EcoDesign for Product Variety: A Multi-Objective Optimization Framework

Suiran YU Satoru KATO Fumihiko KIMURA
The University of Tokyo, Department of Precision Machinery Engineering
Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan
{yu,satoru,kimura}@cim.pe.u-tokyo.ac.jp

Abstract

This paper presents an approach to EcoDesign for product variety. The objective of the research is to get a quantified life cycle scenario to support design, manufacturing and life cycle management. Towards this goal proposed is a novel multi-objective optimization framework in which the problem is structured as minimizing the deviations from the concerned objectives. A mathematic programming method called Goal Programming(GP) help designers to solve the problem, which previously had been based on experience together with evaluation of individual objectives in isolation. Our proposed method is particularly valuable in a multi-objective situation where there are a number of important and incommensurable objectives that belong to several different interest groups(user, maker and/or government). Parametric study is performed to analyze the trend of change of variables with the changes of parameters and objectives priorities. The multi-objective optimization algorithm will provide a set of non-dominant designs where a further improvement for one objective will be at the expense of another. From the set the preferable one can be selected based on selected criteria by life cycle simulation or other means. Fuzzy set is used to quantify and transform incomplete and ambiguous information when determining values of parameters for modeling product life cycle. Existing refrigerator is used as a demonstration example.

1. Introduction

Sustainable manufacturing in the 21st century can be achieved by two approaches. One is to develop methods serving toward the creation of designs with thought given to reuse and recycling from the very early stage. The other is to improve the functions of artifacts, while decreasing the production volume but keeping the level of service and economic activities. This is feasible through redefining the manufacturing industry as a life cycle industry to take wider life cycle issues into consideration. And quantitative approach will lead to better decision making than non-quantitative approach. Based on this recognition, Environmental impacts must be weighed and balanced against other concerns, such as Life Cycle Cost(LCC), availability and time to market etc. These multiple, often conflicting, objectives pose a challenging and complex optimization problem.

Life cycle design can be treated as an optimization problem to maximize societal needs while minimizing resource consumption and waste dispersion activities[1]. Even though the importance of life cycle optimization has been proposed[2][3], and research about life cycle optimization on one stage such as maintenance[4] or on one aspect such as LCC[5][6] or other[7] have been conducted, research about optimization on whole life cycle has seldom come into eyes[8]. This is perhaps mainly because the complexity of a life cycle is enormous because so many variables and constrains should be included, data and models are also insufficient.

LCD can be divided roughly into two types: design of completely new product and design for variety according to existing product. Drastic changes in design topology cannot be dealt with mathematically in any reasonably useful way[9], So only latter type is discussed in this paper. Many authors have written about product variety. Pine [10] discusses the importance for development of product variety in current marketplace. Kimura[11] proposes a methodology for design and management of product life cycle adapted to product usage modes.

The objectives of this paper are: 1)Develop a structured product design methodology based on multi-objective optimization to aid design teams in designing product life cycle. 2)Propose a method to predict parameters' values of product to be developed for life cycle optimization or other design purposes.

2. Life Cycle Optimization Design Model

In order to satisfy customers' service needs of all levels,

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it is necessary to maintain a family of products in the market in proper mount, functions and quality. To realize the development of product variety, an approach to life cycle design modeling based on multi-objective optimization is discussed. Figure 1 shows the realization of product variety by mean of life cycle optimization design.

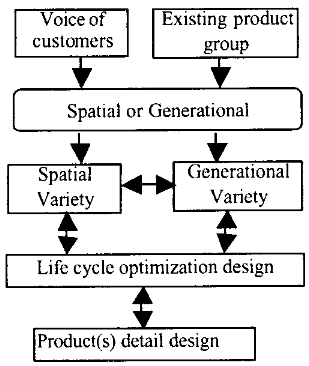


Figure 1. Realization of product variety by life cycle optimization

2.1. Framework of Life Cycle Optimization Design

Life cycle optimization problem is characterized by multi-objective, a large design variable space, and a great number of design constrains. Figure 2 illustrates the framework of life cycle optimization process model. A brief description on Figure 2 is made bellow. The figures on the left sides of the blocks are only block numbers that is used for easy description, not the activities' sequence numbers of the process.

