

A Closed-Loop Design Model for Sustainable Manufacturing by Integrating Forward Design and Reverse Design

Yuan-Jye Tseng, Yi-Shiuan Chen

Abstract—In this paper, a new concept of closed-loop design for a product is presented. The closed-loop design model is developed by integrating forward design and reverse design. Based on this new concept, a closed-loop design model for sustainable manufacturing by integrated evaluation of forward design, reverse design, and green manufacturing using a fuzzy analytic network process is developed. In the design stage of a product, with a given product requirement and objective, there can be different ways to design the detailed components and specifications. Therefore, there can be different design cases to achieve the same product requirement and objective. Subsequently, in the design evaluation stage, it is required to analyze and evaluate the different design cases. The purpose of this research is to develop a model for evaluating the design cases by integrated evaluating the criteria in forward design, reverse design, and green manufacturing. A fuzzy analytic network process method is presented for integrated evaluation of the criteria in the three models. The comparison matrices for evaluating the criteria in the three groups are established. The total relational values among the three groups represent the total relational effects. In applications, a super matrix model is created and the total relational values can be used to evaluate the design cases for decision-making to select the final design case. An example product is demonstrated in this presentation. It shows that the model is useful for integrated evaluation of forward design, reverse design, and green manufacturing to achieve a closed-loop design for sustainable manufacturing objective.

Keywords—Design evaluation, forward design, reverse design, closed-loop design, supply chain management, closed-loop supply chain, fuzzy analytic network process.

I. INTRODUCTION

IN the design stage of a product life cycle, with a given product requirement and objective, there can be alternative ways to design the detailed specifications of the components and product. For example, for a mechanical product, the components can be designed with different geometric shapes, sizes, and dimensions. Similarly, if given the requirement of a material property of a component, the component can be assigned with different materials with detailed processing instructions. Therefore, the detailed specifications such as geometric shape, sizes, dimensions, material, and manufacturing instructions can be assigned differently to

establish the alternative design cases. Although the detailed components and specifications are various in the design cases, the same design requirement and objective can be fulfilled and achieved. Afterwards, in the design evaluation stage, it is required to make analysis and evaluation to decide and select a good design case for the final production purpose.

If the detailed specifications are different, the components and product need to be produced with different manufacturing processes. Subsequently, the manufacturing processes will affect the supply chain. Therefore, it is necessary to evaluate the effects of using the different design cases on the supply chain. For sustainable purposes, it is required to analyze how the different design cases can affect the green criteria and sustainable objective.

In a typical supply chain management system, the supplier evaluation is made mainly based on the criteria of time, cost, and quality. The objective is primary on saving cost and enhancing quality. However, due to increasing sustainable recognition and environmental regulations, the concept of green supply chain has been developed and emerging. In a green supply chain, the criteria of energy usage and environmental impact are the main factors to be considered in order to achieve a sustainable goal.

In this research, a new concept of closed-loop design for designing a product is developed. The closed-loop design model is developed by integrating the forward design and reverse design models. In the development of this research, the forward design model is the traditional design model with the common design considerations and objectives. In the forward design model of the research, the design objectives are functional design, Kensei design, design for manufacturing, design for assembly, and design for supply chain. The Kensei design factor can be categorized as the items that attract people with the shapes, usability, or emotional effects. In the traditional design evaluation stage, the forward way of thinking and objectives are used to evaluate and select a design case.

From a supply chain point of view, the forward design model is linked with the forward supply chain. The forward supply chain can be considered as the traditional supply chain in which the main evaluation indices are time, cost, and quality. By developing the new model of this research, the forward design model not only satisfies the customers' aspects of Kensei and functional needs but also satisfies the objectives of design for manufacturing, assembly, and supply chain. If the above objectives can all be considered in the creation and evaluation

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of the design cases, the design model can be described as a forward design model.

In this research, the new reverse design model can be described as a design model that considers the environmental factors and sustainable objectives. The reverse design model is developed to link with the reverse supply chain. For the purpose of a sustainable environment, at the end of the product life cycle, the product needs to be recycled, disassembled, reused, remanufactured, or properly disposed. In the reverse design model of the research, the design objectives are design for recycle, disassembly, reuse, remanufacture, and disposal. If the above objectives can all be considered in the creation and evaluation of the design cases, the design model can be described as a reverse design model. For example, it is necessary to consider how the product can be recycled, disassembled, reused, remanufactured, or disposed when the product is designed and produced. It is important that the above can all be considered in the reverse design model in order to link the reverse supply chain. The concept of a closed-design model by integrating forward and reverse design is illustrated in Fig. 1.

