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COMMON MODULE PRODUCT FAMILY DESIGN IN VIEW OF COMPROMISE IN FUNCTION AND INTEGRITY

K. Oizumi, K. Aruga and K. Aoyama

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1. Introduction

1.1 Background

The development of modularization and common module design has been focused on the need to contend with an ever expanded and divergent global market for products. As the emergence of developing countries opened new markets, diversity of needs and/or preferences of a product has been increasing. Thus, industries face challenges on how to produce a wide variety of products while keeping or even reducing their cost. Under such conditions, modularization of a product and commonization of modules across several products are regarded as possible ways to cope with this challenge.

1.2 Modularization and commonization

Modularization of a product means to subdivide a product into several subsystems. Subsystems that compose a product are called a 'module'. If several products have common module divisions, those products can share the same module. Such design is called 'common module (product family) design'. Here, product family denotes a group of products whose modules are shared. By communizing modules within a product family, the number of modules can be reduced as a whole. Therefore, a company can expect cost reductions in the design and/or manufacturing phases.

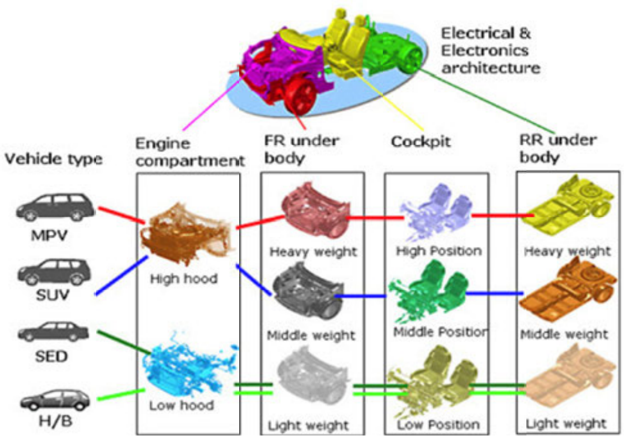


Figure 1. Common module family [Nissan 2012]

Figure 1 shows an example of common module product family design released by [Nissan 2012], an automobile manufacturer. In this example, four products (MPV, SUV, SED, and H/B) are all divided into four modules (Engine…, FR…, Cockpit, and RR…). Several modules are shared by different products. For example, the high hood engine compartment is shared by MPV and SUV. As a result, four products are composed by 11 modules. In contrast, if no module is shared within the product family, number of modules would be 16 (4 x 4). Therefore, this example succeeded in eliminating five modules by means of module commonization.

1.3 Concerns on modularization

Although modularizations' ability to realize wide variety of product family are acknowledged, Japanese industries have hesitated to take steps toward its actual implementation. One of the strongest concerns that Japanese industries have on product modularization is loss of competitive edge. Historically Japanese industries have advantages in their integral quality improvement – *Suriawase*, which can be explained as adjustments of interfaces among parts to achieve higher integrity. However, modular design may impede such *Suriawase* as interfaces among modules need to (or at least, should) be agreed beforehand. Thus, by embedding opportunity for *Suriawase* within a module, common module product family design could be a prominent way of design and development of product for Japanese industries.

1.4 Suriawase

Suriawase is a way of coordinating design of each part. Usually, a product is so large and complex that a person cannot design a whole. Thus, several people are assigned to design of part of a product. But how design of a product is subdivided reflects working cultures. In several countries, design is subdivided with rather clear job descriptions. In contrast, Japanese industries have an unique way. They tend not to have clear job descriptions. Under such conditions, negotiation among designers are strongly encouraged. [Fujimoto 2006] referred it as "organizational capability that emphasized teamwork among a multi-skilled workforce". And he concluded that *Suriawase* fit with integral architectures.

1.5 Aim of this paper

This paper proposes a computational design support method for module commonization structure of a product family. To verify the proposed method, the case study on design of solar boat product family is demonstrated. While there have been several former studies on module commonization design, this paper incorporates the aspect of *Suriawase*, or integrity of a product.

