster. The measure of modularity of the first kind is defined as:

$$M_1 = \frac{\sum_{p=1}^{N} m_p w_p}{\text{Total number of attributes introduced for all parts}} \qquad (3)$$

in which w_p is the empirical weight parameter special to a kind of product. The parameters will be able to be held as important data by makers so as to keep the makers special to the original products. For example, commercial value and toxicity of parts, if necessary, should be reflected on the design as an important factor. The measure of modularity is mainly related to the ratio of number of realized modules to number of common attributes among the component parts and realized modules. The definition M_1 by Eq. (3) is the improvement of the previous definition [5] replacing with the denominator. The previous version of M_1 was defined by the different denominator of "Total number of modules of a product; n."

$$M_1 = \frac{1}{n} \sum_{p=1}^{n} m_p w_p \quad , \quad w_p = 1 \qquad (4)$$

	A	B	C	D	E	⋯
A	1	1	3	4	4	⋯
B	1	1	3	4	4	⋯
C	3	3	1	1	4	⋯
D	4	4	1	1	4	⋯
E	4	4	4	4	1	⋯
⋯	⋯	⋯	⋯	⋯	⋯	⋯

Figure 1 Design Structure Matrix (DSM)

4. The measure of modularity of the second kind

The second kind is mainly related to the spatial layout of the modules and the joint strength among the modules or parts. That is

$$M_2 = \frac{1}{J_p - J_m} \times \frac{\sum_{i=1}^{n} w_i}{n} \qquad (5)$$

J_p : Sum of the joint indices whole of the product
J_m : Sum of the joint indices inside of all the modules
n : Number of the modules

This is the improvement of previous version [5]:

$$M_2 = \frac{J_m}{J_p} \qquad (6)$$

The joint indices between connected parts should be given by the experimental results [7]. For example, the indices 1, 2, 5, 15 are appropriated respectively for a screw driven by electric motor, a screw driven by hand, spotted glue, and welding. Weight w_i is the parameter depending on size, mass, or shape of parts.

5. The measure of modularity of the third kind

Cost of the disassembly will be dependent much by the method of handling. It sometimes needs to rotate the product to detach the parts. Depending on the joint type and parts location, bad design enforces us to do extra works. In addition, it sometimes demands us special and skillful techniques in the phase of disassembly process. But such the laborious handling is avoidable to predict by the measure of modularity of the third kind M_3. The measure is mainly related to the disassembly handling at the site. The definition is

$$M_3 = 1 - \frac{\text{Number of rotation or replacement of product}}{\text{Number of joint to be released}} \qquad (7)$$

The measure of modularity of the third kind is new one originally presented by Kano et.al.[8], Finally, the measure of modularity to a product is calculated by the equation:

$$M = \alpha M_1 + \beta M_2 + \gamma M_3 \, , \quad \alpha + \beta + \gamma = 1 \qquad (8)$$

in which the empirical weight parameters α, β, γ are all the positive, and will be given by makers depending on their products.