Both product innovation design and product variety(modification and improvement) design are all based on the market need analysis as is shown in block 0. Market analysis is to obtain market information that includes (1)total market size and its trend throughout the product life cycle, (2)potential competitor (3)prediction of potential customers and their preference. This information is the basis of future product development.

Block 1 is to conduct the task of determination of new design problem(s). These problems mainly include: (1)how to satisfy the customers' need in different functions and/or levels: one product or a family of product in spatial and/or generational, (2)in what degree and/or in which place does the current product(s) need changing, (3)what is competition strategy: cost leadership, niche market, or others.

Quality Function Deployment(QFD) is a well-known design methodology. Here(block 2) we use the term "QFD-based analysis" to mean that QFD of existing product, that is most close to the developing product, is utilized as a reference(or tool) to predict the values of parameters(block 4) of under developing product in life cycle optimization models. Moreover, QFD of existing products can also be used to as reference to generate QFD of under developing product.

Block 0, 1, 2 and 3 discusses the problem about how to predict the product data to be developed. This problem will be more detailed studied in section 2.4.

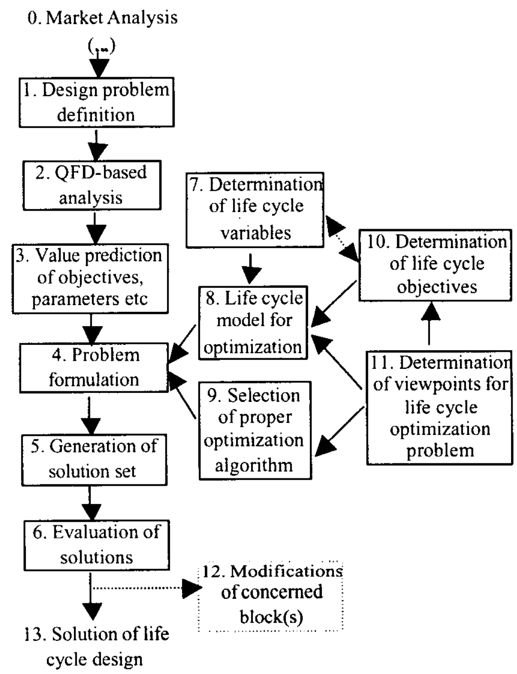


Figure 2. Life cycle optimization process model

Problem formulation(block 4) is to give the mathematic presentation of objectives in terms of life cycle variable. As is shown in Figure 2, Problem formulation is based on life cycle modeling, optimization algorithm selection and value prediction of parameters in life cycle models. Selection of algorithms mainly depends on the following factors:

- Visions on characteristics of practical problem
- Availability of existing software
- Data available

After formulating the problem, we can solve the optimization problem by virtue of the existing software and get one solution of the problem. This solution is only the solution under one supposed condition among many possible cases.

Changes of these conditions may produce different solutions that generate a solution set(block 5) that is often referred to as Pareto set. The evaluation of design alternatives in Pareto set and selection(block 6) of the best possible solution are viewed one main part in life cycle design and is performed chiefly by life cycle simulation[12], LCA[13], multi-criteria decision making[14]etc.

Life cycle variables(block 7) are used to describe life cycle design alternatives. These are quantities that differentiate product life cycle by assuming different values within acceptable range. This will be discussed in section 2.2.

Determination of objectives(block 10) is subject to viewpoint(block 11) of life cycle design teams that will be stated in section 2.3.

2.2. Life cycle variables in LCD

Three types of figures are used in the optimization models: variables, parameters and constant. Variables are used to describe life cycle design alternatives. These are quantities that differentiate product life cycle by assuming different values within acceptable range. Parameters are quantities that given one specific value under particular conditions. Constants are quantities fixed by the underlying phenomenon rather than by the particular model statement, typically natural constants.

We determine life cycle variables for life cycle optimization as shown in Figure 3. These variables cover all stages of product life cycle and relate product itself.

