Product Modularization for Parts Reuse in Inverse Manufacturing

Fumihiko Kimura(1), Satoru Kato, Tomoyuki Hata and Takefumi Masuda
Department of Precision Machinery Engineering, The University of Tokyo
Tokyo, Japan

Abstract
For reducing environmental burden of industrial products, it is mandatory to rationalize product design and to achieve a closed loop product life cycle by use of comprehensive parts reuse and recycling. It is difficult to introduce parts reuse based on conventional product structure, and appropriate product modularization is necessary to efficiently manage a closed loop product life cycle. A new product modularization strategy is proposed across a family of products and successive generation of products, based on product functionality, product commonality and life cycle similarity. Car air-conditioners are examined for the validity of the proposed method.

Keywords: Product design, Module structure, Product life cycle

1 INTRODUCTION

For the future manufacturing technology development, environmentally conscious manufacturing is one of the most critical issues. The target is to reduce the environmental burden, such as resource consumption and disposal, while keeping the proper service level products can offer to customers[1,2].

It is difficult to achieve this target only by optimizing individual product design towards better resource consumption and recycling performance. To cope with this difficulty, it is effective to design the total product life cycle as a whole from product planning, throughout product design and manufacturing, to product usage, maintenance and reuse/recycling/disposal. A sound strategy for product maintenance and improvement during product usage should be established, and all the life cycle processes are to be well controlled. By such approach, reuse/recycling activities are also rationalized. A whole product life cycle can be made visible and controllable. We have called such approach as Inverse Manufacturing by stressing the controllability of reuse/recycling processes, where closed product life cycles, including maintenance, are pre-planned and controlled[3,4].

Aiming at developing the technological basis for Inverse Manufacturing, we have worked for the following research subjects. For reuse and recycling of used products/parts, it is mandatory to make proper quality assurance of used parts[5], and to check the reliability of products throughout the whole life cycle[6]. For determining the most appropriate life cycle, simulation of life cycle burden during product usage is very effective[7], and life cycle should be designed to be adapted to the required product usage modes[8]. It is one of the key issues for designing better life cycle, to effectively apply the concept of reuse rather than the conventional material recycling

The difficult problem is how to increase the ratio of parts reuse, and to reduce bulk material recycling. If used parts are properly reused, it is very effective in terms of reduction of raw material usage and manufacturing energy consumption. However there are many reasons which prevent to justify the parts reuse. For example, due to rapid technological progress, old parts can no longer be used for the next generation products. It may be very difficult and expensive to collect/clean/refurbish used parts, and to make fair quality assurance for them.

For better parts reuse, very different kinds of products and their life cycle concept are necessary. Such examples are seen in the case of a single-use camera, where mechanical units are completely reused for several times and across the successive product generations[9]. Copiers are another example. In this case, comprehensive copier take-back systems are constructed, and product modularization and parts standardization are realized in the product design[10].

With the above situation as background, the objective of this paper is to propose a new method for product structure modularization, and to show a new possibility for designing products with better reuse potential.

2 PRODUCT MODULARIZATION FOR REUSE

In order to increase the possibility of reuse after product usage, it is important to identify appropriate product modularization. Each module is considered as a unit of reuse. It may be a single part or an assembly of many parts with certain functionality. It is complicated how to decide the size and the contents of each module. Traditionally modularization has been determined by the following factors:

- standardization: commonality among products,
- functional independence,
- cost,
- ease of manufacturing,
- ease of maintenance, etc.

