# PROPOSAL OF A MODULAR DESIGN METHOD CONSIDERING SUPPLY CHAIN: COMPREHENSIVE EVALUATION BY ENVIRONMENTAL LOAD, COST, QUALITY AND LEAD TIME

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**ABSTRACT:** For achieving the sustainable consumption and production, designers and manufacturers should provide inexpensive products that create a low environmental load on the user. Accordingly, products and their components should exhibit a modular design, which can be achieved by considering some factors such as future reuse, remanufacturing, and upgrading. Modular design methods primarily focus to reduce the lead time or costs associated with designing an entire family of products. However, resource efficiency is an important consideration associated with reuse as well as with the production and procurement stages of manufacturing. Hence, proper supplier selection is crucial because new products comprise several components and modules supplied by various manufacturers. So, this paper proposes a modular design method and strategy based on supply chain management. Especially, the proposed method evaluates a modular design strategy based on the cost, environmental load in transportation, quality, and procurement lead time. After deriving modular architecture candidates by Design Structure Matrix clustering that divide functionally closer parts into groups, a proposed indicator is used to evaluate the efficiency of the candidates based on the modular architectures and suppliers. This study applies the proposed method to design a laptop computer and derives an appropriate modular architecture and suppliers with respect to each destination.

**KEYWORDS**: *Modular Design; Supply Chain Management; Early Design Phase; Decision-Making Support; Product Architecture*

## 1.0 INTRODUCTION

The attainment of sustainable consumption and production has been discussed as a global agenda. In Europe, for example, the European Commission adopted the circular economy (CE) package in 2015, which aims to obtain environmental and economic benefits by reusing or recycling the residual value that is observed to remain because of idle assets and disposed products [1]. In Japan, the concept of global multivalue circulation has also been discussed and proposed [2]. This concept integrates the production capacity of the Asian countries with the system boundary of the CE and aims to promote the creation of sustainable societies not only in developed countries but also in developing countries. To reutilize the residual value that remains in an idle asset or a disposed product, defining and clarifying this value and developing a scheme to ensure reutilization are essential. Additionally, the products and their components should be preliminarily designed by considering future reuse or remanufacturing to facilitate efficient reutilization of this residual value. A schematic depiction of the ideal situation is presented in Figure 1, wherein a product exhibits an appropriate modular design, and its components are reused in new products and other product families or are recycled at the end of the original product's lifecycle. To adequately assess and optimize these processes, a designer should also consider the resource efficiency not only during the reuse stage but also during the production and procurement stages. Additionally, product designers and manufacturers must strive to simultaneously integrate social responsibility, achieve higher profits, and provide higher user satisfaction.

Therefore, this study proposes a modular design approach and strategy from the perspective of supply chain management. More specifically, the proposed method evaluates the strategy from the perspectives of cost, environmental load, quality, and procurement lead time. The proposed method also designs and evaluates the product architecture from the perspective of sustainability in contrast to the traditional modular design methods that focus on the reduction of development lead time or variety cost. This study simultaneously applies the proposed method to a laptop PC design and derives an appropriate modular strategy from the viewpoints of cost, environmental load, lead time in transportation, and product quality. Finally, this paper discusses the availability and additional considerations of the proposed method based on the result of the case study.