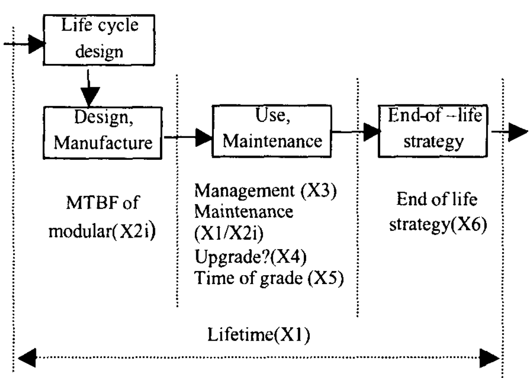


Figure 3. Typical life cycle variables

The clear distinction between variables and parameters is very important at modeling stage[Papalambros,1988]. The choice of what quantities will be classified as variables or parameters is a subjective decision dictated by choices in hierarchical level(e.g. product, modular, component), boundary isolation(e.g. a group of product, all life cycle stages of one product, one or some life cycle stage of one product).

When we define problem variables, we must examine at what level we are operating. The lower level in hierarchy we operate, the more variables will be included generally. Careful examination on hierarchy will clarify the concepts and relations among the nature of the model, the classification of variables, parameters and constant, and the appropriate definition of objectives and constrain functions. Designers' goals also influence the operating level and then influence variables' selections. For example, designers can choose the optimization model until the level to determine whether maintenance is necessary or until the its lower level to determine which maintenance forms should be taken(scheduled, condition-based or corrective) if maintenance is needed. Often the operating level will also be determined by the model complexity and the actual mathematical size of the problem. The best strategy is to start always with the simplest meaningful model, where meaningful means containing trade-offs that can be explored by an optimization study. This characteristic is obviously a subjective one, depending on the judgment of designers.

Table 1 shows typical life cycle variables in proposed life cycle optimization design.

Table 1. Variables in life cycle optimization

Symbol	Name	Unit	Type
X1	Life time	Year	Real
X2i	MTBF of modular I	Year	Real
X3	Management	None	Integer
X4	Upgrade(Yes, No)	None	Integer
X5	Upgrade time	Year	Real
X6	End-of-life strategy	None	Integer

The ranges of variables, as constrains of optimization models, have direct influence on the results of optimization. The basic principle for range determination of variables is making the range as narrow as possible to have constrains more active but without missing possible solutions. Generally the range is wider in the case of less information and is narrower in the case of more sufficient information.

2.3. The identification and modeling of objectives

Objectives are the items of interest for different interest groups that make up of society. They are the things that get included in models and that allow the evaluation of alternative solutions. The practical implication of operationally useful objectives is how much time and effort the decision makers may expend on the identification and measurement of objectives. As decision makers may first perceive evaluation in terms of ideal, and they must persist until a set of objectives has been developed.

Table 2. Objectives and reference factors for value-setting

Names of objectives	Symbols (Obj(i))	Unit	Value-setting factors
Energy consumption	Econ	Kwh	Law, competitors
Waste disposal	Wdis	Kg	Image, profit
LCC from user side	LCCuser	JPY	Affordability
Function	Func	None	User need
Quality	Qual	*	Competitors
LCC from maker side	LCCmaker	JPY	Profit
Time to Market	Tmar	Month /week	Competitors
Availability	Av	None	Profit

Symbol * means quality includes several aspects like performance, feature etc, then has different units.

Different objective has different value-setting method. Table 2 shows reference factors for value-setting of the objectives stated above in this section.

To set up life cycle model for each objective is to set up mathematical models for each objective in terms of the decision variables of a problem. We think that setting up good life cycle models is one of most important factors for performing life cycle optimization. It is considered that life cycle modeling to objective is closely related to the following factors:

- Knowledge concerning life cycle engineering
- Life cycle variables selected
- Data available

When setting up model, we need paying attention to the following points:(1)Items closely related to variable(s) should include variable(s); items that are not or slightly related to variable(s), variable(s) can be neglected, hence regard all these items as one constant. (2)Errors of all items should be balanced if the model is in the form of sum of items.

The relations of objectives should be as independent as possible. But the absolute independence among objectives is difficult to realize. Fortunately, interdependence among objectives has little influence on optimization as long as the relations among objectives are properly modeled.

