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Integrated Evaluation of Green Design and Green Manufacturing Processes Using a Mathematical Model

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Abstract**—**In this research, a mathematical model for integrated evaluation of green design and green manufacturing processes is presented. To design a product, there can be alternative options to design the detailed components to fulfill the same product requirement. In the design alternative cases, the components of the product can be designed with different materials and detailed specifications. If several design alternative cases are proposed, the different materials and specifications can affect the manufacturing processes. In this paper, a new concept for integrating green design and green manufacturing processes is presented. A green design can be determined based the manufacturing processes of the designed product by evaluating the green criteria including energy usage and environmental impact, in addition to the traditional criteria of manufacturing cost. With this concept, a mathematical model is developed to find the green design and the associated green manufacturing processes. In the mathematical model, the cost items include material cost, manufacturing cost, and green related cost. The green related cost items include energy cost and environmental cost. The objective is to find the decisions of green design and green manufacturing processes to achieve the minimized total cost. In practical applications, the decision-making can be made to select a good green design case and its green manufacturing processes. In this presentation, an example product is illustrated. It shows that the model is practical and useful for integrated evaluation of green design and green manufacturing processes.

Keywords**—**Supply chain management, green supply chain, green design, green manufacturing, mathematical model.

I. Introduction

IN the product development stage, with a given product conceptual design, there can be alternative ways to design the detailed product specifications to fulfill the same product requirement. The feasible options for designing the detailed specifications of the product can be described as design alternative cases. To satisfy the product requirements and product concept, the components of the product can be designed with different dimensions, shapes, materials, finishing, and other specifications in the different design alternative cases. In this way, the manufacturing processes for producing the components and the product can be different. As a result, in the design alternative cases, if the detailed material and specifications are different, the manufacturing processes for producing the components and assembling the product can be different. If the manufacturing processes are different, the cost for producing the product can be affected. Therefore, it is necessary to evaluate the different design alternative cases and their effects on the associated manufacturing processes.

In the typical supply chain management concept, the design cases and manufacturing processes are evaluated mainly based on the criteria of cost and quality. The impact of the manufacturing processes on the environment is often not included in the evaluation. As a result, a good product solely developed for low cost in manufacturing may increase the cost associated with environmental impact. For example, a low cost in the manufacturing activities may result in a high cost in the energy usage, environmental impact, and so on. Therefore, it is required to include the green related cost with consideration of energy usage and environmental impact.

In this research, a new concept of integrated evaluation of green design and green manufacturing is presented. A green design can be determined if the designed product can be manufactured with green manufacturing processes by evaluating the specified green criteria to achieve the designated green purposes. In this paper, the criteria of energy usage and environment impact are added in the evaluation model, in addition to the traditional criteria of material cost and manufacturing cost. The integrated evaluation of green design and green manufacturing activities can be described as a green supply chain model.

In a green supply chain, a green design can be decided if the product can be manufactured with green manufacturing processes in which the designated green purposes can be attained. If several design alternative cases are proposed, the different design alternative cases can affect the decisions of manufacturing activities. A design alternative case not only changes the product, but also affects the activities in manufacturing and the green supply chain. Therefore, it is necessary to consider the design alternative cases before the product is actually manufactured and sent to the market. In the product life cycle, to avoid a high cost in the green supply chain, it is important to analyze and evaluate the green design and green manufacturing processes based on the green criteria in a concurrent way. With the above concept, a mathematical model for integrated evaluation of green design and green manufacturing processes is presented in this research.

In the developed mathematical model, the decision variables are modeled as 0-1 integer variables. The integer variables represent whether a material is selected and whether a manufacturing process is selected for the designed product in a design case. There are two main cost items: material cost and

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manufacturing cost. The material cost items include raw material cost, pollution substance cost, and reverse logistics cost. The manufacturing cost items include manufacturing process cost, environmental impact cost, and energy usage cost. From a different point of view of the cost items for a green design, the green related cost items include energy usage cost, pollution substance cost, and environmental impact cost. The manufacturing related cost items include raw material cost and manufacturing process cost. The total cost is the sum of the above described cost items. Given the available design cases, the decision of a design case and the associated materials and manufacturing processes can be made using the decision variables by minimizing the total cost.

