Design for Supply Chain with a Closed-loop Design Evaluation Model Using a PSO Method

Yuan-Jye Tseng†
Department of Industrial Engineering and Management
Yuan Ze University, Chung-Li, Taoyuan City, Taiwan
Tel: (+886) 3-463-8800, Email: ieyjt@saturn.yzu.edu.tw

Yi-Shiuan Chen, and Wan-Tzu Wu
Department of Industrial Engineering and Management
Yuan Ze University, Chung-Li, Taoyuan City, Taiwan
Tel: (+886) 3-463-8800, Email: s1015413@mail.yzu.edu.tw

Abstract. In the design stage of a product life cycle, there can be alternative design decisions for the detailed product specifications to complete the design objective. The different design decisions can affect the manufacturing processes and supply chain activities. The typical concept of design for supply chain is to connect the design criteria and objective with the supply chain activities. In this research, the concept of closed-loop design is developed for linking with the closed-loop supply chain. In the close-loop design model, the model of forward and reverse design is developed to link with the forward and reverse supply chain. A particle swarm optimization (PSO) model is presented for evaluation of the criteria in the closed-loop design model. The design decisions are formulated as decision variables in the model. The decisions in the forward design include material and manufacturing processes. The decisions in the reverse design include recycling, disassembly, reusing, remanufacturing, and disposing. The PSO model is formulated to select the suitable design decisions by optimizing the cost parameters. The evaluation model has been implemented and tested with example products. It shows that the model is useful for integrated evaluation of the closed-loop design and supply chain objectives.

Keywords: closed-loop design, closed-loop supply chain, design evaluation, design for supply chain, supply chain management

1. INTRODUCTION

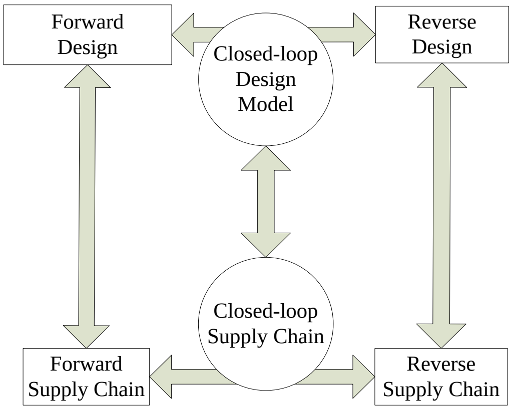
In a product life cycle, the product requirement and design concept are analyzed and evaluated to form the design objectives. In the detailed design stage, the design specification are decided and assigned according to the design objectives. To produce the product, the design specifications are utilized in the manufacturing processes and the associated supply chain activities. In this design and manufacturing flow, the design decisions made in the design stage can affect the downstream manufacturing processes and the supply chain activities. Therefore, it is required to analyze and evaluate how the design decisions can affect the supply chain activities.

With a given design objective, there can be alternative ways to design the detailed specifications of the components and product. A component can be designed with different geometric shapes, sizes, dimensions, and types of material. If the detailed design specifications are different, different manufacturing processes may be required. Subsequently, the manufacturing processes will affect the supply chain activities.

In the typical concept of design for supply chain, the design decisions are made based on the design objectives and the supply chain considerations. In a complete product life cycle, the traditional concept of a supply chain has been further developed as a closed-loop supply chain by integrating the forward supply chain and the reverse supply chain. In a closed-loop supply chain, the supply chain with the manufacturing-related considerations can be described as the forward supply chain. In the reverse supply chain, the decisions are made based on the criteria and objectives for sustainable purposes, for example, recycling, disassembly, reusing, remanufacturing, and disposal.

In this research, to link the design with a complete product cycle, a closed-loop design model is developed to connect with the closed-loop supply chain. In the closed-loop design model, the forward design model is the traditional design model with the common design criteria and objectives. In addition to the original product design objective, the design decisions in the forward design model need to consider the criteria from the manufacturing point of view. In the design evaluation stage, the criteria and objectives of manufacturing processes need to be considered to attain the concept of design for supply chain. From the supply chain point of view, the forward design model is linked with the forward supply chain.