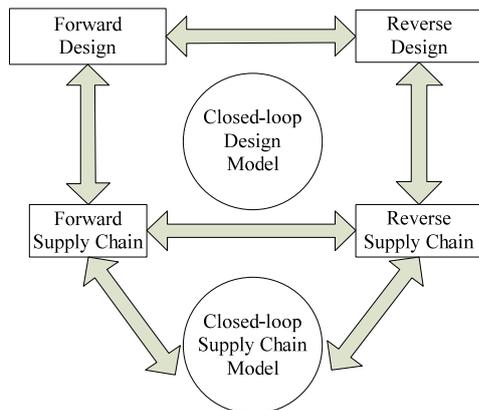


Fig. 1 The framework of the closed-loop design model

In this research, the above forward design model and reverse design model are integrated to form a closed-loop design model. In the closed-loop design model, the concept is to consider and link all the criteria early in the design stage in the product life cycle. For example, when a product is designed for functional and manufacturing purposes, it is also important to consider how the product can be recycled, disassembled, reused, or remanufactured. With this concept, the forward design model and reverse design are integrated to construct a closed-loop design model.

In this research, the concept of closed-loop design for sustainable manufacturing can be achieved by considering minimizing environmental impacts, conserving energy, and maximizing usage of material and resources. To achieve the goal of sustainable manufacturing, the green manufacturing criteria and objectives are developed. In this research, the green manufacturing objectives are considered as green material, green process, transportation, energy usage, and environmental

impact.

Based on the above discussion, a closed-loop design model for sustainable manufacturing is presented in this research. In order to make a complete evaluation of the design cases, three groups of design objectives are utilized to evaluate the design cases. The three groups are the forward design model, reverse design model, and green manufacturing model. The three groups of criteria are used to evaluate the design cases to achieve a closed-loop design for sustainable manufacturing objective, as shown in Fig. 2.

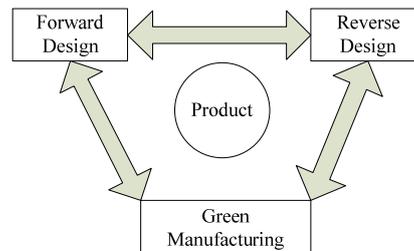


Fig. 2 The closed-loop design model for sustainable manufacturing

The evaluation criteria and objectives are summarized as follows. In the forward design model, the criteria for evaluating a design include functional design, Kensei design, design for manufacturing, design for assembly, and design for supply chain. The Kensei design factor can be described as the factors that attract people with the shapes, usability, or emotional effects. In the reverse design model, the criteria for evaluating a design include design for recycle, design for disassembly, design for reuse, design for remanufacture, and design for disposal. In the green manufacturing model, the criteria for evaluating a design include green material, green process, transportation, energy usage, and environmental impact.

In this research, a closed-loop design for sustainable manufacturing model using the fuzzy analytic network process (FANP) method is presented for evaluating the relationships among the design alternative cases. The evaluation model can be used to analyze the relationships and interactions among the three groups. In applications, the evaluation model can be applied to select a design case based on the evaluating criteria.

To evaluate the relationships among the three groups, a method using the fuzzy analytic network process is presented. A network hierarchical structure is established to represent the relationships among the criteria in the three groups. In the previous research, a product development for green logistics model by integrated evaluation of design and manufacturing and green supply chain has been presented [1]. The model of fuzzy analytic network process was presented and applied for evaluating green supply chains.

In this research, the fuzzy analytic network process method is applied in the evaluation. The main contribution lies in the new concept of a closed-loop design model. In addition, this paper developed the criteria of the three groups in the new models for a complete evaluation of forward design, reverse design, and green manufacturing to achieve the objective of

sustainable manufacturing. The evaluation model has been implemented and tested with example products. The test result shows that the presented methods and models are useful and effective for modeling and solving the integrated evaluation problem. In this paper, the test result of an example product is illustrated and demonstrated.

This paper is organized as follows. In chapter I, an introduction is presented. Chapter II presents a literature review. Chapter III describes the fuzzy analytic network process methods and the evaluation models. In chapter IV, the application of the model is demonstrated and discussed. Finally, a conclusion is presented in Chapter V.