2. Related works

Regarding product family design, there have been several studies that discussed modularization of a product, commonization of modules, or platform design [Jiao et al. 2007].

First of all, modularization of a product has been discussed by many papers. Importantly, [Hino 2011] advocated that interfaces among modules should necessarily be agreed before the design of each module. It agree with the concern that Japanese industries have. However, conventional views on modularization rarely includes *Suriawase* as it might be exceptional to Japanese industries. For instance [Eppinger 2003] proposed a DSM-based (Dependency Structure Matrix) method to subdivide a product into subsystems, which minimises number of dependencies among different subsystems. Though [Eppinger 2003] itself is not a paper about modularization, the method to subdivide a product was one of the relevant view to modularization. However, [Eppinger 2003] or other related works did not discuss loss of opportunity to integral quality improvement

Modular design is often discussed in relation to commonization of modules within a product family. [Xuehong et al. 2001] suggested modularity, commonality and variety as important concerns. Further, as mechanism to generate variety, [Du et al. 2001] suggested attaching/removing, swapping, scaling and variety nesting. In this paper, only swapping is discussed to reduce the calculation load. [Ishii and Martin 2002] proposed a method to divide product into several modules in view of not only dependencies among component but also difference of temporal changes of market requirements. [Simpson et al. 2001] formulated product family design as a tradeoff between non-commonality index and performance deviation index. Which means that commonization may impede performances.

Though [Simpson et al. 2001] discussed design of a common platform in a product family, this way of formulation is common throughout several papers.

As for methods to solve product family design as multi-objective optimization problem, [Fujita et al. 2002a,b,c] proposed a method to optimise module composition of a product family considering quality, cost, and lead time as evaluation criteria. [Simpson and D'Souza 2004] employed the genetic algorithm to optimise a product family. A number of articles suggests that consideration of product modularization is one of the most prominent way to enhance commonization of parts among products. However, as stated in the introduction, there are not many discussions on how modularization affects integral quality improvement – *Suriawase*. This paper emphasizes the aspect of integrity (loss of integrity caused by modularization).

3. Approach

3.1 Modelling a product family

To discuss commonization of modules within a product family, a panoramic view of the composition of products needs to be available and understood. In addition, it is essential to consider the difference of needs among products. However, when a company tries to determine a product family structure, detailed data of products or their components cannot be expected. Therefore, a product family needs to be modelled in accordance with the abstractedness of data (or information) available.

3.2 Advantages and disadvantages with regard to module commonization

When planning module commonization, there are several advantages and disadvantages which need to be considered. Two advantages (1 and 2) and two disadvantages (3 and 4) listed below are discussed in greater detail within this paper:

1. Module commonization:
   How many modules are shared within a product family. This is the primary concern in the planning of module commonization.
2. Structure commonization:
   To what extent the module division structure of a product is common among the product family should be considered. Even if a module is not commonly installed to several products, a common module division taken by different products leads to efficiency of organizational learning, as similar design experiences can be accumulated.
3. Inhibition of coordination:
   When a product is divided into several modules, coordination among modules needs to be done as a form of preliminary agreement, before the design of each module is initiated. Therefore coordination that bridges between modules cannot be regarded as places where designs are to be adjusted making it difficult for *Suriawase* to be done.
4. Requirements compromise:
   When a module is shared, it is difficult (or impossible) to optimise the design of a module to several different requirements given to products simultaneously. Therefore, module commonization leads to compromise on requirements.

In this paper, module commonization planning is formalized as trade-off problem among four aspects raised above. When a module/structure commonization is enhanced, inhibition of coordination and requirements compromise tend to be larger. A company must strategically take a stance on a balance among those four aspects.

On the proposed model of a product family, these four aspects are described as criteria to evaluate module commonization plans. By means of the product family model and four evaluation criteria, this paper proposes a design support method for module commonization planning.