The purpose of the mathematical model is to evaluate the design cases to make selections of the material and manufacturing process. The aim is to decide a green design and its green manufacturing processes with minimized total cost subject to the specified constraints. The decision variables are defined to represent whether a material is selected and whether a manufacturing process is selected in a design case. An integer variable is defined to represent the number of a component produced using a specific material and a specific manufacturing process in the product. The data tables are modeled for a given material and a manufacturing process for each of the design cases. The material and process can be assigned to produce a component of the product based on the constraints in the data tables to achieve the cost objective.

The presented model have been implemented and tested with example products. The main contribution lies in the new concept of integrated evaluation of the design alternative cases, the manufacturing activities, and the activities in the green supply chain. The test results show that the presented model and solution method are feasible and useful for modeling the integrated evaluation problem. In this presentation, the test result of an example product is illustrated and demonstrated.

This paper is organized as follows. In this paper, Chapter I presents an introduction. Chapter II presents a literature review. Chapter III describes the models and the methods. In Chapter IV, the implementation and testing of the model is demonstrated. Finally, a conclusion is presented in Chapter V.

II. Literature Review

In review of the literature, the concept and models for investigating green supply chains have been presented. In the previous research, the problems of supplier selection in supply chains have been presented and modeled [1]-[3]. In the recent research, a literature review of supply chain performance measurement was presented in [4]. The concept of forward and reverse logics and green supply chains has been presented in [5] and [6]. In [7] and [8], the problems of close-loop supply chain were investigated and modeled. In [9] and [10], the models of close-loop supply chain were developed and solved with optimized methods. In [11]-[13], the concept of green design has been discussed. In [14]-[15] the evaluation models for green supply chains have been presented. In [16], an evaluation model for integrating green assembly and disassembly processes has been presented. The models of green designs have been discussed in [17], [18].

Based on review of the previous literature, many of the previous papers presented models for investigating green supply chains and closed-loop supply chains. Many solution methods for solving the supplier selection problems have been developed. Several papers presented models and optimization methods for integrating the and forward and reverse supply chains. In addition, the concept of green design has been discussed. However, the issue that the product design can affect the manufacturing process and the green supply chain has not been discussed. Moreover, the design alternative cases and the affected manufacturing processes have not been evaluated in an integrated way. In summary, a model for integrated evaluation of green design, green manufacturing processes is required. Therefore, in this research, a mathematical model for integrated evaluation of green design and manufacturing processes based on the green criteria and objectives is presented.

III. Research Models and Methods

The purpose of the research is to develop a model for integrated evaluating green design and green manufacturing processes. The goal is to find the suitable design case and the selection of material and manufacturing process. In the developed model, the manufacturing related costs and the green related costs are formulated. The total cost is the sum of the above defined cost items. The decision variables are modeled as 0-1 integer variables representing whether a material is selected and whether a manufacturing process is selected in a design case. The concept and the decision tree can be illustrated as shown in Fig. 1. The mathematical model is presented as follows.

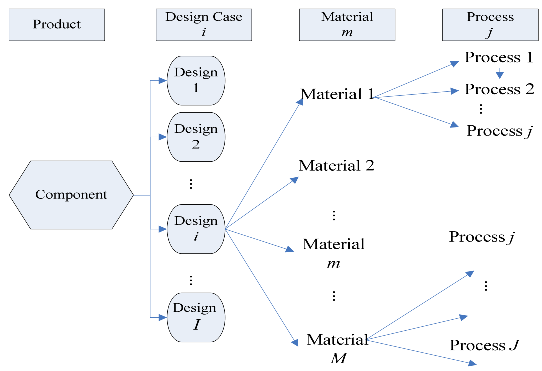

Fig. 1 The concept and decisions of green design and green manufacturing processes

A. Notations

1. Notations

The notations are listed as follows.

i : a design case (i = 1, 2, …, I),
m : a type of material (m = 1, 2, …, M),
s : a type of pollution substance (s = 1, 2, .., S),

j : a manufacturing process (j = 1, 2, …, J).