In this research, the reverse design model is developed to connect with the reverse supply chain. In the reverse design model, the design decisions are made based on the criteria and objectives for reverse logistics and sustainable purposes, for example, recycling, disassembly, reusing, remanufacturing, and disposal. The framework is illustrated in Figure 1. As shown in Figure 1, the forward design and reverse design models can be integrated to form a closed-loop design model to connect with the closed-loop supply chain. In this research, the design decisions and criteria in the forward and reverse design models are integrated in the closed-loop design model.



In order to analyze and evaluate the design decisions, a particle swarm optimization (PSO) model is presented for integrated evaluation of the cost parameters in the closed-loop design model. The decision variables are formulated to represent the design decisions in the forward and reverse design. The PSO evaluation model is formulated and solved by minimizing the total cost.

In practical applications, the decisions of the PSO evaluation model can be used for making decisions to select a good or the best design case to achieve the sustainable objectives. The PSO evaluation model has been implemented and tested with example products. It shows that the model is useful for integrated evaluation of forward and reverse design to form a closed-loop design model.

This paper is organized as follows. In section 1, an introduction is presented. Section 2 presents a literature review. Section 3 describes the mathematical model and section 4 describes the PSO solution model. In section 5, the implementation of the model is demonstrated. Finally, a conclusion is presented in section 6.

2. LITERATURE REVIEW

In the research of Tseng and Chen (2015), a fuzzy analytical network process model was presented to evaluate the criteria in forward design, reverse design, and supply chain. In the research of Tseng and Chen (2013), a product development for green logistics model by integrated evaluation of design and manufacturing and green supply chain has been presented. The literature review in Tseng and Chen (2013) investigated the related literature in closed-loop supply chain research. In previous research, the problems of supplier selection in supply chains have been presented and modeled with various methods. The previous research (Weber et al., 1991, Kasilingam and Lee, 1996, and Humphreys et al., 2003) presented the methods for supplier evaluation and selection. In the research in Akyuz and Erman (2010), a review and model of supply chain performance measurement was presented. The models of forward and reverse logics and green supply chains have been presented in Shultmann et al. (2006) and Alshamrani et al. (2007). In the research of Lu et al. (2007) and Ko and Evans (2007), the problems of close-loop supply chain were discussed and modeled. In the research of Yang et al. (2009) and Kannan et al. (2010), the models of close-loop supply chain were developed and solved with solution methods. The applications of close-loop supply chain models have been presented in Chaung and Wang (2014), Hashemi et al. (2014), and Ramezani et al. (2014).

As discussed in the research (Tseng and Chen, 2015), many of the previous papers presented models for investigating closed-loop supply chains. Many models and solution methods for solving the supplier selection problems have been developed. Several papers presented models and optimization methods for integrating forward and reverse supply chains. However, the issue that the product design can affect the supply chain has rarely been discussed.

Based on the review, the typical design decisions are restricted to the forward design portion. It is observed that the traditional concept of design for supply chain is suitable to be connected with the forward supply chain. It requires a reverse design model for making the design decisions to connect with the reverse supply chain. The link of a design with a closed-loop supply chain needs to be investigated.

Based on the discussion, in this research, the model of closed-loop design is developed by integrating the forward and reverse design models. The concept of design for supply chain can be expanded to form a closed-loop design model for evaluating and connecting with the closed-loop supply chain.

3. THE CLOSED-LOOP DESIGN MODEL

The design decisions are modeled as design cases. In the model, the decision variables are defined as 0-1 integer variables representing whether a design case is selected. A design case represents a set of detailed design specifications including geometric shapes and dimensions. A design case $i = 1, 2, \ldots, I$, represents a forward design case. A design case $l = 1, 2, \ldots, L$, represents a reverse design case. The model is described as follow.

