Genetic Algorithm Approach for Multi-objective Green Supply Chain Design

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Abstract. This paper applies multi-objective genetic algorithm (MOGA) to solve a closed-loop supply chain network design problem with multi-objective sustainable concerns. First of all, a multi-objective mixed integer programming model capturing the tradeoffs between the total cost and the carbon dioxide (CO_2) emission is developed to tackle the multi-stage closed-loop supply chain design problem from both economic and environmental perspectives. The multi-objective optimization problem raised by the model is then solved. Finally, some experiments are made to measure the performance.

Keywords: multi-objective, genetic algorithm, closed-loop, supply chain, mixed integer

1 Introduction

Recent years, carbon asset became a critical subject to global enterprises. Global enterprises need to provide effective energy-saving and carbon-reduction means to meet the policies of Carbon Right and Carbon Trade (Subramanian, *et al.*, 2010). In this scenario, forward and reverse logistics have to be considered simultaneously in the network design of entire supply chain. Moreover, the environmental and economic impacts also need to be adopted and optimized in supply chain design (Gunasekaran, *et al.*, 2004; Srivastava, 2007). Chaabane, *et al.* (2012) introduce a mixed-integer linear programming based framework for sustainable supply chain design that considers life cycle assessment (LCA) principles in addition to the traditional material balance constraints at each node in the supply chain. The framework is used to evaluate the tradeoffs between economic and environmental objectives under various cost and operating strategies in the aluminum industry.

This paper applies multi-objective genetic algorithm (MOGA) to solve a closed-loop supply chain network design problem with multi-objective sustainable concerns. First of all, a multi-objective mixed integer programming model capturing the tradeoffs between the total cost and the carbon dioxide emission is developed to tackle the multi-stage closed-loop supply chain design problem from both economic and environmental perspectives. Then, the proposed MOGA approach is used to deal with multi-objective and enable the decision maker to evaluate a greater number of alternative solutions. Based on the MOGA approach, the multi-objective optimization problem raised by the model is finally solved.

The remainder of this paper is organized as follows. Section II introduces the multi-objectives closed-loop supply chain model and the proposed MOGA. Experiments are conducted to test the performance of our proposed method in Section III. Finally, conclusions are summarized in Section IV.

2 Multi-Objective Closed-Loop Supply Chain Design

2.1 Problem statement and model formulation

This section will firstly propose a multi-objectives closed-loop supply chain (MOCLSCD**)** model to discuss the relationship of forward and reverse logistics, the plant locations of forward and reverse logistics, the capacity of closed-loop logistics, and carbon emission issues. Next, decision makers have to determine the potential location and quantity of production and recycling units in forward and reverse logistics, furthermore, design the capacity and production technology level. Figure 1 includes potential components of the forward and reverse logistics.

Based on the proposed multi-objective genetic algorithm (MOGA) approach, the multi-objective optimization problem raised by the model is finally solved. The assumptions used in this model are:

(1) The number of customers and suppliers and their demand are known.
(2) Second market is unique.
(3) The demand of each customer must be satisfied.
(4) The flow is only allowed to be transferred between two consecutive stages.
(5) The number of facilities that can be opened and their capacities are both limited.
(6) The recovery and disposal percentages are given.

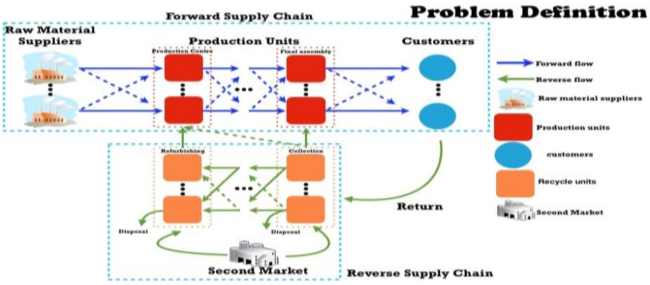

Figure 1. The structure of sustainable closed-loop supply chain.