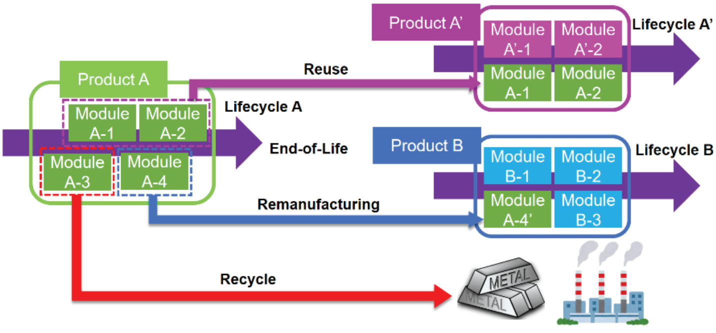


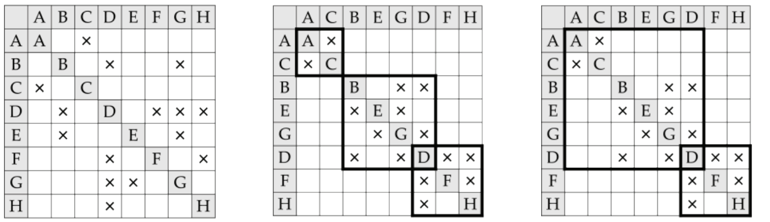

Figure 1: Ideal modular product's material flow during its lifecycle

## 2.0 METHODOLOGY

### 2.1 Previous Researches on Module Design Method

In this section, the paper discusses previous studies that have investigated the modular design methods, including a method that has been formulated as a multiobjective optimization problem related to the product performance in a family of products using the commonality of modules [3], an optimization method for module combinations focusing on product function and production cost [4], and a study focusing on the functionality of integration between components by modularization [5].

As an approach to achieve modularization, a Design Structure Matrix (DSM) method is a renowned, straightforward, and flexible modeling technique that can be used to design, develop, and manage complex systems [6-7]. DSM was created so that the interfaces between the modules are reduced. DSM analysis can achieve partitioning and relocation using various analytical methods in case of modularization [8]. This study focuses on the cluster analysis method. Using DSM clustering, the row and column elements of the DSM are rearranged, where the elements with strong interactions are grouped, and modularization can be pursued. The sorting method is undertaken by consulting with experts, using functions, or using unique algorithms such as Newman method and p-median method. In particular, several methods that focus on the usage of functions have been proposed [8], whereas methods that simultaneously consider the environment and cost have been rarely conducted so far. An example of a DSM model for a product comprising eight components is depicted in Figure 2 (a); two examples of DSM clustering for the case exhibited in Figure 2 (a) are depicted in Figures 2 (b) and (c).



(a) Original DSM (b) Clustering case 1 (c) Clustering case 2

Figure 2: DSM model and clustering for a product comprising 8 components

## 2.2 Supply Chain Management (SCM)

In order to resolve the issues related to global warming, a low-carbon supply chain is necessary, which can reduce the $CO_2$ emissions [9-10]. Regardless of the components being considered, the environmental load, personnel expenses and transportation costs differ depending on the country of manufacture. Generally, when the components are produced in industrialized countries, the cost is higher and the environmental load is lower. By contrast, when the components are produced in countries with emerging economies, the cost is lower and the environmental load is higher [11-12]. Therefore, a supplier selection method that can achieve both low cost and environmental load is optimal.

## 2.3 Procedure for Modular Design

As described in Section 2.1, there are several modular design methods that focus on functions; however, there very few methods that simultaneously consider both environment and economics. Therefore, in this research, the concept of supply chain management is applied [13] to develop a modular design with respect to environmental load, cost, lead time, and product quality simultaneously. The component suppliers are evaluated, and the indicators are proposed to comprehensively evaluate the efficiency of the module strategy from the aforementioned viewpoints, depending on the manner in which the decisions regarding the suppliers and module components are made when multiple suppliers are available for each component. Figure 3 depicts the design flow of the proposed method, and the design solution image is depicted in Figure 4. The product model to which the proposed method is applied is presented in Figure 5. For each component, a company selects suppliers from several candidates (S1–S9). For the components to be modularized by integration, the module production site, M, is further set to an arbitrary global location. Finally, the process site to assemble all the modules and components is defined as the location at which the product is completed. As depicted in Figure 5, all the three components, 1 to 3, are integrated to form one module in Case 1, whereas Case 2 depicts the modularization of components 1 and 2, conducted at Module M, and part 3 is integrated at the final process site, P. The proposed method evaluates each case from the viewpoints of environmental load, cost, quality and lead time; our method further finds out the module strategy by identifying the scenario having the highest score.

