INTEGRATED OPTIMIZATION OF PRODUCT DESIGN CONCEPT AND PRODUCT LIFECYCLE SCENARIO BASED ON GENETIC ALGORITHM

Masakazu Kobayashi and Masatake Higashi
Toyota Technological Institute, 2-12-1 Hisakata, Tempaku, Nagoya, Japan

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Abstract: Due to rise of environmental awareness in recent years, companies are required to assess and reduce environmental burdens of their products. However, in practical product development, since not only environmental burdens but also product characteristics such as performance and cost need to be simultaneously considered for creating attractive products, designers are forced to take a great deal of time and effort to balance them at a higher level at every stage of product development. In response to this, this paper proposes an integrated method for optimizing product design concept and product lifecycle scenario for supporting conceptual design phase. The proposed method combines integrated optimization of functional / layout design which we developed in the previous researches and lifecycle assessment (LCA). Using the proposed method, optimal functional structure, components / parts layout and lifecycle scenario that balance product characteristics and environmental burdens at a higher level can be obtained.

1 INTRODUCTION

Due to rise of environmental awareness in recent years, companies are required to assess and reduce environmental burdens of their products such as carbon emissions. However, in practical product development, since not only environmental burdens but also product characteristics such as performance, cost and size need to be simultaneously considered for creating an attractive product, designers are forced to take a great deal of time and effort to balance them at a higher level.

Based on the above background, this paper proposes a new integrated optimization method for creating a product concept and its lifecycle scenario that balance various criteria including lifecycle ones at a higher level. To allow for such optimal design, the proposed method is based on our integrated optimization method (Kobayashi et al., 2009). This method is an integration of functional / layout optimizations, which are based on genetic algorithm (GA), for supporting a conceptual design phase. During a conceptual design phase, since there are various decision-makings, designers are asked to make optimal decisions to create great product concepts by considering various product characteristics such as performance, cost and size. However, since functional / layout designs, which are main two tasks of a conceptual design phase, are very different tasks, their design problems are highly hierarchized and their solution spaces are vast, it is extremely difficult for designers to build up great concepts only with their own decision makings. To overcome such difficulty, in our previous method, functional / layout optimizations are combined and executed cooperatively by exchanging information. Using this method, both a functional structure and a parts layout that balances various criteria at a higher level can be obtained. To allow for simultaneous consideration of various criteria including lifecycle ones during a conceptual design phase as described above, this paper makes an attempt to combine this integrated optimization method and LCA. As for design variables, in addition to functional structure and parts / components layout, decision makings throughout product lifecycle are considered. As for criteria, in addition to product characteristics, environmental burdens are considered. Using the proposed method, optimal product concept (a functional structure and a components / parts layout) and its lifecycle scenario that balance various criteria

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including lifecycle ones at a higher level can be obtained.

2 INTEGRATED OPTIMIZATION METHOD

2.1 Overview

This paper proposes an integrated method for optimizing a product design concept (a functional structure and a components / parts layout) and its lifecycle scenario by considering various criteria including lifecycle ones, based on our previous method. The improved point is (1) To integrate LCA in order to evaluate environmental burdens as additional criteria of the integrated optimization and (2) To handle decision makings throughout product lifecycle as additional design variables of the integrated optimization.

Figure 1 shows the overview of the proposed integrated optimization method. This method consists of functional / layout optimizations plus LCA. Functional optimization is the main part of the proposed method and executed just one time. Functional optimization is based on the hierarchical genetic algorithm (HGA) (Yoshimura and Izui, 2002) in order to consider hierarchical nature of a functional structure. In the functional optimization, selection of functions and parts (Parts correspond to the functions at the bottom level of the functional structure) from their alternatives and selection of reuse / recycle / disposal scenario at the EOL stage for each parts are considered as design variables. As for criteria, performance, cost, total area and total carbon emission are considered. Although only one decision making throughout product lifecycle and one index of environmental burden are considered in this paper, the proposed method has a potential to handle more design variables and criteria. Any of them can be configured as an objective function and the rest of them are configured as constraint conditions. This paper assumes that performance and cost can be calculated by simply summing up the values associated with each part, whereas to calculate total area and total carbon emission, layout optimization and LCA need to be executed. So, they are repeatedly invoked from the functional optimization for evaluating generated design proposals at its each iteration. In the layout optimization, based on the information about size of parts selected in the functional optimization, layout with minimum area is calculated. Layout optimization is based on the sequence-pair representation and the traditional GA with the special crossover operator (Murata et al., 1996); (Nakaya et al., 2000). In lifecycle assessment, total carbon emission is calculated from the selected parts and lifecycle scenario.