The indices, input parameters, and decision variables are defined as follows:

Indices

s	Index for material suppliers ($s = 1,\ldots,S$)
i	Index for forward production stages ($i = 1,\ldots,I$)
$\Phi(i)$	Set of potential forward production units in each stage i ($\Phi(i) = \{1,\ldots,Num(i)\}$)
(i,k)	Potential forward production unit k in stage i , where $k \in \Phi(i)$
c	Index for end customers ($c = 1,\ldots,C$)
j	Index for recycling stages ($j = 1,\ldots,J$)
$\Psi(j)$	Set of potential recycling units in each stage j ($\Psi(j) = \{1,\ldots,Num(j)\}$
(j,p)	Potential recycling unit p in stage j, where $p \in \Phi(j)$
l	Index for capacity expansion levels ($l = 1,\ldots,L$)
t	Index for technology levels ($t = 1,\ldots,T$)

Parameters

● Cost related parameters	
pc_s^{rm} , pc_j^{sm}	Purchasing cost from material supplier and secondary market
$dc_{(j,p)}$	Disposal cost in potential recycling unit p of stage j
sc_{sk} , $sc_{(i,k)(i',k')}$, sc_{kc}	Transportation cost in forward logistics
$mc_{(i,k)t}$, $mc_{(j,p)t}$	Production cost using technology level t at potential production unit k in stage i and potential recycling unit p in stage j
sc_{cp} , $sc_{(j,p)(j',p')}$, $sc_{(j,p)(i,k)}$	Transportation cost in reverse logistics
$bc_{(i,k)}$, $bc_{(j,p)}$	Fixed installation cost of potential production and recycling unit
$cc_{(i,k)tl}$, $cc_{(j,p)tl}$	Capacity expansion cost of each capacity level using each technology type at potential production and recycling unit
● Capacity related parameters	
$cl_{(i,k)tl}$	Expanded capacity amount of capacity level l using technology level t at potential production unit k in stage i
$cl_{(j,p)tl}$	Expanded capacity amount of capacity level l using technology level t at potential recycling unit p in stage j
● Supply & Demand related parameters	

s_s^{rm}	Supply quantity of supplier *s*
s_j^{sm}	Supply quantity of secondary market in each stage *j* of reverse supply chain
d_c	Demand quantity of customers *c*
r_c	Recycling quantity of customer *c*
● Environment related parameters	
$pce_{(i,k)t}$, $pce_{(j,p)t}$	Carbon emissions quantity of installing potential production unit *k* in stage *i* using technology level *t* and installing potential recycling unit *p* in stage *j* using technology level *t*
$puce_{(i,k)t}$, $puce_{(j,p)t}$	Carbon emissions quantity of technology level *t* at potential production unit *k* in stage *i* and recycling unit *p* in stage *j*
tce_{sk} , $tce_{(i,k)(i',k')}$, tce_{kc}	Carbon emissions quantity in forward logistics
tce_{cp} , $tce_{(j,p)(j',p')}$, $tce_{(j,p)(i,k)}$	Carbon emissions quantity in reverse logistics
● Logistic related parameters	
t_{sk} , $t_{(i,k)(i',k')}$, t_{kc} ; t_{cp} , $t_{(j,p)(j',p')}$, $t_{(j,p)(i,k)}$	Minimum transportation quantity in forward logistics and in reverse logistics
● Ratio related parameters	
re_c	Recycling percentage of customer *c*
$\lambda_{(j,p)}^{dis}$	Disposal percentage of potential recycling unit *p* in stage *j*
γ_{ji}^{ret}	Recovery percentage from stage *j* of reverse supply chain to stage *i* of forward supply chain

Decision Variables

● *Continuous Variables*	
TQ_{sk} , $TQ_{(i,k)(i',k')}$, TQ_{kc}	Transportation quantity in forward logistics
TQ_{cp} , $TQ_{(j,p)(j',p')}$, $TQ_{(j,p)(i,k)}$	Transportation quantity in reverse logistics
$P_{(j,p)}$	Purchasing quantity of potential recycling unit *p* in stage *j* from secondary market
$D_{(j,p)}$	Disposal quantity of potential recycling unit *p* in stage *j*

● *Binary Variables*

$X_{(i,k)} = 1$, if potential recycling unit k in stage i is open; $X_{(i,k)} = 0$, otherwise.

$X_{(j,p)} = 1$, if potential recycling unit p in stage j is open; $X_{(j,p)} = 0$, otherwise.

$AC_{(i,k)tl} = 1$, if existing production unit k in stage i expands capacity level l using technology t; $AC_{(i,k)tl} = 0$, otherwise.