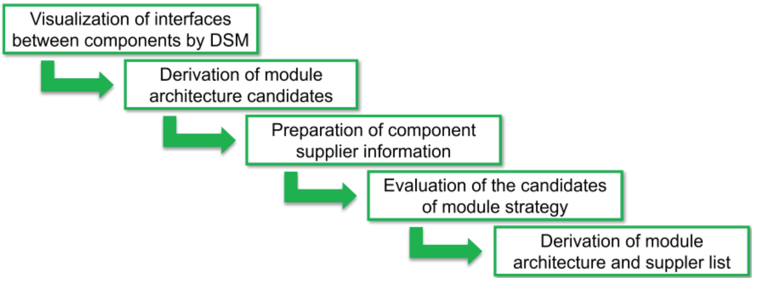



Figure 3: Procedure for modular design

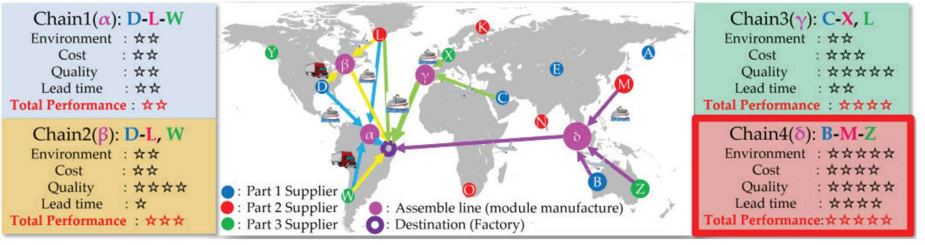



Figure 4: The schematic of modularization by considering the supply chain

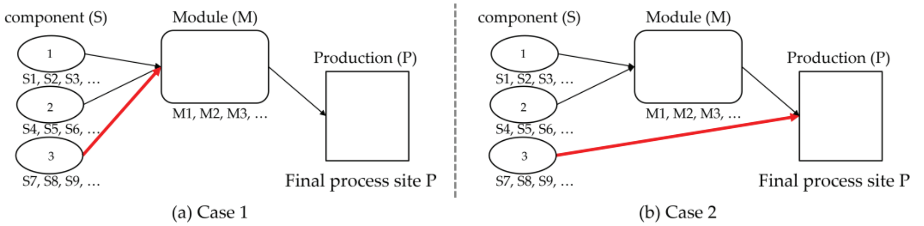



Figure 5: Examples of modularization of components

### 2.3.1 Evaluation of the Environment

In order to evaluate the environmental considerations, the converted $CO_2$ emissions that are associated with transportation are used. As presented in Equation (1), the converted $CO_2$ emissions $E$ (kg-$CO_2$e) are calculated by multiplying the converted $CO_2$ emission intensity ($e$) of each transportation leg (Truck: [149, 178], Container ship: [25.5, 40], Airplane [519, 1490]), the transport distance, $L$ (km) and the weight of the components to be transported, $w$ (t) [14].

$$E = \sum \{e \times L \times w\} \tag{1}$$

#### 2.3.2 Evaluation of the Economy

The total product cost, C, is used to evaluate the economic considerations. C is defined as the sum of the costs that are presented in Figure 6 and is expressed by Equation (2). In Equation (2), $c$, $B$, and $t$ indicate the manufacturing cost of each component, the suppliers' profit, and the transportation cost, respectively. The manufacturing cost of each component is the price of the components that is determined by considering the material procurement and labor costs. While calculating the profits, the difference in labor costs varies depending on the module manufacturing location and can be expressed as the ratio of the GDP (Gross Domestic Product) per capita of the producer country ($GDP_p$) to the GDP per capita of the reference country ($GDP_b$). The profits are defined in Equation (3) by multiplying the GDP ratio with the profit ratio ($Pr$) and the sum of the manufacturing costs ($MC$) of the parts to be modularized. The transportation cost is the cost incurred from the time at which the components are shipped to the time at which the components arrive at the destination which is essentially the fees of the shipping company. Generally, the transportation price is observed to vary depending on the transportation distance and means.

$$C = \sum \{c + B + t\} \tag{2}$$

$$B = MC \times \frac{Pr}{100 - Pr} \times \frac{GDP_p}{GDP_b} \tag{3}$$

Transportation costs are calculated using Equations (4) to (6). The total transportation cost is indicated by the sum of the transportation costs from the site that manufactures the components to the final processing site by considering the truck transportation cost ($t_{truck}$), the container shipping cost ($t_{cs}$), and the air transportation cost ($t_{ap}$). Here, $Mt$ (kg) is defined as the total weight of the transport components. $Cf_{truck}$ (Yen/kg) in the trucking cost of Equation (4) represents the freight rate of the package as defined from 50 to 88. The transportation cost using container ship is presented in Equation (5) whereas the air transportation cost in Equation (6) can be formulated by confirming the dependency relation between transport distance and weight using the actual tariff.