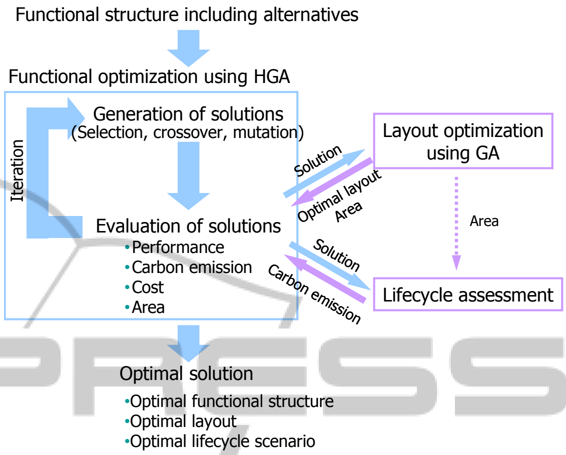

Figure 1: Overview of the integrated optimization.

2.2 Preconditions of the Proposed Method

Before explaining the details of the proposed method, the following assumptions are made.

- A components / parts layout is limited to two-dimensional plane. Shape of components and parts is limited to rectangle.
- All components and parts can be placed freely without any connection constraints.
- Total area of the product equals to the area of rectangle that envelopes all parts placed in a configuration plane.
- Each part has the values associated with performance and cost. Their total values can be calculated by simply summing up these values.

2.3 Functional Optimization using Hierarchical Genetic Algorithm

In practical product designs, functional structure is highly hierarchized and decision makings in the upper level may affect lower functional structures greatly. To optimize such hierarchical selection problems, our method adopts HGA.

The most distinctive feature of HGA is hierarchical genotype representations to exactly describe hierarchical structures of mechanical system designs and special operators of crossover and mutation for manipulating them. Figure 2 shows an example of a hierarchical design problem.

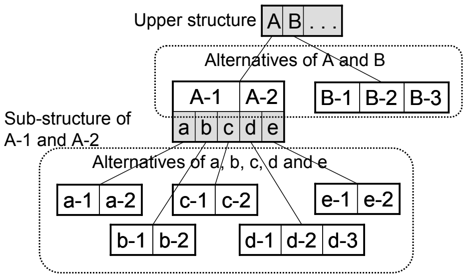

Figure 2: Hierarchical design problem.

In our method, HGA is adopted to optimize product's functional structure in the form of a hierarchical tree structure. An individual of HGA corresponds to one design proposal and its organism strings show selections of functions / parts and selection of reuse / recycle / disposal scenario at the EOL stage in that design proposal. The lowest string corresponds to the combinations of the part selection and its lifecycle scenario selection. In other word, the same parts with different lifecycle scenarios are considered as different alternatives. For example, part A with disposal scenario and part A with reuse scenario are different alternatives. The other higher strings correspond to selection of functions. Since our method adopts single-objective HGA, any of performance, cost, total area and total carbon emission can be configured as an objective function and the rest are configured as constraint conditions. As described the previous section, performance and cost can be calculated by simply summing up the values associated with each part, whereas total area and total carbon emissions can not be calculated by simple summation. Therefore, layout optimization and LCA, as described in the later sections, are executed for evaluating each individual in each generation.

2.4 Layout Optimization using GA and Sequence-pair Representation

In our method, parts shape and a configuration space are limited to rectangle and two dimensional, so components / parts layout can be described by sequence-pair representation and solved by GA.

Sequence-pair was originally developed for VLSI layout design, which is the rectangle packing problem. This method represents relative positions of rectangles by using a pair of rectangle name sequences, called Γ_+ and Γ_-. Γ_+ and Γ_- indicate the rectangle sequences in diagonally right up and diagonally right down respectively. Figure 3 shows a layout example, its relative position and its sequence pair.