4. Product and product family models

4.1 Product model

Product model is inherited from [Oizumi et al. 2011], which comprises three types of elements as follows:

- Component:
  A component is a physical body that composes a product. Each design parameter (explained below) belongs to one component. Each component has at least one design parameter. Only the boundary of a component can be a boundary of a module, and a component cannot be divided into different modules. As this paper focuses on functional structure of a product, geometric relationships among components are ignored.
- Design parameter:
  A design parameter is a parameter of a product that designer can determine directly. Design parameters affects functional metrics (explained below). Thus, design parameters are determined to achieve required levels of functional metrics.
- Functional metric:
  A functional metric is a metric used to evaluate whether a product meets a certain functional requirement. To illustrate different strength of requirements importance is given to each functional metric.

There are relationships among three types of elements above. Figure 2 a) shows an overview of a product model. As shown in Figure 2 a), there are two types of relationships; 1) a design parameter 'belongs' to a component, and 2) a design parameter 'affects' a functional metric. To illustrate different strength of effect on functional metrics that design parameters have, sensitivity is given to this type of relationship. To abstract information, sensitivity is usually dealt as an ordinal scale. But in certain types of calculation, it is regarded as a ratio scale. To describe sensitivity in detail, several levels should be used to illustrate different strength of the effect. In this paper, to ease data acquisition, two levels are employed: 3) strong enough to realize the required level of the functional metric and 1) not strong enough to realize the required level of the functional metric.

This product model can be depicted as a form of a matrix, which has same structure with as QFD [Akao 1990] as shown in Figure 2 b).

4.2 Product family model

A product family model can be described by extending the proposed product model to multiple products. As products included in a product family would be evaluated on whether they can have common modules, it implies those products have quite similar structures. Thus, it is assumed that functional structure of products within a product family is same. In the proposed model, elements and their relationships remain the same while importance of functional metrics are differentiated to illustrate different requirements on each product. Therefore, by incorporating different importance of functional metrics to each product, a product model matrix Figure 2 b) can be extended to a product family model matrix as shown in Figure 2 c).

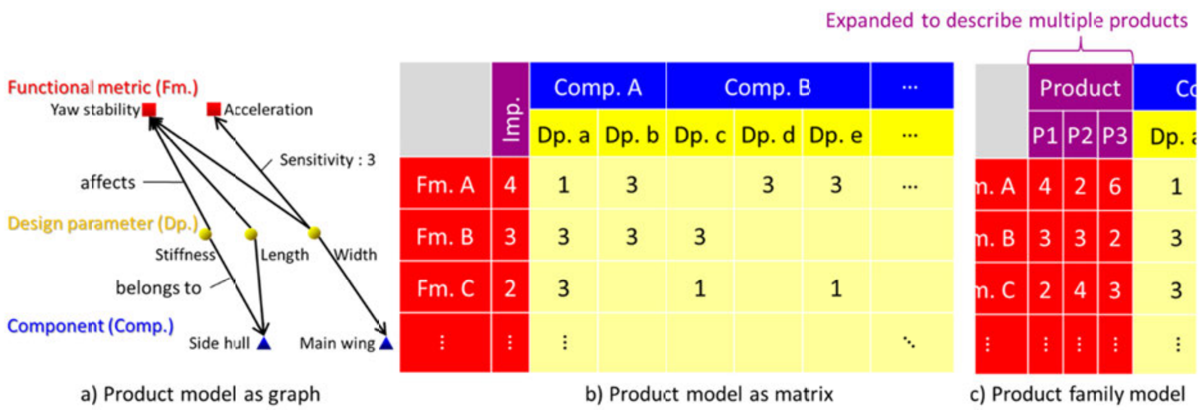


Figure 2. Product family model

5. Expression, evaluation and exploration of module commonization plans

Based on the proposed product family model, this section discuss how to express, evaluate and explore module commonization plans. First of all, before discussing module commonization, this paper explains how to model component commonization. As modules are composed of several components, when a commonization pattern of a product family is determined, it entails how components can be modularized. Accordingly, on this paper, module divisions of products are assumed to be fixed as one pattern to ease the calculation. By combining commonization pattern of components and module division structure, it is called a module commonization plan. Each commonization plan is evaluated by four criteria that reflect the four aspects to be considered discussed in Section 3.2. Details is explained in the following sections.