2. Parameters

The parameters are defined as follows.

h_{ims} : quantity of s in material m in design case i,

W_{im} : weight of material m in design case i,

k_{imj} : quantity of material m in process j in design case i,

L_{si} : limitation of quantity of pollution substance,

B_{im} : rate of recycling of material m,

t_{imj} : production capacity time of a product using design i and material m and process j,

T_j : capacity constraint of process j,

U_i : energy usage constraint of a product using design i,

D_{im} : required quantity of material m in design i,

C_{im} : unit cost of material m in design i,

C^H_{ims} : unit cost of pollution substance s in m in design i,

C^R_{im} : unit cost of reverse logistics of material m in design i,

C^P_{imj} : unit cost of a manufacturing process using process j and material m in design i,

C^F_{imj} : unit cost of environmental impact using process j and material m in design i,

C^K_{imj} : unit cost of energy usage using process j and material m in design i.

3. Variables

The decision variables are defined as follows.

P_{im} : 0-1 integer variable representing whether material m is selected in design i, where a value of 1 represents that material m is selected in design i,

P_{imj} : 0-1 integer variable representing whether process j is selected in material m in design i, where a value of 1 represents that process j is selected for material m in design i,

X_{imj} : number of components in the product using design i with material m and process j.

B. The Mathematical Model

$$\begin{aligned}\text{Min } & \sum_{i=1}^{I}\sum_{m=1}^{M} C_{im}\times D_{im}\times P_{im} \\ & +\sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{m=1}^{M} C^H_{ims}\times h_{ims}\times D_{im}\times P_{im}+\sum_{i=1}^{I}\sum_{m=1}^{M} C^R_{im}\times W_{im}\times B_{im}\times D_{im}\times P_{im} \\ & +\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J} C^P_{imj}\times X_{imj}\times P_{imj}+\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{e=1}^{E}\sum_{j=1}^{J}\left(C^F_{imj}\times X_{imj}\right)\times P_{imj} \\ & +\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J} C^K_{imj}\times k_{imj}\times X_{imj}\times P_{imj}\end{aligned} \tag{1}$$

s.t.

$$\sum_{j=1}^{J} X_{imj} = D_{im}\times P_{im\,i} \qquad \forall\ i,\ m \tag{2}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M} t_{imj}\times X_{imj} \le T_{j\,i} \qquad \forall\ j \tag{3}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M} h_{ims}\times P_{im} \le L_{s\,i} \qquad \forall\ s \tag{4}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J} k_{imj}\times X_{imj} \le U_i \qquad \forall\ i \tag{5}$$

$$\sum_{m=1}^{M} P_{im} \ge 1 \qquad \forall\ i, \tag{6}$$

$$\sum_{j=1}^{J} P_{imj} \ge 1 \qquad \forall\ i,\ m \tag{7}$$

$$X_{imj} \ge 0 \qquad \forall\ i,\ m,\ j, \tag{8}$$

$$P_{im} \in \{0,\ 1\} \qquad \forall\ i,\ m, \tag{9}$$

$$P_{imj} \in \{0,\ 1\} \qquad \forall\ i,\ m,\ j \tag{10}$$

C. Description and Explanation of the Mathematical Model

1. Objective Function

In (1), the objective is to minimize the total cost to achieve the goal of green design and manufacturing by making decisions of design cases, materials, and manufacturing processes. In the objective function of the mathematical model, the decision variables are modeled as 0-1 integer variables. The decision variable P_{im} represents whether material m is selected for design i. The decision variable P_{imj} represents whether a process j is selected for material m in design i. There are two main cost items: material cost and manufacturing cost. The material cost items include raw material cost, pollution substance cost, and reverse logistics cost. The manufacturing cost items include manufacturing process cost, environmental impact cost, and energy usage cost. The total cost is the sum of all the cost items. The objective is to minimize the total of the cost items. The cost items are described as follows.