$AC_{(j,p)tl} = 1$, if potential recycling unit p in stage j expands capacity level l using technology t; $AC_{(j,p)tl} = 0$, otherwise.

$TA_{sk} = 1$, if supplier s ships to existing production unit k in first stage of forward supply chain; $TA_{sk} = 0$, otherwise.

$TA_{(i,k)(i',k')} = 1$, if existing production unit k in stage i ships to existing production unit k' in stage i'; $A_{(i,k)(i',k')} = 0$, otherwise.

$TA_{kc} = 1$, if existing production unit k in last stage of forward supply chain ships to customer c; $TA_{kc} = 0$, otherwise.

$TA_{cp} = 1$, if customer c ships to potential recycling unit p in first stage of reverse supply chain; $TA_{cp} = 0$, otherwise.

$TA_{(j,p)(j',p')} = 1$, if potential recycling unit p in stage j ships to potential recycling unit p' in stage j'; $TA_{(j,p)(j',p')} = 0$, otherwise.

$TA_{(j,p)(i,k)} = 1$, if potential recycling unit p in stage j ships to existing production unit k in stage i; $TA_{(j,p)(i,k)} = 0$, otherwise.

Multi-Objective Closed-Loop Supply Chain Design (MOCLSCD) Problem:

The purpose of the MOCLSCD model aims to identify the trade-off solutions between the economic and environmental performances under several logistic constraints. The economic objective, $F_1 = PC + BC + MC + CEC + TC + DC$, is measured by the total closed-loop supply chain cost. The environmental objective, $F_2 = PCOE + BCOE + TCOE$, is measured by the total carbon (CO_2) emission in all the closed-loop supply chain.

Economic objective (F_1): The economic objective includes the following costs.

- Total material purchasing cost (PC)

$$(1) \sum_{s\in S}\sum_{k\in\phi(1)} pc_s^{rm}\times TQ_{sk}\ ,\ (2) \sum_{j\in J}\sum_{p\in\Psi(j)} pc_j^{sm}\times P_{(j,p)}$$

- Total installation cost (BC)

$$(3) \sum_{i\in I}\sum_{k\in\Phi(I)} bc_{(i,k)}\times X_{(i,k)} + \sum_{j\in J}\sum_{p\in\Psi(J)} bc_{(j,p)}\times X_{(j,p)}$$

- Total production cost (MC)

$$(4) \sum_{s\in S}\sum_{k\in\Phi(1)}\sum_{t\in T} mc_{(1,k)t}\times TQ_{sk}\ (5) \sum_{i=2}^{I}\sum_{k\in\Phi(i-1)}\sum_{k'\in\Phi(i)}\sum_{t\in T} mc_{(i-1,k)(i,k')t}\times TQ_{(i-1,k)(i,k')}$$

$$(6) \sum_{c\in C}\sum_{p\in\Psi(1)}\sum_{t\in T} mc_{(1,p)t}\times TQ_{cp}\ (7) \sum_{j=2}^{J}\sum_{p\in\Psi(j-1)}\sum_{p'\in\Psi(j)}\sum_{t\in T} mc_{(j-1,p)(j,p')t}\times TQ_{(j-1,p)(j,p')}$$

$$(8) \sum_{j\in J}\sum_{p\in\Psi(j)}\sum_{i\in I}\sum_{k\in\Phi(i)}\sum_{t\in T} mc_{(j,p)(i,k)t}\times TQ_{(j,p)(i,k)}$$

- Total capacity expansion cost (CEC)

$$(9) \sum_{i\in I}\sum_{k\in\Phi(j)}\sum_{t\in T}\sum_{l\in L} cc_{(i,k)tl}\times cl_{(i,k)tl}\times AC_{(i,k)tl}\ (10) \sum_{j\in J}\sum_{p\in\Psi(j)}\sum_{t\in T}\sum_{l\in L} cc_{(j,p)tl}\times cl_{(j,p)tl}\times AC_{(j,p)tl}$$