5.1 Commonization of components

This section discusses how to express and evaluate commonization of components. Commonizing a component among several different products implies that a component is designed to meet various functional metrics whose importance is differently given to each product. Thus, a shared component cannot be optimised for specific product by way of evaluating its functional metrics. When importance of functional metrics, to whom design parameters of a certain component affect, has significant differences among products that share the component, it is inevitable that compromise to functional metrics of several products will occur. In this paper, this compromise of a functional metric is defined and calculated as compromise degree.

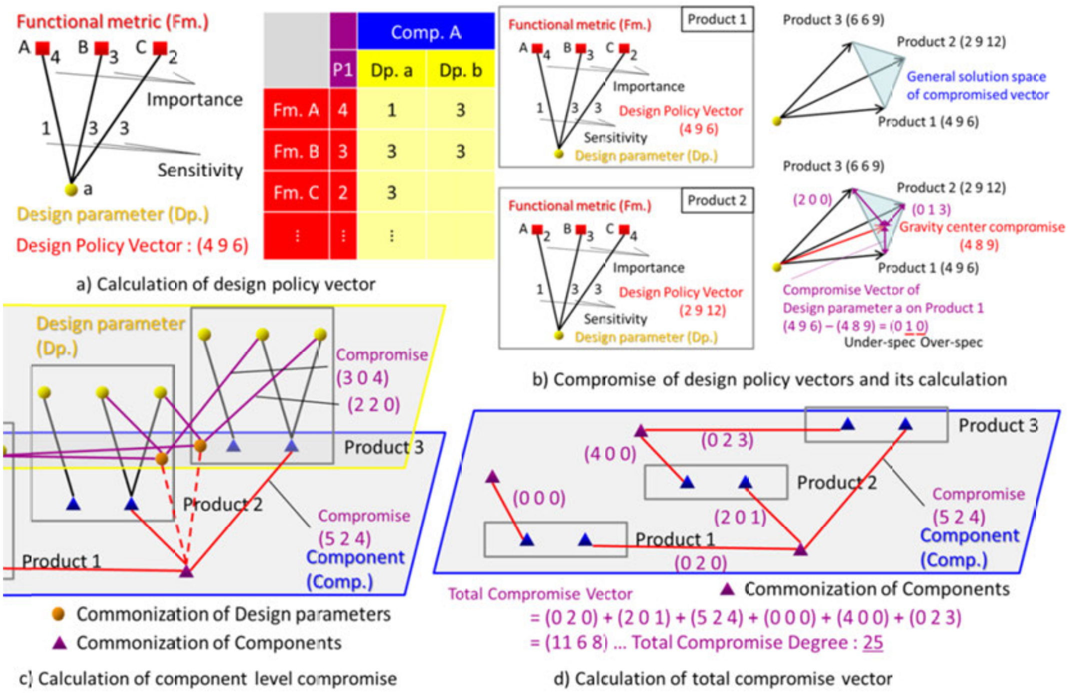


Figure 3. Calculation of compromise based on quantification of design policy

As shown in Figure 3 a), for each design parameter a design policy vector is calculated. Each component of a design policy vector is calculated as the importance of functional metrics multiplied by sensitivity of the functional metrics to the design parameter. The design policy vector denotes the strength of drag force that each functional metric has on a certain design parameter to optimise itself. Therefore, a design policy vector depicts a balance of forces that affects determination of a design parameter.