The notations are listed as follows.

i : a forward design case ($i = 1, 2, \ldots, I$),
j : a type of material ($j = 1, 2, \ldots, J$),
k : a manufacturing process ($k = 1, 2, \ldots, K$),
l : a reverse design case ($l = 1, 2, \ldots, L$).

The parameters are defined as follows.

C : the total cost,
$C_{forward}$: the cost of a forward design connected with the forward supply chain,
$C_{reverse}$: the cost of a reverse design connected with the reverse supply chain,
C_{ijk}^{m} : cost of material j using manufacturing process k in forward design case i,
C_{ijk}^{p} : cost of manufacturing process k using material j in forward design case i,
C_{ijkl}^{r} : cost of recycle in reverse design case l using material j and manufacturing process k with forward design case i,
C_{ijkl}^{e} : cost of reuse in reverse design case l using material j and manufacturing process k with forward design case i,
C_{ijkl}^{f} : cost of remanufacturing in reverse design case l using material j and manufacturing process k with forward design case i,
C_{ijkl}^{d} : cost of disassembly in reverse design case l using material j and manufacturing process k with forward design case i,
C_{ijkl}^{g} : cost of disposal in reverse design case l using material j and manufacturing process k with forward design case i,

The decision variables are defined as follows.

X_{ijk} : 0-1 integer variable representing whether forward design case i is selected with the use of material j and manufacturing process k, where a value of 1 represents that it is selected,
Y_{ijkl} : 0-1 integer variable representing whether reverse design case l is selected with the corresponding forward design case i with the use of material j and manufacturing process k, where a value of 1 represents that it is selected.

The objective function is defined as follows.

$$\text{Min} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} C = C_{forward} + \mathrm{C}_{reverse} \tag{1}$$

$$\begin{aligned} C_{forward} = & \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} (X_{ijk} \times C_{ijk}^{m})\right] \\ & + \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} (X_{ijk} \times C_{ijk}^{p})\right] \end{aligned} \tag{2}$$

$$\begin{aligned} C_{reverse} = & \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} \left(Y_{ijkl} \times C_{ijkl}^{r}\right)\right] \\ & + \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} \left(Y_{ijkl} \times C_{ijkl}^{e}\right)\right] \\ & + \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} \left(Y_{ijkl} \times C_{ijkl}^{f}\right)\right] \\ & + \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} \left(Y_{ijkl} \times C_{ijkl}^{d}\right)\right] \\ & + \left[\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} \left(Y_{ijkl} \times C_{ijkl}^{g}\right)\right] \end{aligned} \tag{3}$$

s.t.

$$X_{ijk} = \begin{cases} 1 \\ 0 \end{cases} \quad \forall \ i, \ j, \ k \tag{4}$$

$$Y_{ijkl} = \begin{cases} 1 \\ 0 \end{cases} \quad \forall \ i, \ j, \ k, \ l \tag{5}$$

The cost parameters can be classified as two main categories: forward design cost and reverse design cost. The forward design cost is linked with the material cost and manufacturing process cost in the forward supply chain. The reverse design cost is linked with the costs in a reverse supply chain. The reverse design cost parameters include recycle, reuse, remanufacturing, disassembly, and disposal in the reverse supply chain. The total cost is the sum of the above defined cost parameters. The objective is to make decision of selecting a design case with corresponding forward design case i and reverse design case l by minimizing the total cost.

4. SOLUTION USING THE PSO METHOD

A PSO method is presented for evaluating the solutions in the closed-loop design model. The PSO method is an evolutionary computation method introduced by Kennedy and Eberhart (1997). In the PSO method, each particle moves around in the multi-dimensional space with a position and a velocity. The velocity and position are constantly updated by the particle's own experience and the experience of the whole swarm. Given a problem, a particle can be encoded to represent a solution. Each solution, called a particle, flies in the search space towards the optimal position.

