Design of Product Modularity for Life Cycle Management

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Abstract

A methodology to develop product modular structures that enhances life cycle management without reducing product variations of family products is proposed. Possible improvements and constraints of life cycle management of products that have modular structures are discussed. Modular structures of air conditioning units for automobiles are examined according to expected life cycle scenarios. Well-designed modular structures could improve life cycle management procedures such as reuse and make recycling operations more efficient.

1. Introduction

1.1. Module

Development of product modular structures is often discussed for reducing cost in assembly and management of product families. From a viewpoint of manufacturing, it is inefficient to have multiple types of products with minor differences. Modular structures are used to reorganize product family. Sharing common modules in a product family can make production more efficient.

In addition, products with modular structures could be more suitable for life cycle management than without them. Upgrade and maintenance are executed much easily if products are modularized functionally. Standardized modules with well designed interfaces will be reused as long as their quality is guaranteed.

As stated above, module itself has different meanings and objectives. In this study, product modular structure for life cycle management is discussed and a method for modularization is proposed. Module is referred as collection of components, and modularization is defined as a process that creates a modular structure by combining or dividing components that build up a product system. Although the modularization method proposed here uses product family management as a part of its steps, the main objective is to improve life cycle management.

1.2. Life Cycle Management

According to Gu et al., modular design can achieve the following life cycle objectives; 1) dividing design task for parallel development, 2) production and assembly improvement, 3) standardization, 4) services, 5) upgrading, 6) Reconfiguration, 7) recycling, reuse and disposal and 8) product variety and customization [3]. Ideally those objectives are achieved simultaneously, but there are many constraints in reality as they mention.

In this study life cycle management is defined as a process that maximizes functionality and performance of a target product, improves the efficiencies of energy and material consumption, and minimizes environmental impacts. The processes of life cycle management consist of service related operations, such as maintenance and upgrade, and inverse processes such as collection and recycling.

Life cycle management of family products with sharing modules has some advantages. Common modules increase the chances for reuse and simplify procedures for maintenance. However, those advantages cannot be expected when product family does not have shared modules.

Many researches have been done for product modularity, and design guidelines of modular structure have been proposed for better life cycle management. From a viewpoint of life cycle design, the following guidelines are reasonable ; 1) Do not combine components made from different materials. 2) Do not combine components that have different physical life. 3) Do not combine components that have different intervals for maintenance and upgrade. There can be more guidelines. If those guidelines are satisfied completely, many life cycle management options are available for the product. However, it is not possible to suffice all of them simultaneously in reality and it is not

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necessary. The important point is to follow the guideline that will fit the expected life cycle scenario.

2. Problem Definition

The objective is to produce substitutive modular structures that can achieve life cycle management, which fits life cycle scenario, by estimating cost and environmental impacts due to usage and life cycle management processes. Possible options of life cycle management and flexibilities of the modularization should be different according to the level of design completion and the way design process is executed. Also the options are affected whether the target has product family or not. To know improvements in life cycle management by modularization, products with some variants are targeted here.

Expected design conditions are as follows.

- Physical structure has been selected from candidates.
- Major components required for desired functionality is selected from a component catalog. Properties of a component that is on the catalog are known.
- Major components are not divided in modularization processes.

3. Modeling Product Structures

3.1. Objects and Functional Relations

A product, whose components have been already selected, is modeled with a graph structure for examining suitable modular structures. A product is modeled as a collection of modules, components and relations among them. A module is a collection of components, and components are physically connected in a module in general.

Functional relations among components are expressed with exchange of either or combinations of energy, signal and substances. If the exchange is important for achieving target function and performance, the relation is considered as strong. This information is important for deciding modular structures.

3.2. Functional Dependency Graphs

A relation graph, where nodes are objects and edges are relations, is created for every specification when the different components are used. This graph represents functionally important relations and used for deciding modular structures.

3.3. Other Constraints

In addition to functional dependency graphs, other constraints for manufacturing and assembly are noted. Those constraints could be suppliers of components and standardized interfaces.

4. Modularization Procedures

The process of modularization consists of two parts. In the first stage modularization for a common platform is aimed at. Functional relation graph and constraint information are used to obtain common modules or common platforms. In the second stage modularization to achieve correspondences of life cycle management among components is executed.

4.1. Combining and Dividing Components for Organizing Product Family

Functional dependency graph, which consists of components and relations and represented in a graph structure, is constructed for each type of product variants according to the procedures explained in section 3.2.