When a component is to be shared among several products, obviously values of design parameters become the same as well. Accordingly, design parameters of different products whose design policy vectors are unique have one solution compromising those different design policy vectors. A compromised design policy vector is taken to be the gravity centre of several design policy vectors, this is show diagrammatically in Figure 3 b). a compromise vector, to what extent each design policy vector is compromised, can be calculated as distance of a compromised design policy vector from an original design policy vector. When design parameters that have similar design policy vectors are compromised norms of compromise vectors would be smaller.

If a component is shared among several products, it is possible to see that design parameters of the shared component are all shared by those products. Thus, as shown in Figure 3 c), by summing up compromise vectors of design parameters on each component, it is possible to calculate how much compromise is made when a certain component is shared. As sharing pattern may different to each component, compromise vector is calculated regarding each component. By summing up compromise vector of components, a total compromise vector, functional compromise of each commonization plan, can be evaluated, as shown in Figure 3 d). While a total compromise vector evaluates possible compromise of each functional metric independently, to ease the exploration of commonization plans, total compromise degree, which is manhattan norm of a total compromise vector, is employed.

5.2 Module division

Commonization of components causes difficulty of coordination among components, in other words, opportunity for *suriawase* – integral quality improvement. As shown in Figure 4 a), the component A_1 needs to coordinate with 2 types of B and 3 types of C. It is rational to have preliminary agreements on their specification before the design of each component is initiated, in order to avoid turbulence in the design process. However, as specifications are agreed beforehand, it is quite difficult to adjust their designs once they are agreed.

In this paper, boundaries among components where such agreements are needed are assumed to be boundaries among modules. When a component has one-on-one coordination with another component, these components are regarded as in a same module. In Figure 4 a) as the component C_3 coordinates only with the component B_2 in the B component position, components C_3 and B_2 are in a same module. Under this definition of module boundaries, module divisions of all products within a product family are uniquely determined when commonization of components are decided as shown in Figure 4 b).