These factors may have conflicting effects for module decision. The new requirement of module reuse will add further complications. For the increase of reuse possibility, the following module characteristics are important:

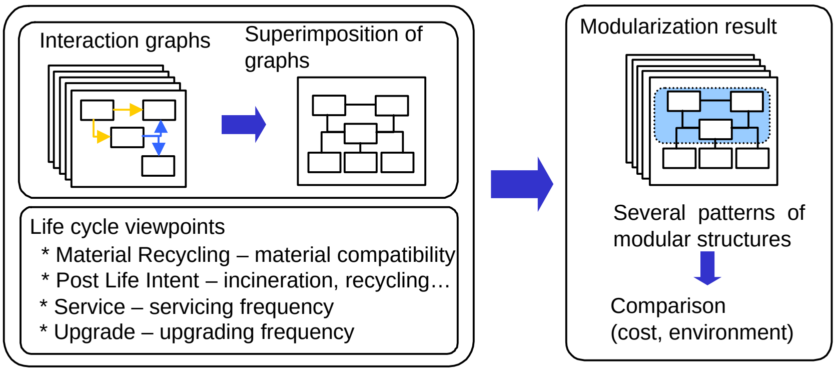

Figure 1: Modularization procedure.

- technological stability,
- functional up-gradability,
- long life,
- ease of quality assurance,
- ease of cleaning, repair, etc.

These new requirements may lead to a new modular structure that has been practically useless under the traditional modularization requirements, because it is too expensive without reuse. Such new modular structure will be a good basis for increasing the reuse opportunity. However it is cumbersome and not easy to enumerate such new modular structures under these new conditions, because human designers are often bounded by traditional thinking.

There are several research works concerning with product modularization, such as [11,12]. However moduralization for parts reuse, as described in the above context, has not been well investigated. Here we consider the above problem in the following way. Designers are given a set of old traditionally designed products. Designers' task is to improve the product modular structure with better reuse potential for the next-generation products. It is assumed that the products to be considered here are technically matured, and there are many past design examples. It will be a strong computer support for designers to enumerate all possible modular structures based on the past design examples by computer simulation under new modularisation criteria. Among those enumerated structures, expert designers can easily find out possible structures better for reuse.

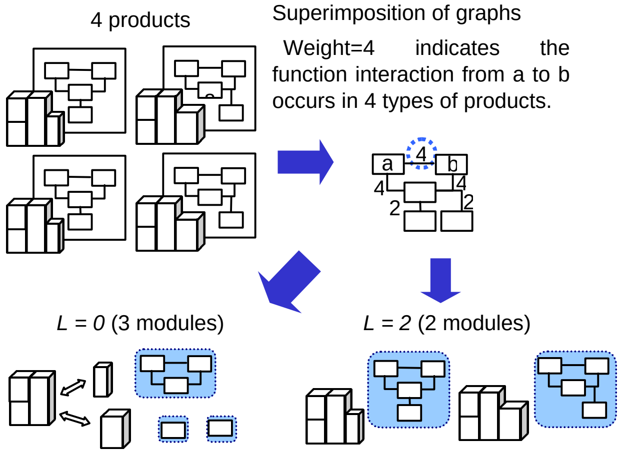

Figure 2: Commonality among products.

3 MODULARIZATION PROCEDURE

According to the candidate enumeration approach described in the previous section, a modularization procedure, as shown in Figure 1, is explained below. This procedure can be extended to include more modularization criteria.

3.1 Functional Dependency

As the first step of the procedure, based on the past design examples, modules and/or parts structure of target products are described by a graph structure. Nodes of graphs are modules/parts, and arcs are functional or other relations. Level of details of graph structure may depend on the design requirements. In the early design stages, it is necessary to identify only essential important functional components. After making such graph structures for many past products with similar functionality, these graph structures are superimposed with the identification of the same or similar nodes, as shown in Figure 2. Multiplicity of superimposition with respect to each arc is counted for the next step processing.

3.2 Commonality

Number of multiplicity of arcs are identified, as shown in an example of Figure 2. Number of multiplicity is called as weight. If difference of values of arc weight is within a specified parameter value L, nodes connected by those weighted arcs are combined as a module[13].