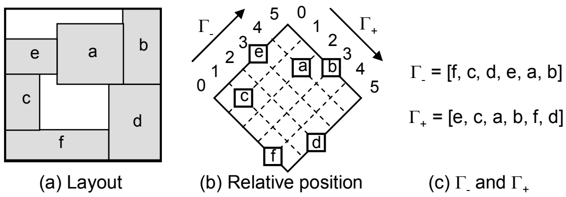

Figure 3: Example of layout and its sequence-pair.

When relative positions of rectangles are described by Γ_+ and Γ_-, the absolute positions of the rectangles without overlap within minimum area can be uniquely obtained by making horizontal and vertical constraint graphs based on Γ_+ and Γ_- and by calculating longest paths in both graphs. Figure 4 shows their examples. See the reference (Murata et al., 1996) for the details.

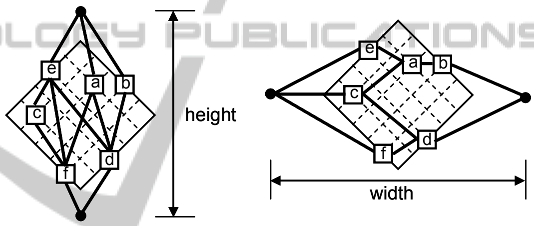

Figure 4: Horizontal / Vertical constraint graphs.

The original research (Murata et al., 1996) uses simulated annealing for searching the optimal layout with minimum area, whereas, our method uses GA with the special crossover operator called PREX (Placement-based Partially Exchanging Crossover) (Nakaya et al., 2000).

Since components / parts layout of a practical product is hierarchized, layout optimization is repeatedly executed from a part level to a product level to obtain hierarchical components / parts layout. Figure 5 shows its concept.

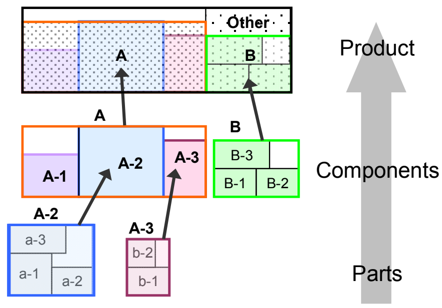

Figure 5: Hierarchical layout optimization.

2.5 Lifecycle Assessment

In the practical LCA, there are various indexes of environmental burden such as emissions of CO_2, SO_x and NO_x throughout entire product lifecycle, usage rate of renewable material and reuse / recycle rate, which are determined by entire product lifecycle scenario. However, because this research is at an early stage, the proposed method handles only selection of reuse / recycle / disposal scenario at the EOL stage and carbon emission as a design variable and an index of environmental burden respectively.

Total carbon emission of each design proposal is calculated by the following concepts.

- Carbon emission is evaluated for each part and sum of them is defined as total carbon emissions GHG_{total}. GHG is an acronym for Green House Gas.
- There are two types of parts. One has the fixed value of carbon emission GHG_i and the other has the value of carbon emission per unit area $uGHG_i$. Most parts belong to the former type, whereas some parts such as an electronic substrate belong to the latter type. In the latter type, actual value of carbon emission is calculated by multiplying $uGHG_i$ by the area $Area_i$ calculated by layout optimization.
- The value of carbon emission varies with the selection of reuse / recycle / disposal scenario, so the value for each scenario needs to be assessed by LCA. The selection also affects performance and cost of the part, so the relationship among scenario selection, carbon emission, cost and performance needs to be assessed. For example, use of recycled material increases manufacturing cost in exchange for lower carbon emission. Reuse of used parts considerably reduces both carbon emission and cost but performance of such parts can not be expected. In particular, in the field where rate of technological evolution is high, old parts become rapidly obsolete, so reuse of such parts equals use of low performance parts. Thus the proposed method is useful in balancing product eco-friendliness and other criteria at higher level.

Finally, total carbon emission GHG_{total} is calculated by the below equation.

$$GHG_{total} = \sum_{i=1}^{m} GHG_i + \sum_{j=1}^{n} Area_j \times uGHG_j \qquad (1)$$

Where GHG_i is the fixed value of carbon emissions of part i, whereas, $uGHG_j$ is the value of carbon emissions per unit area of part j. $Area_j$ is the value of area of part j.