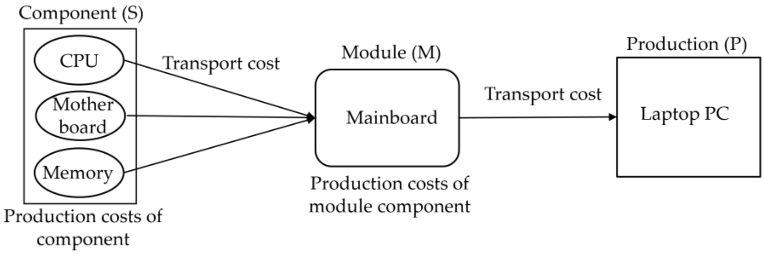



Figure 6: Definition of costs

$$t_{truck} = Cf_{truck} \times Mt \tag{4}$$

$$t_{cs} = \left(\frac{1.6}{1000}L + 120\right)Mt + (0.4L + 1450) \tag{5}$$

$$t_{ap} = \left\{\begin{array}{l|l} 10269 & Mt < 20 \\ 513 \times Mt & Mt = [20, 45] \\ 399 \times Mt & Mt = [45, 1000] \\ 342 \times Mt & Mt > 100 \end{array}\right\} \tag{6}$$

### 2.3.3 Evaluation of the Components' Quality, *Q*

A 5-point scale is used to evaluate the difference in quality and manufacturing technology depending on the supplier's manufacturing site, with 1 being the lowest quality and 5 being the highest quality. It is assumed that quality can be judged using the data handled by a company, such as failure and/or yield rate, and that the total product quality $Q$ is defined as the average of the quality scores of the suppliers and the modularization site.

### 2.3.4 Evaluation of the Lead Time, *D*

The lead time $D$ indicates the number of days between the time when an order is placed for a certain item by a buyer to the time of delivery of the item. To simplify this comparison, the lead time for each form of transportation is defined and described using the following terms. With respect to truck and air transportation, this study assumes that each lead time is one day when used once. The lead time ($Dcs$) (day) due to the transportation of the shipping container is assumed to be dependent on the transportation distance, as defined in Equation (7). To obtain the solution of Equation (7), the value obtained by rounding down to the decimal point is defined as the lead time. Additionally, by considering the delay caused by unseasonable weather, pirates, and some other factors, the total lead time is defined as the time range required to complete the entire transportation plus 2 days.

$$D_{cs} = 0.0015 \times L \tag{7}$$

### 2.3.5 Supply Chain Evaluation Index

The supply chain evaluation indicator (*SCEI*) that is defined in Equation (8) is calculated using the evaluation variables that have been derived in Sub-Sections 2.3.1 to 2.3.4. As the value of *SCEI* increases, the modular strategy is considered to be appropriate. More specifically, this case indicates high quality, low cost, low environmental load, and short delivery time, and this determines the best modular strategy. Using this *SCEI* value, a designer can search for a combination of clusters that can ensure appropriate modularization by considering multiple suppliers.

$$SCEI = \frac{Q}{C \times E \times D} \tag{8}$$

## 3.0 RESULTS AND DISCUSSION

### 3.1 Case Study: Setting the Design Problem

This study demonstrates the application of the proposed method to compile and assemble the laptop components. In particular, this case study focuses on the modularization of three components of a laptop, including the CPU, motherboard, and memory. By applying the proposed method to these three components, an appropriate module configuration and suppliers are defined in terms of supply chain management. A laptop was selected to perform this study because each component is standardized and because individual modules are separately purchased from multiple manufacturers, which makes it easy to obtain information about the pricing as well as the manufacturing location under realistic conditions. In actual laptop manufacturing, more than three compnents are used. However, these components are assembled as independent modules from the viewpoint of maintainability or are integrated to form a module from the viewpoint of beauty and miniaturization. Therefore, because modularized products are mixed, a sustainable modular strategy can be validated using a three-component evaluation scenario.