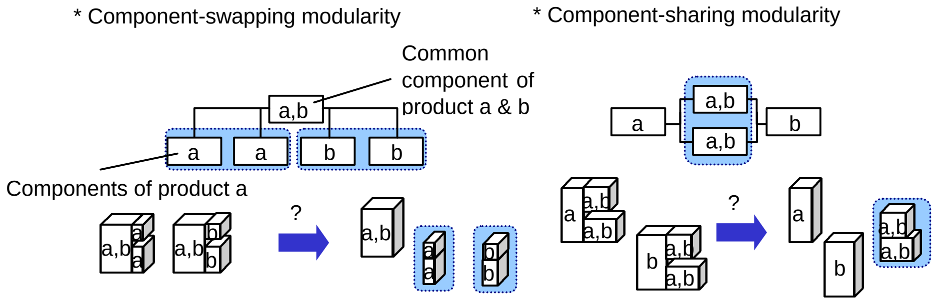

Figure 3: Component-swapping modularity and component-sharing modularity.

Different values of L give different module structures, as shown in Figure 2. Larger L value means less importance of structural commonality inside modules.

3.3 Types of Modules

As shown in Figure 3, two different types of modules are identified: component-swapping modularity and component-sharing modularity[14]. Component-swapping modularity means that several different swappable modules are connected with a common component to generate product variety. Component-sharing modularity means that various modules sharing the same basic component create different product variants. Based on this concept, swappable modules and/or shared modules are combined to constitute new modules.

3.4 Division of Modules

Modules with similar property can be combined by dividing different portions from the main parts, as shown in Figure 4. This process is performed for parts/module pairs with component-sharing modularity. Total number of modules is decreased by this operation. Steps 3.2, 3.3 and 3.4 are repeatedly applied to achieve a stable modular structure.

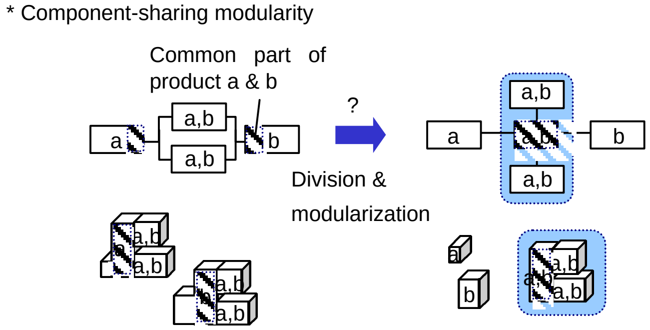

Figure 4: Division and modularization.

3.5 Life Cycle Consideration

For taking into account of life cycle characteristics, two factors CR(Correspondence Ratio) and CI(Cluster Independence) are introduced[15]. CR indicates life cycle characteristics. CR takes high value, if life cycle characteristics are same or similar among parts within a module. Life cycle characteristics include material property, end of life options, such as reuse/recycling/incineration, maintenance, and upgradability, etc. CI means ratio of strength of various relationships within a module compared with the strength of outside relationships. High CI value means strong relational independence of a module. By combining CR and CI values with weighting coefficients, appropriateness of modularity is evaluated.

4 MODULARIZATION EXAMPLE

For demonstrating the usefulness of the procedure described in section 3, an analysis example is shown. A product considered here is a car air-conditioner. Car air-conditioners are rather different according to their functionality, size, use-area, price, etc. As an example, here we took five air-conditioners of similar type for medium-size cars. They include automatic and manual control types, and standard and high-power specification. They roughly consists of 19 functional units(nodes), such as an evaporator, doors, a heater core, various pipes, motors, mechanical units and cases.

Based on the behaviour of air-conditioners, various relations among functional units are identified, such as power transmission, air/water/coolant flow, control information flow, etc. Corresponding to the five types of air-conditioners, functional units and their relations are represented as graph structures, as described in section 3.1. And these five graph structures are superimposed, as shown in Figure 5. Three dimensional models of major components are shown.