3 CASE STUDY

3.1 Problem Description

In the case study, internal devices of a personal computer are designed using the proposed method . “Internal devices” means that input devices, a display and an enclosure are not included. To make the case study simpler, only reuse and disposal are considered as alternatives of the lifecycle scenario at the EOL stage. Reuse scenario means reuse of the part used in the previous generation whereas disposal one means use of the new part.

A computer consists of the following 5 components: motherboard, HDD, cooling system, power supply and auxiliary storage. Motherboard, cooling system and power supply can be decomposed into more than one part, whereas HDD and auxiliary storage can not be decomposed any more. Figure 6 shows its functional structure. Note that, due to space limitation, the lower functional structure of Motherboard B is not described in this figure. Motherboard B is similar to Motherboard A, but has powerful CPU, more Memory and discrete graphic card. (R) writen after the part name means that the part is reused one. Table 1 shows examples of their alternatives and specifications. As for the new parts, prices and sizes are based on their retail price surveys and size measurments. Performances are subjectively and intuitively configured. Carbon emission is based on the reference (Japan Environm ental Management Association For Industry, 2007). As for the reused parts, their specifications are estimated from ones of the similar or same new parts.

Table 1: Part example (HDD).

HDD	Cost (USD)	Dimension (cm)	Perfor mance	CO_2 (kg)
MK8009GAH	75	5.5*8.0	2	1.31
MK1214GAH	150	5.5*8.0	3	1.31
MK4007GAL (R)	30	5.5*8.0	1	0.78
WD1600BEVT	42	7.0*10.0	4	2.72
WD3200BEVT	66	7.0*10.0	5	2.72
MK8025GAS (R)	21	7.0*10.0	2	1.63
WD5000AAKB	160	10.0*14.5	7	10.88
WD1002FBYS	220	10.0*14.5	10	10.88
6L320R0 (R)	80	10.0*14.5	4	6.53

As for criteria, performance is handled as an objective function, whereas cost, total area and total carbon emission are handled as constraint conditions. Table 2 shows parameters of HGA and GA.

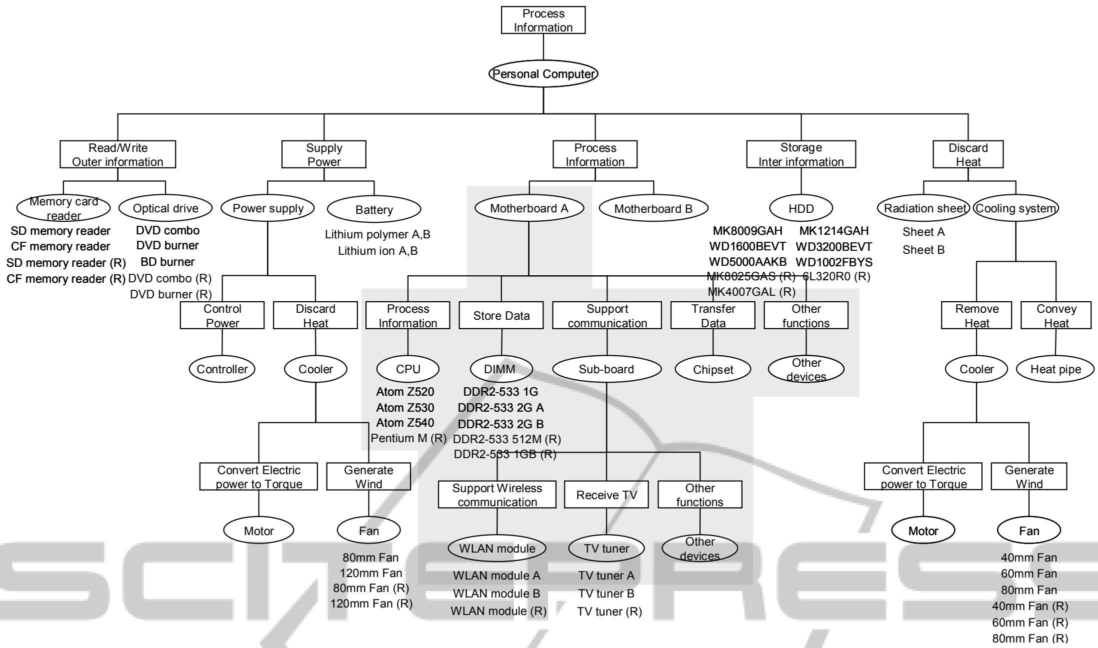

Figure 6: Functional structure designed in the case study.