In the original PSO method, a particle is defined by its position and velocity. The position of a particle i in the D-dimension search space can be represented as $X_i=[x_{i1}, x_{i2}, \ldots, x_{id}, \ldots, x_{iD}]$. The velocity of the particle i in the D-dimension search space can be represented as $V_i=[v_{i1}, v_{i2}, \ldots, v_{id}, \ldots, v_{iD}]$. Each particle has its own best position $P_i=[p_{i1}, p_{i2}, \ldots, p_{id}, \ldots, p_{iD}]$ representing the particle's personal best objective (*pbest*) at time t. The global best particle is denoted as p_g and the best position of the entire swarm (*gbest*) is denoted as $P_g=[p_{g1}, p_{g2}, \ldots, p_{gd}, \ldots, p_{gD}]$ at time t. To search for the optimal solution, each particle adjusts its velocity according to the velocity updating equation and position updating equation.

$$v_{id}^{new} = w_i \cdot v_{id}^{old} + c_1 \cdot r_1 \cdot \left(p_{id} - x_{id}\right) + c_2 \cdot r_2 \cdot \left(p_{gd} - x_{id}\right) \quad (6)$$

where d =1, …, D, i =1, …, E (number of particles),

v_{id}^{new} : the new velocity of i in the current iteration t,
v_{id}^{old} : the velocity of i in the previous iteration (t - 1),
c_1, c_2 : constants called acceleration coefficients,
w_i : the inertia weight,
r_1, r_2 : independent random numbers with a uniform distribution [0, 1],
p_{id} : the best position of each individual particle i,
p_{gd} : the best position of the entire swarm.

$$x_{id}^{new} = x_{id}^{old} + v_{id}^{new}, \quad (7)$$

where x_{id}^{new} is the new position in the current iteration t, x_{id}^{old} is in the previous iteration (t - 1).

This research applies the PSO method to solve the problem by developing an encoding and decoding scheme. A particle is represented by a position matrix. The position of a particle p = 1, …, E, is represented by a position matrix A_{ijk}. The elements in the position matrix is denoted as a_{ijk}, i = 1, 2, …, I, j = 1, 2, …, J, and k = 1, …, K. The decoded value of a_{ijk} represents a solution.

$$A_{ijk} = \begin{array}{cc} & \begin{array}{cccc} 1 & 2 & \cdots & K \end{array} \\ \begin{array}{c} 1 \\ 2 \\ 3 \\ \vdots \\ J \end{array} & \left[\begin{array}{cccc} a_{i11} & a_{i12} & \cdots & a_{i1k} \\ a_{i21} & a_{i22} & \cdots & a_{i2k} \\ a_{i31} & a_{i32} & \cdots & a_{i3k} \\ \vdots & \vdots & x_{ijk} & \vdots \\ a_{ij1} & a_{ij2} & \cdots & a_{ijk} \end{array}\right] \end{array}, \quad \forall i \in I \quad (8)$$

$$A_{1jk} = \begin{array}{cc} & \begin{array}{cccc} 1 & 2 & \cdots & K \end{array} \\ \begin{array}{c} 1 \\ 2 \\ 3 \\ \vdots \\ J \end{array} & \left[\begin{array}{cccc} a_{111} & a_{112} & \cdots & a_{11k} \\ a_{121} & a_{222} & \cdots & a_{12k} \\ a_{131} & a_{132} & \cdots & a_{13k} \\ \vdots & \vdots & x_{ijk} & \vdots \\ a_{1j1} & a_{1j2} & \cdots & a_{1jk} \end{array}\right] \end{array}$$