This case study assumes that the target laptop is a mobile laptop with a 13.3-inch LCD screen and a weight of 1.6 kg. It is further assumed that production volume of each component is 100. Table 1 presents the component information of the subject laptop. The cost of each component was investigated by considering the actual selling prices, and the weight of each component was estimated by disassembling and weighing the components of an actual laptop even though the change in weight due to integration of the components was not considered. For each component, the location of the supplier candidates and the final process site at which all the components and modules are assembled are presented in Table 2. A similar letter represents the same country except that P1 and P2 indicate country C and H, respectively. Major companies that actually manufacture each component were researched and selected, by identifying the country in which the respective production factories are located. Additionally, the product quality, which depends on the producer country and the quality parameter, summarized in Table 2, are considered. The supplier of each component was selected from Table 2. Further, the location for module production by integrating the components was configured using the nearest port or airport from the supplier. The final process site was further chosen using Table 2 to assemble all the components and modules.

Table 1: Information about each component of the laptop

| Part/Module | Weight (g) | Cost (Yen) |
|---|---|---|
| CPU | 7 | 18,000 |
| Motherboard: MB | 100 | 10,000 |
| Memory | 15 | 8,000 |
| Module (CPU+ MB) | 107 | 18,000 |
| Module (MB +Memory) | 115 | 28,000 |

Table 2: The supplier and its quality set of each laptop component

| | Supplier candidate (its quality) | | | |
|---|---|---|---|---|
| | Supplier 1 | Supplier 2 | Supplier 3 | Supplier 4 |
| CPU | A1 (*Q*: [3, 5]) | B1 (*Q*: [2, 4]) | C1 (*Q*: [3, 5]) | – |
| MB | A2 (*Q*: [3, 5]) | D1 (*Q*: [2, 3]) | E1 (*Q*: [2, 3]) | F1 (*Q*: [3, 4]) |
| Memory | A3 (*Q*: [3, 5]) | G1 (*Q*: [4, 5]) | C2 (*Q*: [3, 5]) | – |
| The final process site | P1 | P2 | – | – |

## 3.2 Evaluation Results of Proposed Methods

For each of the two final process sites, P1 and P2, each evaluation value was obtained using the proposed method. Tables 3 and 4 present the results of the modular architecture and suppliers used in these cases, respectively. In Tables 3 and 4, the supplier column provides the supplier and transportation means. Transport by container ship: CS includes truck transportation: Tr from the supplier's factory to the nearest port and container vessel transport from that particular port to the port nearest to the modularization location or final process site. Transport by airplane: Ap includes truck transportation from the supplier's factory to the nearest airport and transportation from that airport to the airport nearest to the modularization location: ML or final process site.

The modular architecture with the highest *SCEI* value is presented in Tables 3 and 4. The highest score of the best case is primarily associated with the lowest environmental load and cost as compared with that associated with the others because additional transport of components from the supplier's factory to the modularization site and from the modularization site to port by truck is not necessary. Furthermore, there is no need to pay cost for modularization by integrating the components. In addition, there are two reasons for these results. First, the evaluation of the environmental load only considers the amount of carbon dioxide emissions that is associated with transportation. Because the distance of truck transportation, which depicts the highest emission intensity unit, becomes large when modularization is performed, the environmental load increases proportionally. Second, when the *SCEI* values are calculated, variations in *C*, *E*, *D*, and *Q* are observed to be different. Therefore, the influence of the environmental load with the largest variations becomes large, and the results are observed to be largely dependent on the transport distance and transportation means.