Table 2: Parameters of HGA and GA.

	HGA	GA
Population	100	60
Crossover rate	1	1
Mutation rate	0.05	0.01
Generation gap	0.9	0.5
Terminal generation	200	50

3.2 Results

For comparison, both our previous method that considers neither lifecycle scenario nor carbon emission and the proposed method are executed here. Figure 7 shows the results using our previous method. In this case, 12 optimizations ars executed under 12 various cost constraints from 550 USD to 2550 USD and constant area constraint (Area < 1200 cm^2). Note that reused parts are not available in this case. The optimal layouts of the design solutions denoted by two stars in Figure 7 are shown in Figure 8.

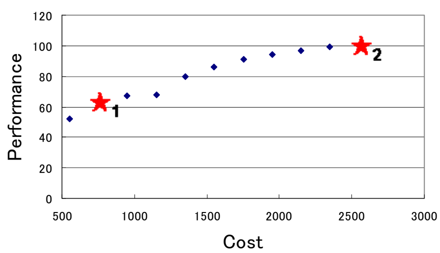

Figure 7: Relationships between performance and cost of the obtained solutions using our previous method.

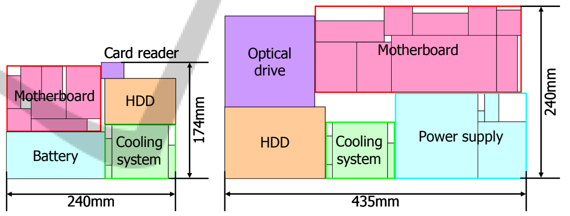

Figure 8: Optimal layouts (Left: star 1, Right: star 2).

Figure 9 shows the result using the proposed method. In this case, 16 optimizations are executed under 16 various constraints of carbon emission from 7.5 kg to 45 kg and constant const and area constraints (Cost < 3000 USD and Area < 1500 cm^2). This results shows that the constraint of carbon emission makes it difficult to design high performance PCs even if the constraints of cost and area are sufficiently relaxed. The design solusions with higher performance tend to consist of only new parts whereas the design solutions with lower performance tend to consists of many reused parts. From the other point of view, the parts that are making rapid progress such as CPUs and HDD are infrequently reused, whereas the parts that are not making progress such as auxiliary storages and cooling fans are frequently reused. Use of reused parts can reduce carbon emission, but at the same time makes it difficult to achieve high performance. Thus the proposed method is useful in balancing product eco-friendliness and other criteria at a higher level.

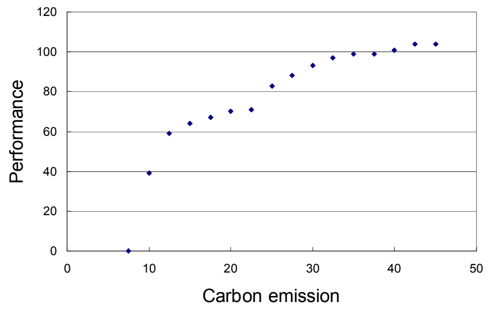

Figure 9: Relationships between performance and cost of the obtained solutions using the proposed method.

4 CONCLUSIONS

Due to rise of environmental awareness in recent years, companies are required to assess and reduce environmental burdens of their products. In response to this, this paper proposes a new integrated method for simultaneously optimizing a product concept and its lifecycle scenario by evaluating product characteristics such as performance, cost and size and environmental burdens such as carbon emission as criteria. Using the proposed method, optimal product concept and its lifecycle scenario that balance product characteristics and environmental burdens at a higher level can be obtained. In the case study, the proposed method is applied to a design of a personal computer and the results show the needs of consideration of lifecycle scenario and environmental burdens during conceptual design phase.

As for future works, we are planning to consider modularization of parts and components. In recent products, components and parts are modularized due to various reasons. Modularization also affects lifecycle characteristics of the product. Therefore, to allow optimal modular design for product lifecycle, we are planning to expand our method proposed in this paper.

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