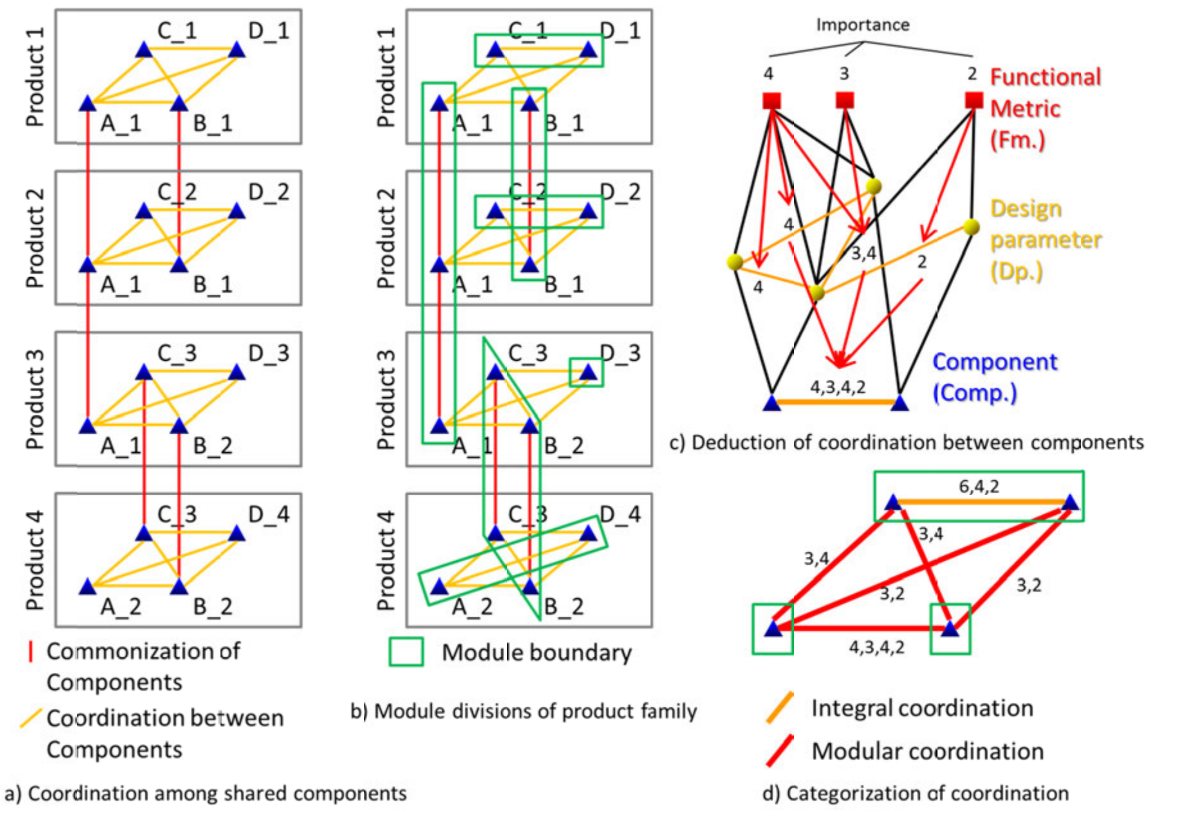


Figure 4. Modularization of a product family and calculation of coordination inhibition

5.3 Calculation of coordination inhibition degree

As explained in section 3.2, *suriawase* does not work when coordination bridges over different modules, thus, modularization entails inhibition of coordination. However if there are more opportunities for *suriawase*, integral quality improvement is enhanced. To evaluate this it on the a proposed model, coordination inhibition degree is defined and evaluated as follows.

Suriawase is adjustments among design of each part to improve quality or achieve higher integrity. On the proposed model, it can be converted as adjustments of design parameters to improve functional metrics. Thus, as shown in Figure 4 c), when design parameters affect a same functional metric, it is regarded that there should be coordination between them. It is defined as coordination link, whose importance is given as importance of the functional metric.

As shown in Figure 4 d), coordination links can be categorized into two types; 1) coordination links within a module (modular coordination), and 2) coordination links bridging different modules (integral coordination). As stated above, coordination links that bridge different modules implies *suriawase*-type coordination is inhibited. Therefore, coordination inhibition degree is calculated as sum of importance of coordination links bridging different modules.

5.4 Calculation of part/structure commonization ratio

Total compromise vector and coordination inhibition degree quantify disadvantages of module commonization. The advantages are reduction of component count and shared structure throughout a product family. These aspects are evaluated by part commonization ratio and structure commonization ratio respectively. Part commonization ratio explains to what extent parts are shared within a product family and is calculated as Equation (1). Structure commonization ratio explains to what extent module divisions of a product are shared within a product family and is calculated as Equation (2). Notations of Equations (1) and (2) are shown in Table 1.

$$PCR = 1 - ((\#Parts - \#PartTypes) / (\#Products * \#PartTypes - \#PartTypes)) \quad (1)$$

$$SCR = 1 - (\#ModuleTypes / \#Modules) \quad (2)$$

Table 1. Notations of Equations

Symbol	Definition
PCR	Part Commonization Ratio
SCR	Structure Commonization Ratio
#Parts	Number of parts in a product family
#Products	Number of products in a product family
#PartTypes	Number of part types in a product family
#Modules	Number of modules in a product family
#ModuleTypes	Number of module types in a product family

5.5 Exploration of module commonization plans of a product family

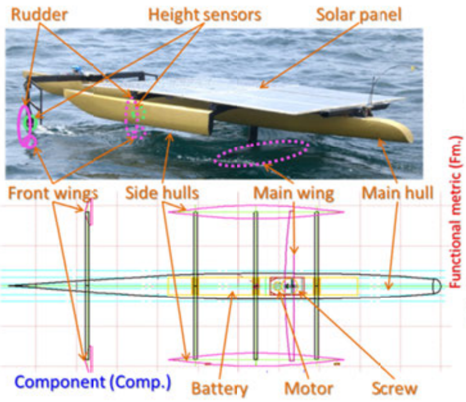
By combining commonization pattern of components and module division structure a module commonization plan can be defined. The purpose of this paper is to propose a computer-aided support method for module commonization planning. However, as evaluation criteria are related to each other and have trade-off with each other, it is impossible to employ deterministic algorithm to find out the optimal plan. In this paper, a multi-objective optimization method that makes use of genetic algorithm is proposed to solve the said problem.