Functional dependency graphs are piled up to find possibilities to combine components, and the obtained graph is referred as a functional dependency model hereafter. According to the importance of types of relations and the amount of production of each specification, weights of the links in the functional dependency model are assigned to the links in the functional dependency model. With regard to the amount of production, when A-B-C appears in a certain specification and 5 units are expected, and A-B appears in another specification and 10 units are expected, the weight of the link between A and B are set 15, and link B and C is 5. The weight of the link is called bonding index and expressed as B_i, where i indicates the identification number of a link. The bonding index is calculated considering the importance of relation types, expected amount of production, and standard components and interfaces.

Then the designer is expected to define component sharing index L. The index is used to decide whether the components connected with a link is combined [1]. Components are combined when $|B_i - B_j| \leq L$, where link i and j are in the module ($i \neq j$), otherwise components are not combined as a module. In general, when the value of L is larg, more components are combined into a module.

In addition to the linked components, possible combinations between unlinked components and possible partitioning of objects are tested, and new structures are created. Standard modular structure such as component sharing modularity and component swapping modularity [2] is considered.

The modular structures obtained so far are clustered with functional relations and the expected amount of production. Created modules are commonly shared or replaceable according to specifications. Replaceable modules usually characterize variants.

4.2. Modification for Life Cycle Management

Modular structures obtained from the previous operations are modified to achieve correspondent features of life cycle management. The index by Newcomb is employed [4] and slightly modified for this step. The features of components selected for representing life cycle management are treatment for end of life stage (R_1), material attribute for recycling (R_2), physical life (R_3), and functional life (R_4).

For every index i ($i = 1,\ldots,4$), $R_i(j,k)$ is defined as 1 if the component j and k ($j \neq k$) have the same attribute, otherwise set to 0. When a module M contains n components, the correspondence ratio of the module $CR(M)$ is calculated as

$$CR(M) = \frac{\sum_{i=1}^{4}\{w_i \sum_{j,k\in M, j\neq k} R_i(j,k)\}}{n(n-1)/2},$$

where w_i is the weight for the ith index and defined to satisfy $\sum w_i = 1$ and $w_i \geq 0$. Correspondence ratio of the product CR is calculated as the average of all $CR(M)$. Modifications that make CR larger will bring modular structure where each module is independent in the sense of life cycle operations. To obtain larger CR, the sizes of the modules become smaller and the number of modules become larger.

With regards to life cycle operation such as maintenance and upgrade by replacing modules, modules should be physically independent from other modules. Cluster independence index CI is introduced to deal with this metric. CI is calculated as the average of $CI(M)$, where

$$CI(M) = \frac{\text{Number of links inside } M}{\text{Number of links related to } M}.$$

The larger CI means that the product contains more modules, and that those modules are physically independent from others.

Modular structure is modified to make CR and CI larger. It is not an easy task to increase both CR and CI simultaneously. To compromise this, CR and CI are combined with weighting parameter a ($0 \leq a \leq 1$).

$$Obj = a \cdot CR + (1-a) \cdot CI$$

Larger a directs the modules clustered with the same life cycle attributes, and smaller a aims at easy handling of modules that are physically independent. Modular structures that have larger Obj are generated by recombining and dividing modules.

4.3. Life Cycle Management of Modularized Products

Modular structures, aiming at sharing common components and modified from the viewpoint of life cycle attributes and physical separation, are obtained by arranging modularity adjustment parameters. However, with regard to life cycle management, it is not clear whether the derived modular structures are adapted to the expected life cycle scenario although parameters are decided to achieve the targeted properties. The derived modular structures are evaluated following the expected life cycle scenarios.

It might not be possible to derive an ideal modular structure that fits the life cycle scenario. In that case, life cycle scenario or life cycle design would be modified to achieve a better solution as a whole.

5. Example

The proposed approach is applied to air conditioning unit of automobiles. Though there are different types of air conditioning units adapted to the specification, the differences are small when the automobiles to which they are installed are similar. Specific components are required to satisfy the demand and to be installed in the target automobiles. Standard types of components are also widely used in the development.

The target air conditioning unit, especially HVAC unit, contains a case, heater core, evaporator, an expanding valve, doors, links, servo motors, levers and some hoses and pipes. There are some constraints in the shape of cases and piping for installation, so those components have some variations adapted to the specifications. For heater cores and other major components, standard components are used if the difference in required capacities of those components is small.