Lots of modularization experiments have been done with different L values and different assignment of life cycle characteristics. In this example, life cycle characteristics have been assigned fairly conservatively, because the example products are rather old. There have been generated many unique modularizations which have not been considered before due to traditional engineering constraints. Many of them are of course meaningless in normal engineering sense, but some of them may deserve serious investigation. Particularly if we put more focus on the commonality across different

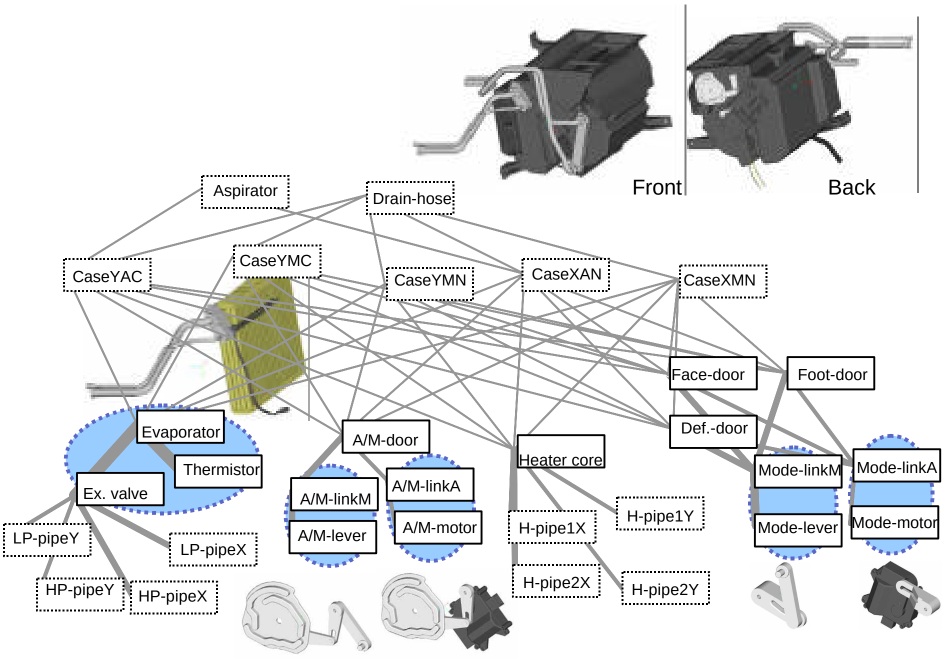

Figure 5: Air-conditioner example.

products and/or some of the life cycle characteristics, new modularization can be generated. One example is shown in Figure 6, where some of the functional units are modularized as larger modules than before. This result is a candidate for better reuse of components, and additional design work is necessary for final design decision.

5 CONCLUSION

A method for enumerating possible candidates of product modularisation towards better parts reuse is discussed. By giving appropriate conditions increasing the potential of reuse, new product modularisation structure could be generated for further elaboration by expert human designers.

A method can be extended to include various other conditions, and further experiments will be effective with increased product types and design examples.

6 ACKNOWLEDGMENTS

We extend our sincere thanks to Dr.M.Hanai and his staffs in Denso Co. for giving us the technical data about car air-conditioners. This research is partially supported by the Inverse Manufacturing Forum, Manufacturing Science and Technology Center.

7 REFERENCES

[1] Alting, L., Legarth, J.B., 1995, Life Cycle Engineering and Design, Annals of CIRP, 44/2:569-580.

[2] Westkaemper, E., Alting, L., Arndt, G., 2000, Life Cycle Management and Assessment: Approaches and Vision Towards Sustainable Manufacturing, Annals of CIRP, 49/2:501-522.

[3] Kimura, F., 1999, Life Cycle Design for Inverse Manufacturing, Proc. EcoDesign'99, IEEE, Tokyo, 995-999.

[4] Van Houten, F.J.A.M., Kimura, F., 2000, The Virtual Maintenance System: A Computer-based Support Tool for Robust Design, Product Monitoring, Fault Diagnosis and Maintenance Planning, Annals of CIRP, 49/1:91-94.

[5] Kimura, F., Hata, T., Suzuki, H., 1998, Product Quality Evaluation Based on Behaviour Simulation of Used Products, Annals of CIRP, 47/1:119-122.

[6] Hata, T., Kobayashi, N., Kimura, F., Suzuki, H., 2000, Representation of Functional Relations among Parts and its Application to Product Failure Reasoning, Proc. Int. CIRP Design Seminar, ed. Shpitalni, M., Haifa, 393-398.