$$A_{2jk} = \begin{array}{cc} & \begin{array}{cccc} 1 & 2 & \cdots & K \end{array} \\ \begin{array}{c} 1 \\ 2 \\ 3 \\ \vdots \\ J \end{array} & \left[\begin{array}{cccc} a_{211} & a_{212} & \cdots & a_{21k} \\ a_{221} & a_{222} & \cdots & a_{22k} \\ a_{231} & a_{232} & \cdots & a_{23k} \\ \vdots & \vdots & x_{2jk} & \vdots \\ a_{2j1} & a_{2j2} & \cdots & a_{2jk} \end{array}\right] \end{array}$$

$$\cdots$$

$$A_{ijk} = \begin{array}{cc} & \begin{array}{cccc} 1 & 2 & \cdots & K \end{array} \\ \begin{array}{c} 1 \\ 2 \\ 3 \\ \vdots \\ J \end{array} & \left[\begin{array}{cccc} a_{i11} & a_{i12} & \cdots & a_{i1k} \\ a_{i21} & a_{i22} & \cdots & a_{i2k} \\ a_{i31} & a_{i32} & \cdots & a_{i3k} \\ \vdots & \vdots & x_{ijk} & \vdots \\ a_{ij1} & a_{ij2} & \cdots & a_{ijk} \end{array}\right] \end{array}$$

After the PSO enumeration, the final particle represents a solution of the decision variable. The position matrix of a particle can be decoded as a solution of the decision variable. A heuristic rule for decoding is developed. In a position matrix, the largest value of a_{ijk} is assigned a value of 1. The value of 1 indicates a selected decision of the 0-1 variable. For example, for X_{ijk} variable, a value of 1 represents the forward design case i is selected with the use of material j and manufacturing process k. The same encoding and decoding scheme can be applied to Y_{ijkl}.

Using equation (1), the fitness function can be formulated. In the PSO evaluation, the objective is to minimize the fitness function *Fitness*.

$$\text{Min } Fitness = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} C = C_{forward} + \mathrm{C}_{reverse} \quad (9)$$

The execution steps of the PSO solution method is described as follows.

Step 1. Setup parameters.
  1) Set iteration $t = 0$.
  2) T_{Number}: the iteration (generation) number.
  3) P_{Size}: the number of particles.

Step 2. Initialize a population of particles $i = 1, \ldots, E$, with random positions and velocities.
  1) A particle i is defined by a multi-dimensional position matrix as shown in equation (7).
  2) The position of particle i is defined by X_{ijk}.
  3) The velocity of particle i is defined by V_{ijk}.

Step 3. Evaluate the fitness function.
  1) $t = t + 1$.
  2) $Fitness$ = Total Cost.

Step 4. Update the velocity of each particle i.

$$v_{id}^{new} = w_i \cdot v_{id}^{old} + c_1 \cdot r_1 \cdot (p_{id} - x_{id}) + c_2 \cdot r_2 \cdot (p_{gd} - x_{id}),$$

v_{id}^{new} is the new velocity in the current iteration t,

v_{id}^{old} is the velocity in the previous iteration (t-1),

Step 5. Move the position of each particle i.

$$x_{id}^{new} = x_{id}^{old} + v_{id}^{new},$$

where x_{id}^{new} is the new position in the iteration t,

x_{id}^{old} is the position in the iteration (t - 1).

Step 6. Check the feasibility of the solution and the number of iteration t.
  If ($t > T_{Number}$), then go to Step 7, else go to Step 2.

Step 7. Decode the best particle position matrix and interpret the solution of the decision variable.

5. IMPLEMENTATION AND TESTING

In this research, the model has been formulated and solved using a PSO solution method with programming software on a personal computer. A simplified mobile phone is used as an example product for demonstration. As shown in Figure 2, a simplified mobile phone is illustrated. The information and data of the product are modeled and defined for testing and computation. In the design cases, the selections of material and the manufacturing processes are modeled as decision variables.