6. Example of application to coffee maker and the re-design

Figure 2 Coffee drip maker checked by the measure of modularity

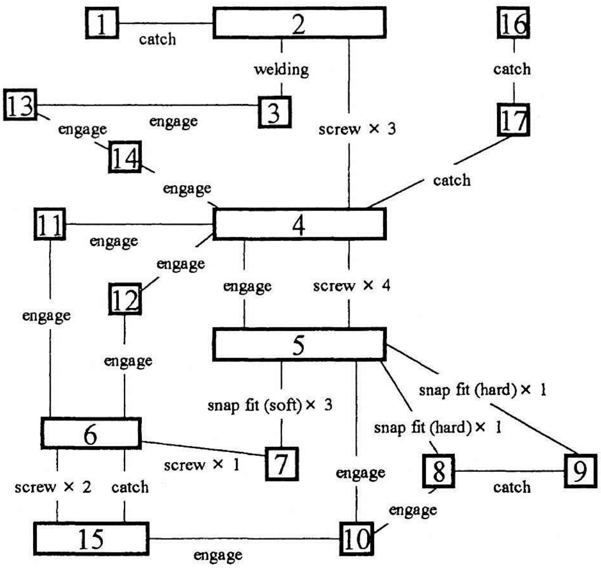

Figure 3 Assembly arrangement of the coffee maker

No.	1	2	3	4	16	17	5	9	6	7	8	10	11	12	13	14	15
1		1															
2	1		2	3													
3		2													1		
4		3				1	5						1	1		1	
16						1											
17				1	1												
5				5				5		3	5	1					
9							5				1						
6										1			1	1			3
7							3		1								
8							5	1				1					
10							1				1						1
11				1					1								
12				1					1								
13			1													1	
14				1											1		
15									3			1					

Figure 4 Design structure matrix for the inspection.

Table 1. Attributes of seven-teen assembly parts of the coffee drip maker

No.	Assembly	Material	Post life intent
1	Top Cover 1	Polycarbonate	Thermal Recycle
2	Top Cover 2	Polycarbonate	Thermal Recycle
3	Pump Stopper	PD	Thermal Recycle
4	Body	Polypropylene	Material Recycle
5	Under Body	Polypropylene	Material Recycle
6	Hot Plate Assy	Mix	Reuse
7	Bottom	Steel	Material Recycle
8	Cord	Mix	Dispose
9	Cord Sub Assy	Polypropylene	Material Recycle
10	Switch	Mix	Reuse
11	Tube 1	Rubber	Thermal Recycle
12	Tube 2	Rubber	Thermal Recycle
13	Pomp	PD	Thermal Recycle
14	Pomp Tube	Rubber	Thermal Recycle
15	Sensor/Controller	Mix	Dispose
16	Upper Drip Housing	Polypropylene	Material Recycle
17	Lower Drip Housing	Polypropylene	Material Recycle

Table 2 Intersection of the cluster of the coffee maker

	Polypropylene 4,5,9,16,17	Polycarbonate 1,2	PD 3,13	Mix 6,8,10, 15	Steel 7	Rubber 11,12,14
Material Recycle 4,5,7,9,16,17	5/6	0	0	0	1/6	0
Thermal Recycle 1,2,3,11,12,13,14	0	2/7	2/7	0	0	3/7
Reuse 6,10	0	0	0	2/4	0	0
Dispose 8,15	0	0	0	2/4	0	0

Table 3 Attributes of the four-teen assemblies improved

No.	Assembly	Material	Post life intent
1	Top Cover 1	Polycarbonate	Thermal Recycle
2	Top Cover 2	Polycarbonate	Thermal Recycle
3	Pump Stopper	Rubber	Thermal Recycle
4	Body	Polycarbonate	Thermal Recycle
5	Under Body	Polycarbonate	Thermal Recycle
6	Hot Plate Assy	Mix	Reuse
7	Bottom	Polycarbonate	Thermal Recycle
8	Cord	Mix	Dispose
9	Switch	Mix	Reuse
10	Tube 1	Rubber	Thermal Recycle
11	Tube 2	Rubber	Thermal Recycle
12	Pomp	Rubber	Thermal Recycle
13	Sensor/Controller	Mix	Dispose
14	Drip Housing	Polycarbonate	Thermal Recycle

Table 4 Intersection of the improved coffee maker clusters

	Polycarbonate 1,2,4,5,7,14	Mix 6,8,9,13	Rubber 3,10,11,12
Thermal Recycle 1,2,3,4,5,7,10,11,12,14	6/10	0	4/10
Reuse 6,9	0	2/4	0
Dispose 8,13	0	2/4	0