Table 3: Evaluation result of the modular strategy (final process site: P1)

| Modular architecture | Supplier | | | ML | *C* (mil. Yen) | *E* (kg-$CO_{2e}$) | *D* (day) | *Q* | *SCEI* ($\times 10^{12}$) |
|---|---|---|---|---|---|---|---|---|---|
| | CPU | MB | Memory | | | | | | |
| High evaluation (Top 4) values were observed for each architecture, Final process site: P1 | | | | | | | | | |
| Individual | A1 (CS) | A2 (CS) | A3 (CS) | – | 3.61 | [0.17, 0.25] | [2, 4] | [3.0, 5.0] | [82.5, 400] |
| CPU+MB | A1 (Tr) | A2 (Tr) | A3 (CS) | A (CS) | 379 | [0.35, 0.45] | [2, 4] | [3.0, 5.0] | [44.2, 189] |
| MB+Memory | A1 (CS) | A2 (Tr) | A3 (Tr) | A (CS) | 372 | [0.37, 0.47] | [2, 4] | [3.0, 5.0] | [43.3, 184] |
| Integration | A1 (Tr) | A2 (Tr) | A3 (Tr) | A (CS) | 384 | [0.36, 0.46] | [2, 4] | [3.0, 5.0] | [42.2, 179] |
| Lowest evaluation of all the architectures, Final process site: P1 | | | | | | | | | |
| CPU+MB | C1 (Tr) | D1 (Tr) | C2 (Ap) | C1 (Ap) | 409 | [16.1, 35.8] | [19, 21] | [2.8, 4.5] | [0.09, 0.36] |

Table 4: Evaluation result of the modular strategy (final process site: P2)

| Modular architecture | Supplier | | | ML | *C* (mil. Yen) | *E* (kg-$CO_{2e}$) | *D* (day) | *Q* | *SCEI* ($\times 10^{12}$) |
|---|---|---|---|---|---|---|---|---|---|
| | CPU | MB | Memory | | | | | | |
| High evaluation (Top 4) values were observed for each architecture, Final process site: P2 | | | | | | | | | |
| Individual | C1 (Ap) | F1 (Tr) | G1 (Ap) | – | 362 | [39.5, 64.8] | [2, 4] | [3.3, 4.7] | [36, 163] |
| MB+Memory | C1 (Ap) | F1 (Tr) | G1 (Ap) | H (Tr) | [368, 369] | [39.5, 64.8] | [2, 4] | [3.3, 4.7] | [34, 163] |
| CPU+MB | C1 (Ap) | F1 (Tr) | G1 (Ap) | H (Tr) | 372 | [39.5, 64.8] | [2, 4] | [3.3, 4.7] | [34, 162] |
| Integration | C1 (Ap) | F1 (Tr) | G1 (Ap) | H (Tr) | 375 | [39.5, 64.8] | [2, 4] | [3.3, 4.7] | [33, 161] |
| Lowest evaluation of all the architectures, Final process site: P2 | | | | | | | | | |
| CPU+MB | C1 (Ap) | F1 (Tr) | G1 (CS) | F (Tr) | 378 | [2167, 2595] | [24, 26] | [3.3, 4.5] | [0.13, 0.23] |

## 4.0 CONCLUSION

This study proposed a modular design and an evaluation method based on the concept of supply chain management to promote the formation of sustainable societies. The proposed method comprised a DSM and an evaluation index that evaluated the modular architecture and supply chain based on four perspectives, including the environmental load in transportation, production and transportation costs, procurement lead time, and product quality. The proposed index, referred to as the *SCEI*, evaluated the design of the modular strategy from the four aforementioned perspectives, with comprehensively ranging parameters, to deal with the uncertainty associated with procurement. Finally, this study applied the proposed method and index to the modular design of a laptop and derived an appropriate modular architecture and the necessary supplier information. Thus, the proposed method depicted an availability of designer support by presenting the modular architecture and supplier information with respect to each destination.

The result of the case study also depicted that the evaluation result was strongly dependent on the environmental load, which exhibited the widest parameter range. This study only considered the transport-influenced environmental load that depended on the transportation distance. Further, the lifecycle stage that emitted the highest environmental load was observed to differ based on the product. Therefore, future studies should preliminarily consider the appropriate evaluation range of a product’s lifecycle by understanding the proportion of environmental load during the entire product lifecycle. Additionally, the amount of environmental load in the production stage depends on the supplier’s technique level and composition of power sources. Hence, modeling the variation of environmental load that is associated with the production country should also be considered in future studies.

## ACKNOWLEDGMENTS

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