Modeling objectives in terms of variables appears the form like:

$$Obj(i)=fi(X1,X2i,X3,X4,X5,X6)$$

In practical case, designers can add other variable(s) and/or objective(s) to, or delete variable(s) and/or objective(s) from, table 2 and table 3 respectively.

2.4. Product data prediction

In order to get more accurate values of life cycle variables in the life cycle optimization models, the most important thing is to obtain the values of the parameters in these models. From the set of LC optimization models, we know that the parameters mainly include objectives and coefficients of variables.

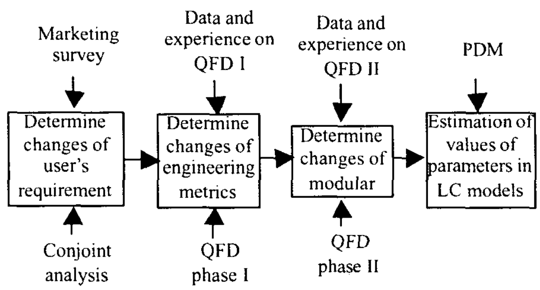


Figure 4. Process diagram for values estimation of parameters

The method proposed in this paper for derivation of parameters' values of product to be designed is based on process modeling tool like IDEF(Integrated Definition Methodology) and SDG(Signed Direct Graph), and is with the support of QFD(Quality Function Deployment), PDM(Product Data Management). Because the estimation of data about product to be designed across its life cycle is very difficult and often is with the uncertainty, a membership function of fuzzy sets is introduced to quantify incomplete and ambiguous information of process variables.

Knowledge and experience on the concerned methods like QFD, SDG, IDEF3 are very important for the proposed method. So a qualitative and quantitative analysis knowledge base is considered very helpful for reasoning of value generation of product parameters in life cycle optimization models.

Even if the calculation in the proposed method is rough because something about the product to be developed is difficult to estimate, it is considered to be acceptable for the reasons that life cycle design itself is a rough design in macro, and that some error is permitted from the viewpoint of engineering.

3. Case Study

To demonstrate the application of proposed life cycle optimization method, family-use refrigerator(2 doors, 130L, energy consumption yearly is about 500KWh, price is thirty thousand Japanese Yen(National product catalogues based)) is used as an example.

In order to simplify the discussion, the following assumptions are made:

1 Three modular(compressor, controller and valves) with different MTBF(Mean Time Between Failure) are considered among total five modular.

2 Upgrade is influenced by customers' requirement and technology status at the time. Here only one modular(compressor) is considered.

3 Different modular have different producing cost.

4 Non-linear relations are linearized in many places.

5 Data in the models is predicted by the method presented in section 2.4. But some data are imagined and made as close as possible to reality.

6 Three objectives: (1) LCC from user side(LCCuser), (2) LCC from maker side(LCCmaker), (3) Availability(Av) and six variables are selected in the example.

A mathematical programming model called Goal Programming(GP) is employed to solve the life cycle optimization problem. All the objectives are incorporated into the objective function in which different priorities to each objectives can de assigned. Goal programming is to minimize the sum of deviations from the desired objectives.

With the elimination of formulating process, the formulation results are as follows:

Minimize: $Z=D1+D2+D3$

Subject to: $f_1(X1,X21,X22,X23,X4,X5)+D1^-=B1$

$f_2(X1,X21,X22,X23,X4,X5)+D2^-=B2$

$f_3(X1,X21,X22,X23,X4,X5)-D3^+=B3$

Constrains: $0=<X1=<20$; $8=<X21=<10$; $7=<X22=<10$; $8=<X23=<10$; $X4=0,1$; $8=<X5=<20$;

Where Di are deviations from the desired objectives; Bi are values of objectives.