The calculation is carried out providing that the parameters of weight w_p are set even. Rotation of the light weight coffee drip maker is very easy then the calculation weight γ is set 0. α and β are set 0.5. Using the data on assembly parts shown Table 1 and the structure shown in Figure 2, we have the results:

$$M_1=\frac{3}{24}=0.125 \tag{9}$$

$$M_2=\frac{1}{41-8}=0.0303 \tag{10}$$

$$M=0.5\times(0.125+0.0303)=0.0777 \tag{11}$$

Trial re-design of the coffee maker is made as the change of attributes and the re-arrangement as shown respectively in Table 3 and Figure 5. Then, the intersection and the DSM are re-developed as Table 4 and Figure 6, instead of Table 2 and Figure 4. The measures calculated are as follows:

$$M_1=\frac{3}{9}=0.333 \tag{12}$$

$$M_2=\frac{1}{30-3}=0.037 \tag{13}$$

Both the measures increase due to change the attributes and the re-arrangements of the parts. The improvement of M_1 is mainly dependent on the number of material variation and the parts. Meanwhile, the improvement of second kind M_2 is mainly dependent on the strength of joints. M_2 has small reflections by the re-design, because, the trial re-design was mainly the change of attributes of parts. If the joint strength and number of joint to be released were reduced, M_2 would be increased. The normalized value of M_j is positive, and it commonly takes the value between 0 and 1. Relative difference between the values of old and new designs of products, informs us about important clues how to improve the design for environmental oriented products. The higher value of M_j is recommended.

7. Conclusions

The paper shows quantitative method of the measure of modularity by introducing empirical weights. Evaluation of the modularity of products in the conceptual design process, is generally very important for planning the treatment at the end of product life. However, the quantitative study is on the way of development. Up to the present, there are no integrated quantitative evaluation methods, because the methods as a decision making tool are not widely amenable to the various sense of value. The sense is ordinary different depending on viewpoints of various product makers, various users, various designers, and so forth. Consequently, the convenient way to realize is the specialization of the method to an individual product at hand. Rational quantitative treatise is then possible by introducing weight numerical factors in each the required positions indicated by the expressions for the measures of modularity. Empirical knowledge on the factors and data, accumulated in the course of developing industrial product, will become original property of the manufacturer. The other manufacturers could not make the imitation without the empirical knowledge. That is the biggest profit of the specialized methods.

Such the practical way fosters the empirical quantitative method based on the modular design concept. The practice of quantitative estimations along with the expressions of M_1, M_2, M_3, makes the modular oriented design easy. M_1, M_2, M_3 are related respectively to the attributes of parts, the joint of the parts, and the handling of disassembly. Their definitions have been improved for their consistency in order to make them available for wide combinations of component parts in practice.

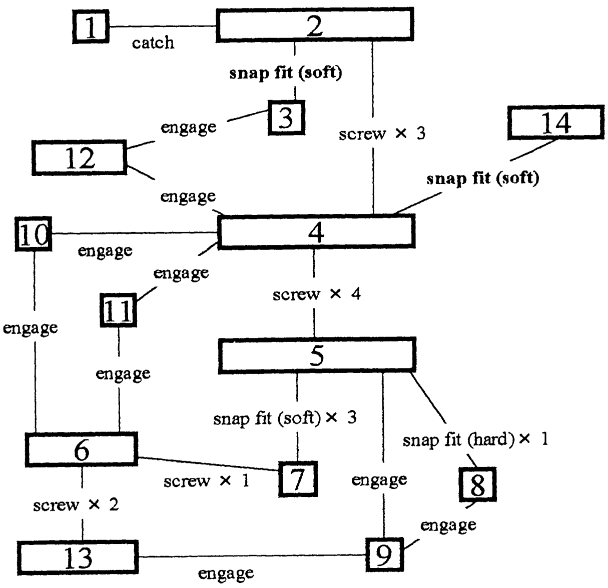

Figure 5 Assembly arrangement of the improved coffee maker

No.	1	2	3	12	4	14	5	6	7	8	9	10	11	13
1		1												
2	1		1		3									
3		1		1										
12			1		1									1
4		3		1		1	4						1	
14					1									
5					4				3	5	1			
6									1			1	1	2
7							3	1						
8							5				1			
9							1			1				1
10								1						
11					1			1						
13				1				2			1			

Figure 6 DSM of the improved coffee maker

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