6. Case study

6.1 Applied case

To verify the proposed method, a case study was conducted on the solar-boat shown in Figure 5 a). Figure 5 b) shows matrix depiction of the product model where it is clear many design parameters affect many functional metrics. Conventionally modularization has not been considered for such a highly integral product. But, recent trend of module commonization in automobile industry motivated the authors to apply the proposed method to a rather integral products.

Figure 6 is the flow of the prototype computer-aided support system for module commonization design.



a) Solar-boat examined in case study

Design parameter (Dp.) / Functional metric (Fm.)

	dp1	dp2	dp3	dp4	dp5	dp6	dp7	dp8	dp9	dp10	dp11	dp12	dp13	dp14	dp15	dp16	dp17	dp18	dp19	dp20	dp21	dp22	dp23
fn1	1	3	1	1	1	1	1	1	1	1	1	1				3	1	1	3	3	3	1	1
fn2	1	1	1	1	1	1	3	3	1	1	1	1				3	1	3	1	3	3	1	1
fn3		1	1	1	1		1	3	1	1	3	1	3	1	1			1				1	1
fn4		1	1	1	1		1	3	1	1	3	1	3	1	1			1				1	1
fn5	3	1	1					1	1		1	1						1				3	1
fn6	3	1	1	3	1	1		1	1		1	1						1				3	1
fn7	1	1		1	1		1	1		1	1			3	3	3	3	1	3	1	1	1	1
fn8	1	1		1	1		1	1		1	1			3	3	3	3	1	1	1	1	1	1
fn9	1	1		1	1		1	1		1	1			1	1	3	3	1	3	1	1	1	1
fn10	1	1		1	1		1	1		1	1			1	1	3	3	1	1	1	1	1	1
fn11	3			3			1	1	1	1	1	1										3	3
fn12	3						1	1	1	1	1	1										3	3

b) Matrix depiction of solar-boat product model

Figure 5. Solar-boat used for case study

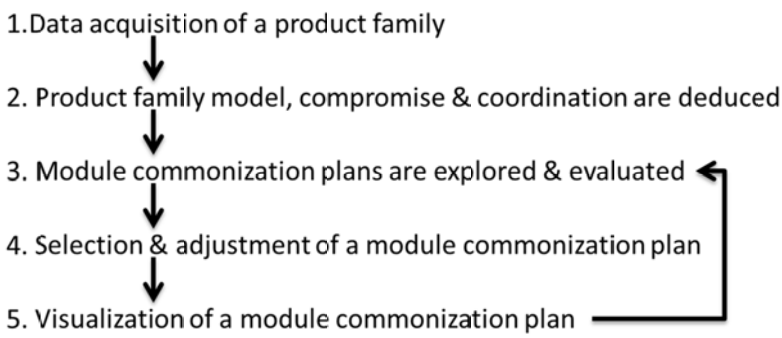


Figure 6. Flow of prototype system

6.2 Results

Figure 7 shows comparison of two module commonization plans chosen from the pareto-optimal solutions. The plan in a) enlarges modules to keep opportunities for *suriawase* within the modules. In contrast, the plan in b) subdivides modules rather smaller and raises part commonization ratio. As this comparison suggests, the proposed method can support the exploration of wide variety of module commonization plans.

Figure 8 illustrates comparison of coordination inhibition on Product 1 of each commonization plan. In Figure 8, rectangle nodes and links denote components and coordination links respectively. Enclosures on network denotes modules. Width of the links expresses importance of the coordination link. Thus, if many fat links bridge among enclosures, coordination inhibition would be worse. By comparing two plans, it is obvious that Plan b has more coordination links that bridges modules. As Plan b weigh commonization ratio, modules tend to be smaller that leads to higher coordination inhibition. On the other hand, as Plan a weigh coordination (*suriawase*), modules tend to be larger.