- Total transportation cost (TC)

$$(11) \sum_{s\in S}\sum_{k\in\Phi(1)} sc_{sk}\times TQ_{sk}\ (12) \sum_{i=2}^{I}\sum_{k\in\Phi(i-1)}\sum_{k'\in\Phi(i)} sc_{(i-1,k)(i,k')}\times TQ_{(i-1,k)(i,k')}\ (13) \sum_{k\in\Phi(i-1)} sc_{sk}\times TQ_{kc}$$

$$(14) \sum_{c\in C}\sum_{p\in\Psi(1)} sc_{cp}\times TQ_{cp}\ (15) \sum_{j=2}^{J}\sum_{p\in\Psi(j-1)}\sum_{p'\Psi(j-1,p)(j,p')} sc_{(j-1,p)(j,p')}\times TQ_{(j-1,p)(j,p')}$$

$$(16) \sum_{j\in J}\sum_{p\in\Psi(j)}\sum_{i\in I}\sum_{k\in\Phi(i)} sc_{(j,p)(i,k)}\times TQ_{(j,p)(i,k)}$$

- Total disposal cost (DC)

$$(17) \sum_{j\in J}\sum_{p\in\Psi(j)} dc_{(j,k)}\times D_{(j,k)}$$

Environmental objective (F_2): The environmental objective includes following.

- Total production carbon emission (PCOE)

$$(18) \sum_{s\in S}\sum_{k\in\Phi(1)}\sum_{t\in T} puce_{(1,k)t}\times TQ_{sk}\ (19) \sum_{i=2}^{I}\sum_{k\in\Phi(i-1)}\sum_{k'\in\Phi(i)}\sum_{t\in T} puce_{(i-1,k)(i,k')t}\times TQ_{(i-1,k)(i,k')}$$

$$(20) \sum_{c\in C}\sum_{p\in\Psi(1)}\sum_{t\in T} puce_{(1,p)t}\times TQ_{cp}\ (21) \sum_{j=2}^{J}\sum_{p\in\Psi(j-1)}\sum_{p'\in\Psi(j)}\sum_{t\in T} puce_{(j-1,p)(j,p')t}\times TQ_{(j-1,p)(j,p')}$$

$$(22) \sum_{j\in J}\sum_{p\in\Psi(j)}\sum_{i\in I}\sum_{k\in\Phi(i)}\sum_{t\in T} puce_{(j,p)(i,k)t}\times TQ_{(j,p)(i,k)}$$

- Total installation carbon emission (BCOE)

$$(23) \sum_{i\in I}\sum_{k\in\Phi(I)} pce_{(i,k)}\times X_{(i,k)} + \sum_{j\in J}\sum_{p\in\Psi(J)} pce_{(j,p)}\times X_{(j,p)}$$

- Total transportation carbon emission (TCOE)

(24) $\sum_{s\in S}\sum_{k\in\Phi(1)} tce_{sk}\times TQ_{sk}$ (25) $\sum_{i=2}^{I}\sum_{k\in\Phi(i-1)}\sum_{k'\in\Phi(i)} tce_{(i-1,k)(i,k')}\times TQ_{(i-1,k)(i,k')}$ (26) $\sum_{k\in\Phi(I)}\sum_{c\in C} tce_{kc}\times TQ_{kc}$	
(27) $\sum_{c\in C}\sum_{p\in\Psi(1)} tce_{cp}\times TQ_{cp}$ (28) $\sum_{j=2}^{J}\sum_{p\in\Psi(j-1)}\sum_{p'\in\Psi(j)} tce_{(j-1,p)(j,p')}\times TQ_{(j-1,p)(j,p')}$ (29) $\sum_{j\in J}\sum_{p\in\Psi(j)}\sum_{i\in I}\sum_{k\in\Phi(i)} tce_{(j,p)(i,k)}\times TQ_{(j,p)(i,k)}$	

Constraints

- *Material supply constraints*

(30) $\sum_{k\in\Phi(1)} TQ_{sk}\le s_s^{rm},\forall s\in S$ (31) $P_{(j,p)}\le s_j^{sm},\forall j\in J,\forall p\in\Psi(j)$

- *Flow conservation constraints*

(32) $\sum_{s\in S} TQ_{sk}+\sum_{j\in J}\sum_{p\in\Psi(j)} TQ_{(j,p)(i,k)}=\sum_{k'\in\Phi(i+1)} TQ_{(i,k)(i+1,k')},\forall i=\{1\},\forall k\in\Phi(1)$