II. LITERATURE REVIEW

In the previous research, the problems of supplier selection in supply chains have been presented and modeled with various approaches and methods. In [1], a product development for green logistics model by integrated evaluation of design and manufacturing and green supply chain has been presented. The researches [2]-[4] presented the methods for supplier evaluation and selection. In [5], a literature review of supply chain performance measurement was presented. The models of forward and reverse logics and green supply chains have been presented in [6] and [7]. In [8] and [9], the problems of close-loop supply chain were discussed and modeled. In [10], [11], the models of close-loop supply chain were developed with solution methods. The applications of close-loop supply chain models have been presented in [12]-[14]. In [15] and [16], the evaluation methods of analytic network process methods and fuzzy applications were presented.

As discussed in [1], 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 manufacturing activities and forward and reverse supply chains. However, the issue that the product design can affect the green supply chain has not been discussed. Moreover, the relationships among forward design activities, reverse design activities, and green manufacturing activities have not been evaluated in an integrated way.

Based on observation of the paper, in previous research, the traditional design activities are restricted to the forward design domain. It shows that the traditional design activities are suitable to link with the forward supply chain. However, the traditional forward design activities lack the required connection to link with the reverse supply chain. Therefore, it requires a new model of reverse design model to link with the reverse supply chain. In this way, in the design stage, the closed-loop design model can be utilized to analyze and evaluate the closed-loop supply chain.

Based on the review and discussion, in the previous research, the new concept of reverse design has not been found. To make a more complete evaluation of design activities, in this research, the new model of closed-loop design is developed by

integrating the forward design and reverse models. With the new concept, in this paper, a closed-loop design model for sustainable manufacturing using the fuzzy analytic network process method is presented for evaluating the relationships among the design alternative cases to decide the final design case.

III. RESEARCH METHODS AND EVALUATION MODELS

In this chapter, the model using the fuzzy analytic network process approach is presented. In previous research [1], the fuzzy analytic network process method was presented and applied for evaluating green supply chains. The detailed mathematical formulation can be found in [1], [15], and [16]. For the purpose of integrated evaluation of closed-loop design for sustainable manufacturing, this paper adapted and applied the model. The methods and formulations are introduced as follows.

To evaluate the relationships among forward design, reverse design, and green manufacturing, the fuzzy analytic network process evaluation model is presented. A network hierarchical structure is developed to represent the interactive relationships among the criteria in the three groups.

The interactive relationships of the criteria in the three groups are shown in Fig. 3. The evaluation criteria and objectives are summarized as follows:

- 1) Forward design model: functional design, Kensei design, design for manufacturing, design for assembly, and design for supply chain.
- 2) Reverse design model: design for recycle, disassembly, reuse, remanufacture, and disposal.
- 3) Green manufacturing model: green material, green process, transportation, energy usage, and environmental impact.

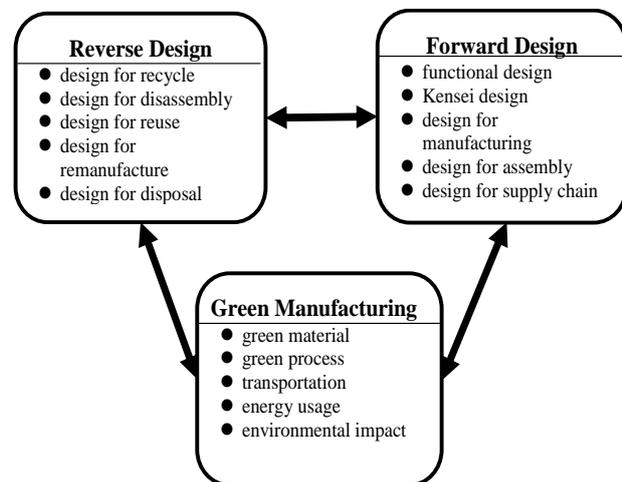


Fig. 3 The interactive relationships of the criteria in the forward design, reverse design, and green manufacturing models

A network hierarchical structure is development to link the criteria in the three groups as shown in Fig. 4. Given the network hierarchical structure, the comparison matrices for evaluating the relationships between each of the pairs of the

criteria among the three groups are established. The comparison matrices are modeled as fuzzy relational matrices. After the relational values of the pairs of the three groups are evaluated and graded, a defuzzy process is utilized. The relational values of the different criteria in the three groups can be calculated. A higher relational value indicates that a pair of the criteria has a higher relationship and a higher interactive effect.