2. Material cost

The material cost items include raw material cost, pollution substance cost, and reverse logistics cost. The three cost items are described as follows.

i. Raw material cost: $\sum_{i=1}^{I}\sum_{m=1}^{M} C_{im}\times D_{im}\times P_{im}$

Raw material cost can be obtained by multiplying unit cost of material m (C_{im}), quantity of material m (D_{im}), and decision variable P_{im} indicating whether material m is selected in design case i.

ii. Pollution substance cost: $\sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{m=1}^{M} C_{ims}^{H} \times h_{ims} \times D_{im} \times P_{im}$

Pollution substance cost can be obtained by multiplying unit cost of pollution substance in material m (C_{ims}^{H}), weight of material m (W_{im}), quantity of material m (D_{im}), quantity of s in material m (h_{ims}), and decision variable P_{im} indicating whether material m is selected in design case i.

iii. Reverse logistics cost: $\sum_{i=1}^{I}\sum_{m=1}^{M} C_{im}^{R} \times W_{im} \times B_{im} \times D_{im} \times P_{im}$

Reverse logistics cost can be obtained by multiplying unit cost of reverse logistics in material m (C_{im}^{R}), weight of material m (W_{im}), quantity of material m (D_{im}), rate of recycling of material m (B_{im}), and decision variable P_{im} indicating whether material m is selected in design case i.

3. Manufacturing Cost

The manufacturing cost items include manufacturing process cost, environmental impact cost, and energy usage cost.

i. Manufacturing process cost: $\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J} C_{imj}^{P} \times X_{imj} \times P_{imj}$

Manufacturing process cost can be obtained by multiplying unit manufacturing cost of a product using process j and material m in design i (C_{imj}^{P}), number of products using design i with material m and process j (X_{imj}), and decision variable representing whether process j is selected in material m in design case i (P_{imj}).

ii. Environmental impact cost: $\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{e=1}^{E}\sum_{j=1}^{J}\left(C_{imj}^{F} \times X_{imj}\right) \times P_{imj}$

Environmental impact cost can be obtained by multiplying unit environmental impact cost in material m (C_{imj}^{F}), number of products using design i with material m and process j (X_{imj}), and decision variable representing whether process j is selected in material m in design case i (P_{imj}).

iii. Energy usage cost: $\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J} C_{imj}^{K} \times k_{imj} \times X_{imj} \times P_{imj}$

Energy usage cost can be obtained by multiplying unit cost of energy usage in material m (C_{imj}^{K}), number of products (X_{imj}), and decision variable representing whether process j is selected in material m in design case i (P_{imj}).

4. Manufacturing and Material Constraints

i. Product requirement constraint: $\sum_{j=1}^{J} X_{imj} = D_{im} \times P_{imj}$

The product requirement is equal to the required quantity of material m in design i (D_{im}) multiplying the variable represents that process j is selected in material m in design case i (P_{imj}).

ii. Manufacturing capacity constraint: $\sum_{i=1}^{I}\sum_{m=1}^{M} t_{imj} \times X_{imj} \leq T_{j}$

iii. Constraint of pollution substance: $\sum_{i=1}^{I}\sum_{m=1}^{M} h_{ims} \times P_{im} \leq L_{s}$

iv. Constraint of energy usage: $\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{j=1}^{J} k_{imj} \times X_{imj} \leq U_{i}$

5. Assignment Constraints

i. $\sum_{m=1}^{M} P_{im} \geq 1$

This assignment constraint represents that at least one material is selected for a design case i.

ii. Assignment constraint: $\sum_{j=1}^{J} P_{imj} \geq 1$

This assignment constraint represents that at least one process is selected for material m in a design case i.

6. Variable Constraints

i. $X_{imj} \geq 0$: integer variable

ii. P_{im} : 0-1 integer variable

iii. P_{imj} : 0-1 integer variable

The above mathematical model is formulated to minimize the objective of total cost under the constraints. From a green design and green manufacturing process point of view, the cost items can be classified into two main categories: manufacturing related cost and green related cost. The manufacturing related cost items are the traditional cost items that are considered and evaluated in the typical supply chain management models. The manufacturing related cost items include raw material cost and manufacturing process cost. The green related cost items are the additional cost items developed in the model. To realize the concept of green design and manufacturing, the green related cost items are added in the evaluation model. The considered green related cost items include energy usage cost, pollution substance cost, and environmental impact cost. The total cost is the sum of the above defined cost items. The objective is to decide a design case by minimizing the total cost under the constraints of product requirement constraint, pollution substance constraint, and energy usage constraint.

IV. Application and Implementation of the Model

The mathematical model has been implemented using the CPLEX software on a personal computer. An example product as shown in Fig. 2 is modeled for illustration. In Fig. 2, a mobile phone is used as an example for testing. The information and data of the product and the components are defined for testing and computation. The graphical models of the product and components are modeled for illustration. There are seven components in the mobile phone product, as shown in Table I. Based on the developed concept and the presented models, the product can be designed with different design alternative cases. In the different design cases, the selections of material and the manufacturing processes for producing the components and the product can be different.