(33) $\sum_{k'\in\Phi(i-1)} TQ_{(i-1,k')(i,k)}+\sum_{j\in J}\sum_{p\in\Psi(j)} TQ_{(j,p)(i,k)}=\sum_{k''\in\Phi(i+1)} TQ_{(i,k)(i+1,k'')},\forall i=\{2,\ldots,I-1\},\forall k\in\Phi(i)$

(34) $\sum_{k'\in\Phi(I)} TQ_{(i-1,k')(i,k)}+\sum_{j\in J}\sum_{p\in\Psi(j)} TQ_{(j,p)(i,k)}=\sum_{c\in C} TQ_{kc},\forall i=I,\forall k\in\Phi(I)$

(35) $\sum_{k\in\Phi(I)} TQ_{kc}=\sum_{c=1}^{C} d_c,\forall c\in C$ (36) $\sum_{p\in\Psi(j)} TQ_{cp}=\sum_{c=1}^{C} r_c,\forall c\in C$

(37) $\sum_{c\in C} TQ_{cp}+P_{(j,p)}=\sum_{p'\in\Psi(j+1)} TQ_{(j,p)(j+1,p')}+D_{(j,p)}+\sum_{i\in I}\sum_{k\in\Phi(i)} TQ_{(j,p)(i,k)},\forall j=\{1\},\forall p\in\Psi(1)$

(38) $\sum_{p'\in\Psi(j-1)} TQ_{(j-1,p')(j,p)}+P_{(j,p)}=\sum_{p'\in\Psi(j+1)} TQ_{(j,p)(j+1,p')}+D_{(j,p)}+\sum_{i\in I}\sum_{k\in\Phi(i)} TQ_{(j,p)(i,k)},\forall j=\{2,\ldots,J-1\},\forall p\in\Psi(j)$

(39) $\sum_{p'\in\Psi(j-1)} TQ_{(j-1,p')(j,p)}+P_{(j,p)}=D_{(j,p)}+\sum_{i\in I}\sum_{k\in\Phi(i)} TQ_{(j,p)(i,k)},\forall j=J,\forall p\in\Psi(J)$

(40) $D_{(j,p)}=\lambda_{(j,p)}^{dis}\times\left(\sum_{c\in C} TQ_{cp}+P_{(j,p)}\right),\forall j=\{1\},\forall p\in\Psi(1)$. (41) $D_{(j,p)}=\lambda_{(j,p)}^{dis}\times\left(\sum_{p'\in\Psi(j-1)} TQ_{(j-1,p')(j,p)}+P_{(j,p)}\right),\forall j=\{2,\ldots,J\},\forall p\in\Psi(j)$.

(42) $\sum_{k\in\Phi(i)} TQ_{(j,p)(i,k)}\le\gamma_{ji}^{ret}\times\left(\sum_{c\in C} TQ_{cp}+P_{(j,p)}-D_{(j,p)}\right),\forall i\in I,\ \forall j=\{1\},\ \forall p\in\Psi(1)$

(43) $\sum_{k\in\Phi(i)} TQ_{(j,p)(i,k)}\le\gamma_{ji}^{ret}\times\left(\sum_{p'\in\Psi(j-1)} TQ_{(j-1,p')(j,p)}+P_{(j,p)}-D_{(j,p)}\right),\forall i\in I,\forall j=\{2,\ldots,J\},\forall p\in\Psi(j)$

- *Capacity expansion and limitation constraints*

(44) $\sum_{s\in S} TQ_{sk}+\sum_{j\in J}\sum_{p\in\Psi(j)} TQ_{(j,p)(i,k)}\le\sum_{t\in T}\sum_{l\in L}\left(cl_{(i,k)tl}\times AC_{(i,k)tl}\right),\forall i=\{1\},\forall k\in\Phi(1)$

(45) $\sum_{k'\in\Phi(i-1)} TQ_{(i-1,k')(i,k)}+\sum_{j\in J}\sum_{p\in\Psi(j)} TQ_{(j,p)(i,k)}\le\sum_{t\in T}\sum_{l\in L}\left(cl_{(i,k)tl}\times AC_{(i,k)tl}\right),\forall i=\{2,\ldots,I\},\forall k\in\Phi(i)$