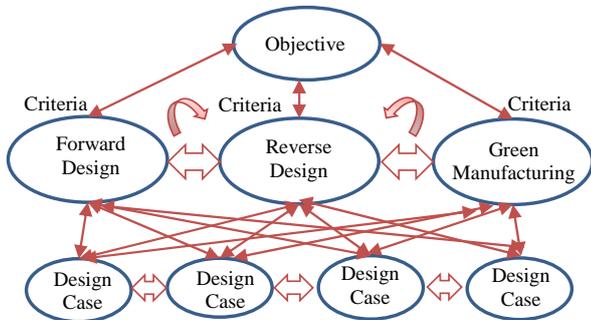


Fig. 4 The network hierarchical structure of the criteria of the FANP method

The methods and formulations of the fuzzy analytic network process model are described as follows. This paper did not create new formulations. For the purpose of integrated evaluation of closed-loop design model for sustainable manufacturing, this paper adapted and applied the model.

- 1) Create design cases. In the design stage, the detailed specifications such as geometric shape, sizes, dimensions, material, and manufacturing instructions can be designed differently to establish alternative design cases.
- 2) Create relational matrices of the forward design criteria for the design alternative cases. The relational matrix of each of the forward design criteria is built for the design cases. The forward design criteria are listed in Table I. This step develops relational matrix of all forward design criteria of the design cases as shown in Table II.
- 3) Create relational matrix of the reverse design criteria for the reverse design activities. The reverse design criteria are listed in Table III. This step develops relational matrix of all reverse design criteria of the design cases as shown in Table IV.
- 4) Create relational matrix of the green manufacturing criteria for the green manufacturing activities. The green manufacturing criteria are listed in Table V. This step develops relational matrix of all green manufacturing criteria of the design cases as shown in Table VI.
- 5) Create relational network structure. The network hierarchical relational structure of the three groups of forward design, reverse design, and green manufacturing is developed and shown in Fig. 4. The detailed information is shown in Tables I-VI.
- 6) The notations in the tables are as defined as follows.
 - α : Set of components in design cases
 - β : Set of components in design cases

p_{α} : Components in design cases

p_{β} : Components in design cases

- 7) Develop comparison matrix between the criteria of the three groups of forward design, reverse design, and green manufacturing, as shown in Table VII.
- 8) Evaluate pair-wise comparison with evaluation and grading values provided by the decision makers.

$$A_{ij} = \begin{bmatrix} 1 & a_{12} & a_{13} & \dots & a_{1p} \\ a_{21} & 1 & a_{23} & \dots & a_{2p} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{p1} & a_{p2} & a_{p3} & \dots & 1 \end{bmatrix} \quad (1)$$

A_{ij} : The matrix of j criterion in i group. a_{mn} : The n evaluation value of m criterion. P : number of criteria.

$$a_{nm} = 1/a_{mn}, \quad \forall m, n = 1, 2, \dots, p.$$

- 9) Check consistency of the evaluation and grading. Check consistency using consistency index ($C.I.$). If $C.I.$ is equal to 0, it indicates that the evaluation and judgment is consistent. If $C.I.$ is greater than 0, then it is inconsistent. If $C.I.$ is equal to or smaller than 0.1, it can be decided as consistent:

$$C.I. = \frac{(\lambda_{max} - p)}{(p - 1)} \quad (2)$$

If $C.I. \leq 0.1$, it is consistent.

$$C.R. = \frac{C.I.}{R.I.} \quad (3)$$

If $C.R. \leq 0.1$, it is consistent.

$R.I.$: Random Index.

- 10) Construct the fuzzy relational matrix.

$$\tilde{a}_{mn} = (l_{mn}, a_{mn}, u_{mn})$$

l_{mn} : The left value of the fuzzy number of the n evaluation value of m criterion. a_{mn} : The middle value of the fuzzy number of the n evaluation value of m criterion. u_{mn} : The right value of the fuzzy number of the n evaluation value of m criterion.

$$\tilde{A}_{ij} = [\tilde{a}_{mn}] = \begin{bmatrix} 1 & \tilde{a}_{12} & \tilde{a}_{13} & \dots & \tilde{a}_{1p} \\ \tilde{a}_{21} & 1 & \tilde{a}_{23} & \dots & \tilde{a}_{2p} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{p1} & \tilde{a}_{p2} & \tilde{a}_{p3} & \dots & 1 \end{bmatrix} \quad (4)$$