The numerical data of the cost parameters can be modeled in a table format as shown in Table 1. A design case i represents a set of detailed design specifications including geometric shapes and dimensions. A design case $i = 1, 2, \ldots, I$, represents a forward design case. A design case $l = 1, 2, \ldots, L$, represents a reverse design case. With the given information and data, the mathematical model can be formulated and solved using the PSO method. For each component, the best forward design case can be determined as indicated in the decision variable X_{ijk}. The best reverse design case can be determined as indicated in the decision variable Y_{ijkl}. Therefore, the best design combination of forward design and reverse design can be decided. With the decision variables and cost parameters in equation (1) and (9), the optimized total cost can be calculated. As shown in Figure 3, in this example, the near optimized solution can be found in the generation of 57. The solution of the total cost is 9,330(dollars). The computer execution time is 2.62(seconds).

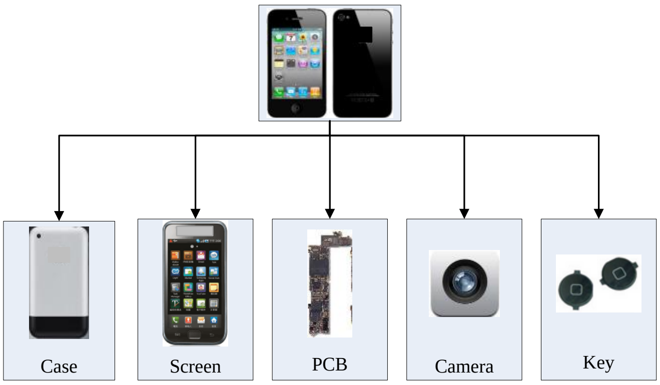


Figure 2. A simplified mobile phone is used as an example for illustration.

Table 1. The data format for modeling the cost parameters.

Forward Design i	Material j	Process k	Reverse Design l	C_{ijkl}^{r}	C_{ijkl}^{e}	C_{ijkl}^{f}	C_{ijkl}^{d}	C_{ijkl}^{g}
i=1, …, I	j=1, …, J	k=1, …, K	l=1					
			l=2					
			l=3					
			l=L					

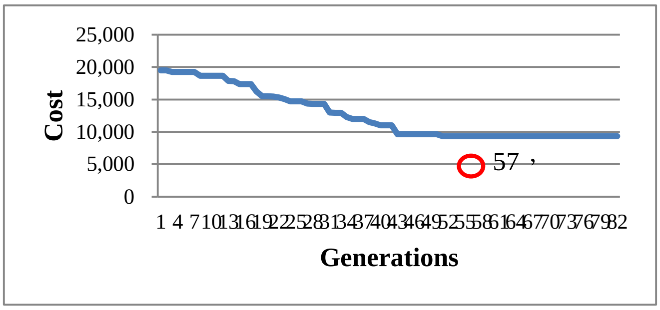


Figure 3. The test result of the PSO method of the example.

6. CONCLUSIONS

A closed-loop design model is developed by integrating forward design and reverse design. A mathematical model for integrated evaluation of forward and reverse design is presented. To evaluate the design cases, the decision variables are formulated to represent the design cases in the forward and reverse design. The cost parameters of a forward design model include the costs of material and manufacturing processes. The cost parameters of a reverse design model include the costs of recycling, disassembly, reusing, remanufacturing, and disposing. The mathematical model is formulated to minimize the fitness function of the total cost. The PSO method is applied to solve the model by developing an encoding and decoding scheme of the design decision variables. It shows that the model is useful and efficient for integrated evaluation of forward and reverse design to achieve the closed-loop design objective. The goal of expanding the concept of design for supply chain to form a closed-loop design for closed-loop supply chain can be achieved. In practical applications, the decisions of the closed-loop design model can be used for decision-making to select a good or the best design case to achieve the design objectives. In the research, the models have been tested with practical products and demonstrated with an example. Future research can be planned to investigate more design decisions and cost parameters for further evaluation.

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