As shown in Figure 8 b), the power system, structural system, and electric system tend to be distinguished. This distinction agrees with the designers' considerations quite well. Likewise, formation of pareto module commonization plans are ascertained to reflect designers consideration on what should be shared and how extent the drawback would be.

Products	Height sensor	Side hull	Screw	Main wing	Front wing	Main hull	Solar panel	Battery	Motor	Rudder
Product 1	1,2,3,4	1,4		1,2,4						
Product 2	1,2,3,4	2		1,2,4						
Product 3	1,2,3,4	3								
Product 4	1,2,3,4	1,4		1,2,4						

a) Coordination inclined module commonization plan

Products	Height sensor	Solar panel	Side hull	Main wing	Front wing	Main hull	Screw	Battery	Motor	Rudder
Product 1	1,2,3,4		1					1,2,4		
Product 2	1,2,3,4		2,3,4	2,4				1,2,4		
Product 3	1,2,3,4		2,3,4	3						
Product 4	1,2,3,4		2,3,4	2,4				1,2,4		

b) Commonization ratio inclined module commonization plan

Figure 7. Comparison of module commonization plans

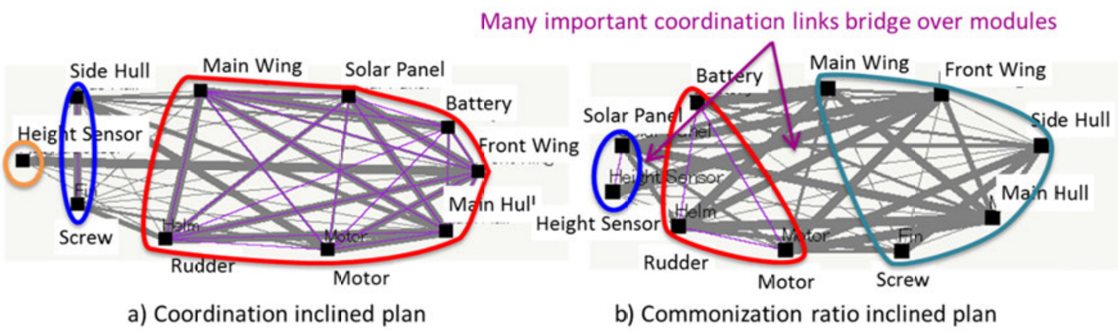


Figure 8. Comparison of coordination inhibition of Product 1

7. Validation

Through the case study on the solar-boat, applicability of the proposed method has been confirmed. Although in this paper a solar-boat, a rather small and simple product, is used for the case study the proposed method has also been applied by the authors in an academic industrial cooperative research project where it also proved its applicability. However it is not possible to share the results due to a confidentiality agreement.

8. Conclusion

This paper proposed a computational design support method for module commonization planning that takes integral quality improvement – *Suriawase*, into consideration. To evaluate multiple aspects regarding commonization and modularization of a product family, four evaluation criteria are introduced: 1) total compromise vector, 2) coordination inhibition, 3) part commonization ratio and 4) structure commonization. Through the solar-boat case study, the proposed model and the four criteria are verified to be useful for exploring wide variety of module commonization plans. The study suggests that that integrity can be taken into consideration when module commonization of a product family is examined.

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Dr. Kazuya Oizumi, Project Researcher
The University of Tokyo, Department of Systems Innovation
7-3-1, Hongo, Bunkyo, Tokyo, 113-8656, Japan
Telephone: +81 3 5841 6506
Telefax: +81 3 5841 6506
Email: oizumi@m.sys.t.u-tokyo.ac.jp
URL: http://www.m.sys.t.u-tokyo.ac.jp