TABLE I
FORWARD DESIGN CRITERIA

D ₁	D ₂	D ₃	D ₄	D ₅
functional design	Kensei design	design for manufacturing	design for assembly	design for supply chain

TABLE II
RELATIONAL MATRIX OF FORWARD DESIGN CRITERIA

	α	β	Relational value				
			D ₁	D ₂	D ₃	D ₄	D ₅
Design Case	$p_{\alpha i}$		$P_{\beta 1}$				
		$P_{\beta 2}$					
		\vdots					
		$P_{\beta i}$					
		Sum					
		Average					

TABLE III
REVERSE DESIGN CRITERIA

R ₁	R ₂	R ₃	R ₄	R ₅
design for recycle	design for disassembly	design for reuse	design for remanufacture	design for disposal

TABLE IV
RELATIONAL MATRIX OF REVERSE DESIGN CRITERIA

	α	β	Relational value				
			R ₁	R ₂	R ₃	R ₄	R ₅
Design Case	$p_{\alpha i}$		$P_{\beta 1}$				
		$P_{\beta 2}$					
		\vdots					
		$P_{\beta i}$					
		Sum					
		Average					

TABLE V
GREEN MANUFACTURING CRITERIA

G ₁	G ₂	G ₃	G ₄	G ₅
green material	green process	transportation	energy	environmental impact

TABLE VI
RELATIONAL MATRIX OF GREEN MANUFACTURING CRITERIA

	α	β	Relational value				
			G ₁	G ₂	G ₃	G ₄	G ₅
Design Case	$p_{\alpha i}$		$P_{\beta 1}$				
		$P_{\beta 2}$					
		\vdots					
		$P_{\beta i}$					
		Sum					
		Average					

11) Calculate defuzzification according the center of gravity defuzzification method.

$$DF_{mn} = \frac{(l_{mn} + a_{mn} + u_{mn})}{3} \quad (5)$$

DF_{mn} : Defuzzy weighted value.

$$H_{ij} = \begin{bmatrix} 1 & DF_{12} & DF_{13} & \dots & DF_{1p} \\ DF_{21} & 1 & DF_{23} & \dots & DF_{2p} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ DF_{p1} & DF_{p2} & DF_{p3} & \dots & 1 \end{bmatrix} \quad (6)$$

12) Calculate comparison between the criteria of the three groups and calculate the final relational values.

$$PV_{[j]m} = \frac{\sum_{n=1}^N \left(\frac{DF_{[j]mn}}{\sum_{m=1}^M DF_{[j]mn}} \right)}{N} \quad (7)$$

13) Calculate the final relational values of the criteria and build a super matrix of the three groups as shown in (8).

$$W = \begin{bmatrix} Model\ 1^{Criterion} & PV_{[1]1} & PV_{[1]2} & PV_{[1]3} & \dots \\ \dots & \dots & \dots & \dots & \dots \\ Model\ 2^{Criterion} & PV_{[2]1} & PV_{[2]2} & PV_{[2]3} & \dots \\ \dots & \dots & \dots & \dots & \dots \\ Model\ 3^{Criterion} & PV_{[3]1} & PV_{[3]2} & PV_{[3]3} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix} \quad (8)$$

TABLE VII
THE COMPARISON MATRIX AND THE RELATIONAL VALUES OF THE THREE GROUPS OF THE FANP MODEL

	Forward Design		Reverse Design		Green Manufacturing	
	D ₁ ..	D ₅	M ₁ ..	M ₅	G ₁ ..	G ₅
Forward Design	D ₁	...	D ₅			
Reverse Design	M ₁	...	M ₅	G ₁	...	G ₅
Green Manufacturing	G ₁	...	G ₅			

TABLE VIII
THE SUPER MATRIX OF THE FANP MODEL FOR EVALUATING DESIGN CASES USING THE CRITERIA OF THE THREE MODELS

	Relational Value Evaluation Score	Design Case t					
		1	2	3	4	5	Sum
Forward Design	functional design						W_{D1}
	Kensei design						W_{D2}
	design for manufacturing	$PV_{[1]m}$	$\sum_{i=1}^I k_{1i[n_i]} / I \times PV_{[1]m}$				W_{D3}
	design for assembly						W_{D4}
	design for supply chain						W_{D5}
Reverse Design	design for recycle						W_{R1}
	disassembly						W_{R2}
	reuse	$PV_{[2]m}$	$\sum_{i=1}^I k_{1i[n_i]} / I \times PV_{[2]m}$				W_{R3}
	remanufacture						W_{R4}
	disposal						W_{R5}
Green Manufacturing	green material						W_{G1}
	green process						W_{G2}
	transportation	$PV_{[3]m}$	$\sum_{i=1}^I k_{1i[n_i]} / I \times PV_{[3]m}$				W_{G3}
	energy						W_{G4}
	environmental						W_{G5}