Major components in a HVAC unit, which includes heater, ventilator and air conditioner, are shown in Figure 1. 9 types of HVAC units are required according to the combinations of the platforms of automobiles, types of temperature control and the destinations. The amount of production of each type is different.

In addition to cost reduction in assembly, improvement of life cycle management is desired. It is expected that HVAC units are free from maintenance and sufficient reliability is usually achieved. Usually options in designing life cycle scenarios are limited to product family management and end-of-life treatments.

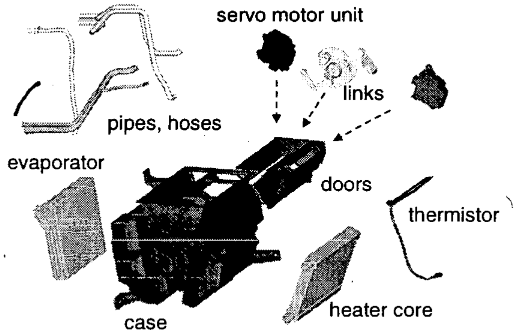

Figure 1. Components in a HVAC Unit

5.1. Design of Modular Structures

A functional dependency model is created by piling up 9 types of functional relation graphs. Figure 2 shows a simplified functional dependency model of HVAC.

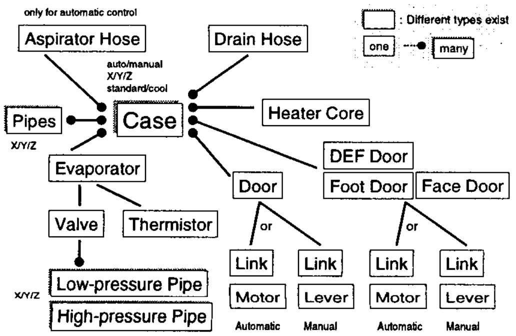

Figure 2. Functional Dependency Model

Then modularization adjustment parameters, L and a, are applied. A result of modularization with $L = 0, a = 0.2$ is shown in Figure 3. In this example, $L = 0$ is applied aiming at increasing component sharing in a family.

5.2. Life Cycle Management

According to the result, components dependent on specific types, such as pipings and a case, are separated and the main module that contains a heater core and an evaporator is shared. The parameter $a = 2$ aims at independence of modules. When reuse of a main module is planed, this modular structure may suffice if interfaces are designed properly. To perform material recycle, the parameter a should be larger. When the parameter a is set to 0.8 (still $L = 0$), the main module is not combined, which means the components should not be integrated as a unit. That is because the materials of the components are different. They should be assembled considering segregation process. However, if a recycling process that has crush and segregation without disassembly can be applied, the structure of $a = 0.2$ may fit.

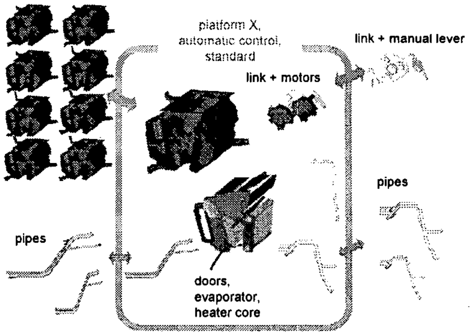

Figure 3. Modular Structure (L=0, a=0.2)

6. Conclusion

A procedure for product modular design, which can take both product family management and life cycle operations, is suggested. Modular design can be arranged by parameters, and a modular structure that fits the expected life cycle scenario is obtained.

The relation between modular structure and life cycle management is still ambiguous in this study even after modularization is completed. The effects of modularization on life cycle management should be estimated more clearly for designing life cycle and product modularity.

Acknowledgement

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References

[1] Andrew Kusiak, Chun-Che Huang. Development of modular products. *IEEE Transactions on Components, Packaging, and Manufacturing Technology — Part A*, 19(4):523–538, 1996.

[2] Karl Ulrich, Karen Tung. Fundamentals of product modularity. *DE-Vol. 39, Issues in Design Manufacture/Integration, ASME*, pages 73–79, 1991.

[3] P. Gu, S. Sosale. Product modularization for life cycle engineering. *Robotics and Computer Integrated Manufacturing*, 15(5):387–401, 1999.

[4] P. J. Newcomb, B. Bras, D. W. Rosen. Implications of modularity on product design for the life cycle. *Journal of Mechanical Design, Transactions of the ASME*, 120(3):483–491, 1998.