The optimization results by software LINDO are listed as follows:

VARIABLE	VALUE	REDUCED COST
X4	1.000000	0.000000
D1	0.000000	1.000000
D2	0.000000	1.000000
D3	0.000000	1.000000
X1	16.750000	0.000000
X5	8.000000	0.000000
X21	8.000000	0.000000
X22	8.839744	0.000000
X23	8.480769	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
LCCUSER)	0.000000	0.000000
LCCMAKER)	0.000000	0.000000
AVI)	0.000000	0.000000
X1X5)	0.750000	0.000000

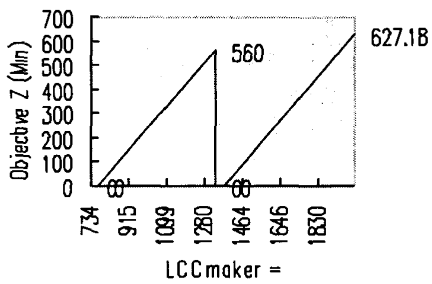
From the optimization results we know (1) optimal lifetime is 16.75 years, (2) optimized MTBF of the three modilar are 8, 8.84 and 8.48, (3) upgrade of compressor is necessary(X4=1), upgrade time is 8 years from the use of the product, (4) It is implied that maintenance is necessary for controller and valves from product lifetime(16.75) and MTBF of the two modular(8.84, 8.48), (5) All the three objectives are achieved(D1=D2=D3=0). Other listed information, REDUCED COST, SLACK OR SURPLUS and DUAL PRICES, is for the purpose of sensitivity analysis.

After the solution has been obtained, designers should check the effect of changes in the values of parameters in LC optimization model. Small changes in these values are studied by sensitivity analysis as stated above. Lager change in parameters values are more useful but also difficult to study. Generally speaking, parametric study needs to solve the problem once and again with the change of one parameter value or with change of sets of parameter values, so the optimal solution is not one but a solution set. This is important because the classification of variables and parameters is subjective. From the designers' viewpoint, parametric study is extremely important because it provide information about the nature of the optimal design problem. These parameters mean objectives' values and coefficients of variables in the model. Moreover, change of other conditions like objectives' priority and range of variables may also greatly influence the optimization results and then need a complete study together with the parametric study.

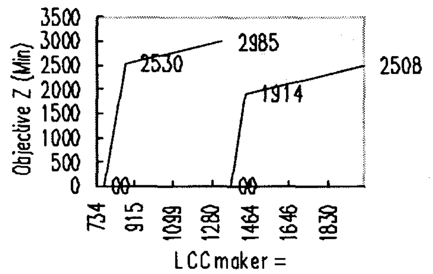
In the paper, only a few examples are presented for discussion. Figure 5 shows realization degree of objectives with the change of objective(LCCmaker), and the compare between the two conditions of without priority((a) in Figure5) and with priority((a) in Figure 5)

From Figure 5, we can understand the differences between (a) and (b): (1) there is a range(1331~1333) within which no optimal solution can be avilable, (2) under the impossible cases of realization of objectives, the degree of deviation from objectives is different.

Figure 6 shows the influence of change of objective(LCCmaker) to variables. From the figure, we know that the values of variables changes greatly at the point where the value of LCCmaker is 1334, and right at this point maintenance status changes from unnecessary to necessary.



(a) without priority



(b) with priority

Figure 5. realization degree of objectives with the change of objective(LCCmaker)

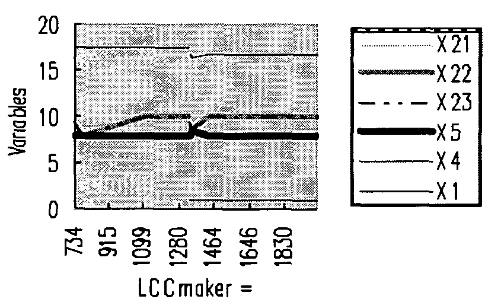


Figure 6. Influence of change of objective(LCCmaker) to variables

4. Conclusions

A multi-objective optimization based EcoDesign method is proposed for realization of life cycle design for variety correspondent to the customers' requirements. Example demonstrated that the proposed method is of practical value. Data obtained from proposed product data prediction method can be widely used for different purposes in product design. Parametric study was performed to analyze the trend of changes of solutions with the changes of parameters and objectives priorities. The future work will focus on the improvement of life cycle models and accuracy enhancement of data prediction.

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