In this research, a super matrix model is created to represent the relational values between the criteria of the three groups, as shown in (8). The detailed super matrix model is shown in Tables VIII and IX. Using the super matrix, the presented FANP model can be applied to analyze and evaluate the interactive relationships in the three models of forward design, reverse design, and green manufacturing. In applications, the FANP model can be applied to evaluate the design cases of a product and to perform decision-making to select the final design case.

TABLE IX
THE SUPER MATRIX OF AN EXAMPLE PRODUCT WITH FIVE DESIGN CASES
USING THE FANP METHODS AND MODELS

Design case evaluation		Design Case 1	Design Case 2	Design Case 3	Design Case 4	Design Case 5
Design	functional design	Values	...			
	Kensei design	...				
	design for manufacturing					
	design for assembly					
Reverse Design	design for supply chain	Values	...			
	design for recycle	...				
	disassembly	...				
	reuse					
Green Manufacturing	remanufacture	Values	...			
	disposal	...				
	green material	Values	...			
	green process	...				
	transportation					
	energy					
	environmental					

IV. APPLICATION TO EVALUATION OF DESIGN CASES USING THE MODEL

In this research, the methods and models have been implemented using the programming software on a personal computer. In this presentation, a simplified notebook computer is used as an example product for demonstration. By executing and applying the methods and formulations, the format of the final super matrix for evaluating the different design cases is shown in Table VIII. The example product is shown Fig. 5. As shown in Fig. 5, a simplified notebook computer is illustrated. After performing the presented methods, the format of values of the final super matrix is shown in Table IX. As shown in Table IX, the numerical values in the table represent the relational values of the criteria for design cases. The evaluation scores can be assigned in the evaluation process. The sum of the evaluated scores of the relational values can be used in the selection of design cases. Based on the objective, a design case with a desired scoring value can be selected as the final design case in the design evaluation stage. In the research, the methods and models have been implemented and tested with practical products. In this presentation, the example product is demonstrated and discussed.

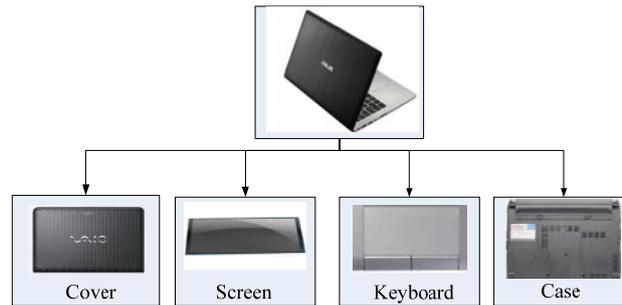


Fig. 5 A notebook computer is used as the example product for testing and demonstration

V. CONCLUSIONS

In this paper, a new concept of closed-loop design model is presented. The closed-loop design model is developed by integrating forward design and reverse design. Based on this new concept, a model for integrated evaluation of forward design, reverse design, and sustainable manufacturing using the fuzzy analytic network process method is developed. In the design stage, there can be different design cases to achieve the same design requirement and objective. This research presents a closed-loop design for sustainable manufacturing model by integrated evaluating the forward design model, reverse design model, and green manufacturing model. A fuzzy analytic network process model is presented for integrated evaluation of the criteria in the three models. A network hierarchical structure is established to represent the relationships among the criteria in the three groups. This research develops the detailed criteria in the three groups to present a complete model. A super matrix model is created to represent the relationship among the criteria in the three groups of the network structure. The total relational values of the different design cases can be compared to select the most suitable design case. In applications, the total relational values can be used to evaluate the design cases for decision-making to select the final design case. In the research, the methods and models have been tested with practical products. An example product is presented in this presentation. It shows that the model is useful for integrated evaluation of forward design, reverse design, and green manufacturing to achieve a closed-loop design for sustainable manufacturing objectives. Future research can be planned to investigate more detailed cost-oriented and value-oriented evaluation methods and more practical evaluation criteria.

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