The numerical data of the cost parameters can be modeled in a table format as shown in Tables II and III. The table format in Table II can be used for representing the cost parameters related to P_{im}. The table format in Table III can be used for representing the cost parameters related to P_{imj}. The table format in Table IV can be used for representation input data of manufacturing information, for example, capacity t_{imj}. After the modeling and computation using the CPLEX software, the solutions can be found. For each component of the product, the best design case can be determined as indicated in the decision variables. The solution format is shown in Table V. In Table V, using component 1 as an example, the screen frame can be designed with two material types, aluminum and plastic. If aluminum is selected, two types of manufacturing processes can be selected, press and punch and machining. If plastic is selected, two types of manufacturing process can be selected, injection and press. With the detailed information and data, the best design case can be decided and the results can be shown in the format as illustrated in Table V.

Fig. 2 The example product

TABLE I
Components of the Example Product

Component	Name of component
1	Screen frame
2	Top case
3	Holes
4	Push buttons
5	Keyboard
6	Bottom case
7	Battery cover

TABLE II
Format for Representing Cost Parameters Related to P_{IM}.

		Material m						
	P_{im}	1	2	3	4	5	6	7
Design case i	1	1	1	0	0	0	0	0
	2	1	1	0	0	0	0	0
	3	0	1	0	0	0	0	0
	4	0	0	1	1	0	0	0
	5	0	0	1	1	0	0	0
	6	0	0	0	0	1	1	0
	7	0	0	0	0	0	0	1

TABLE III
Representation Format for Cost Parameters Related to P_{IMJ}.

Cost of i		Process j					
	m \ j	1	2	3	4	5	6
Material m	1						
	2						
	3						
	4						
	5						
	6						
	7						

TABLE IV
Representation Format for Input Data T_{IMJ}

Data of i		Process j					
	m \ j	1	2	3	4	5	6
Material i	1						
	2						
	3						
	4						
	5						
	6						
	7						

V. Conclusions

In this research, a new concept of integrated evaluation of green design and green manufacturing is presented. A green design can be evaluated and decided if the designed product can be manufactured with green manufacturing processes by evaluating the green related cost, in addition to the typical manufacturing related cost. In the product development stage, a product and its components can be designed with different specifications to satisfy the same product requirement and design concept. The different design alternatives cases can affect the manufacturing processes and the related costs. In this research, a mathematical model is developed for integrated evaluation of green design and green manufacturing processes. In the presented mathematical model, the decision variables represent whether a material is selected and whether a manufacturing process is selected in a design case. There are two main cost items: green related cost and manufacturing related cost. The green related cost items include energy usage cost, pollution substance cost, and environmental impact cost. The manufacturing related cost items include raw material cost and manufacturing process cost. The total cost is the sum of the above described cost items. Given the available design cases, the decision of a design case and the associated materials and manufacturing processes can be made using the decision variables by minimizing the total cost. The developed models and solution methods have implemented and tested. An example product is illustrated in the presentation. It shows that the presented model is feasible for evaluating the design cases. The test results show that the model is practical and useful for integrated evaluation of green design and green manufacturing for the purpose of design for green logistics. Future research can be directed to investigate more detailed green related cost functions and explore more practical evaluation criteria.

TABLE V
SOLUTION FORMAT OF THE MODEL OF THE EXAMPLE

Component	Design i	Material m	Process j
1		Aluminum	Press and punch
		Aluminum	Machining
		Plastic	Injection
		Plastic	Press
2		Aluminum	Machining
		Aluminum	Press and punch
		Plastic	Injection
		Plastic	Press
3		Aluminum	Press and punch
		Copper	Press and punch
4		Plastic	Injection
		TPU	Press
		Glass	Casting
5		Plastic	Injection
		TPU	Press
		Glass	Casting
6		Aluminum	Machining
		Aluminum	Press and punch
		Plastic	Injection
		Plastic	Press
7	Battery cover	Aluminum	Machining
		Aluminum	Press and punch
		Plastic	Injection

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