[7] Hata, T., Kato, S., Sakamoto, H., Kimura, F., Suzuki, H., 2000, Product Life Cycle Simulation with Quality Model, Proc.7th CIRP Int. Seminar on Life Cycle Engineering, Tokyo, 60-67.

[8] Kimura, F., 2000, A Methodology for Design and Management of Product Life Cycle Adapted to Product Usage Modes, Proc. 33rd CIRP Int. Seminar on Manufacturing Systems, Stockholm, 139-142.

[9] Tanaka, H., 2000, Fully Automatic Inverse Factory for Re-Using Single-Use Cameras, Proc.7th CIRP Int. Seminar on Life Cycle Engineering, Tokyo, 256-257.

[10] Watanabe, T., 2000, Closed Loop Manufacturing System for Copiers Based on Parts/Module Reuse, Proc.7th CIRP Int. Seminar on Life Cycle Engineering, Tokyo, 258-263.

[11] Umeda, Y., Shimomura, Y., Yoshioka, M., Tomiyama, T., 2000, A Proposal of Design Methodology for Upgradability, Proc.7th CIRP Int. Seminar on Life Cycle Engineering, Tokyo, 90-97.

[12] Ishii, K., 1998, Modularity: A Key Concept in Product Life Cycle Engineering, Handbook of Life Cycle Engineering, ed. Molina, A. Kusiak, A. and Sanchez, J., Kluwer Academic Publishers, 511-531.

[13] Kusiak, A., Hung, C.-C., 1996, Development of Modular Products, IEEE Transactions on Components, Packaging, and Manufacturing Technology-Part A, 19/4:523-538.

[14] Ulrich, K., Tung, K., 1991, Fundamentals of Product Modularity, ASME Issues in Design Manufacture/Integration DE-39:73-79.

[15] Newcomb, P.J., Bras, B. Rosen, D.W., 1998, Implications of Modularity on Product Design for the Life Cycle, Journal of Mechanical Design, 120:483-490.

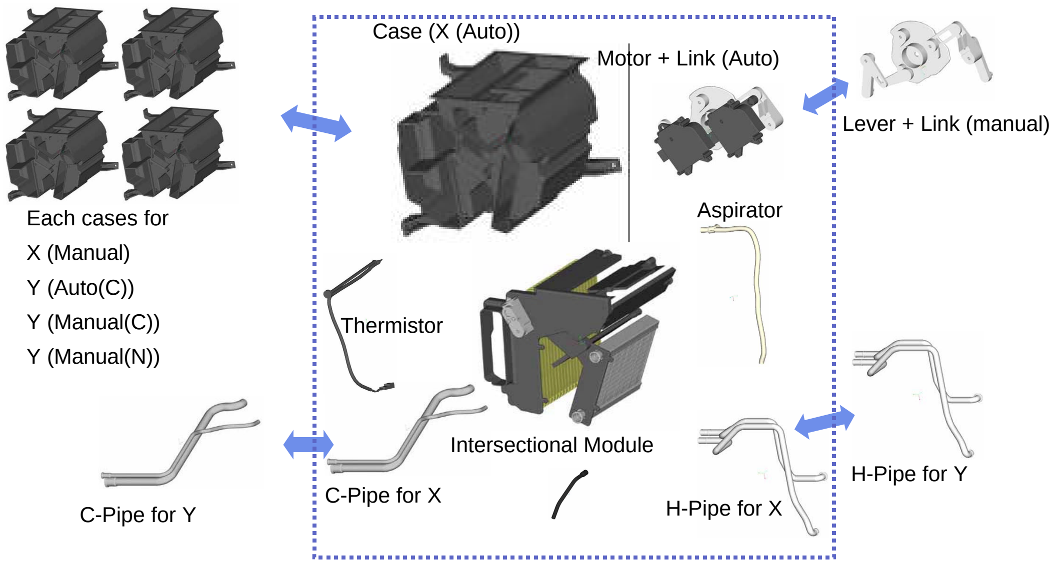

Figure 6: Example modularization.