(46) $\sum_{t\in T}\sum_{l\in L} AC_{(i,k)tl}\le X_{(j,p)},\quad \forall i\in I,\forall k\in\Phi(i)$

(47) $\sum_{c\in C} TQ_{cp}+P_{(j,p)}\le\sum\sum_{t\in T}\sum_{l\in L}\left(cl_{(j,p)tl}\times AC_{(j,p)tl}\right),\forall j=\{1\},\forall p\in\Psi(1)$

(48) $\sum_{p'\in\Psi(j-1)} TQ_{(j-1,p')(j,p)}+P_{(j,p)}\le\sum_{t\in T}\sum_{l\in L}\left(cl_{(j,p)tl}\times AC_{(j,p)tl}\right),\ \forall j=\{2,\ldots,J\},\forall p\in\Psi(j)$

(49) $\sum_{t\in T}\sum_{l\in L} AC_{(j,p)tl}=X_{(j,p)},\ \forall j\in J,\ \forall p\in\Psi(j)$

- *Transportation constraints*

(50) $t_{sk}\times TA_{sk}\le TQ_{sk}\le TA_{sk}\times M,\forall s\in S,\forall k\in\Phi(1)$

(51) $t_{(i-1,k)(i,k')} \times TA_{(i-1,k)(i,k')} \le TQ_{(i-1,k)(i,k')} \le TA_{(i-1,k)(i,k')} \times M, \forall i = \{2,\ldots,I\}, \forall k \in \Phi(i-1), \forall k' \in \Phi(i)$
(52) $t_{kc} \times TA_{kc} \le TQ_{kc} \le TA_{kc} \times M, \forall k \in \Phi(I), \forall c \in C$ (53) $t_{cp} \times TA_{cp} \le TQ_{cp} \le TA_{cp} \times M, \forall c \in C, \forall p \in \Psi(1)$
(54) $t_{(j-1,p)(j,p')} \times TA_{(j-1,p)(j,p')} \le TQ_{(j-1,p)(j,p')} \le TA_{(j-1,p)(j,p')} \times M, \quad \forall j = \{2,\ldots,J\}, \forall p \in \Psi(j-1), \forall p' \in \Psi(j)$
(55) $t_{(j,p)(i,k)} \times TA_{(j,p)(i,k)} \le TQ_{(j,p)(i,k)} \le TA_{(j,p)(i,k)} \times M, \quad \forall j \in J, \forall p \in \Psi(j), \forall i \in I, \forall k \in \Phi(i)$

- *Domain constraints*

(56) $TQ_{s(i,k)}, TQ_{(i,k)(i',k')}, TQ_{(i,k)c}, TQ_{c(j,p)}, TQ_{(j,p)(j',p')}, TQ_{(j,p)(i,k)}, P_{(j,p)}, D_{(j,p)}, N_c \ge 0$ $\forall s \in S, \forall i \in I, \forall k \in \Phi(i), \forall c \in C, \forall j \in J, \forall P \in \Psi(j)$
(57) $X_{(j,p)}, AC_{(i,k)tl}, AC_{(j,p)tl}, TA_{s(i,k)}, TA_{(i,k)(i',k')}, TA_{(i,k)c}, TA_{c(j,p)}, TA_{(j,p)(j'p')}, TA_{(j,p)(i,k)} \in \{0,1\}$ $\forall s \in S, \forall i \in I, \forall k \in \Phi(i), \forall c \in C, \forall j \in J, \forall P \in \Psi(j)$

2.2 Multi-Objective Genetic Algorithm

In this section, a novel multi-objective genetic algorithm (MOGA) with ideal-point non-dominated sorting is designed to find the optimal solution of the proposed MOCLSCD model. First of all, the proposed ideal-point non-dominated sorting for non-dominated set is as follows.

a. Calculate $(F_1', F_2')_{x_i} = (\frac{F_1 - F_1^{\min}}{F_1^{\max} - F_1^{\min}}, \frac{F_2 - F_2^{\min}}{F_2^{\max} - F_2^{\min}})$ and the distance $dist_{x_i} = \sqrt{F_1'^2 + F_2'^2}$ between $(F_1', F_2')_{x_i}$ and zero, where $(F_1, F_2)_{x_i}$ is an element in non-dominated set; $F_1^{\max}$ and $F_2^{\max}$ are the highest values of the first and second objectives among experiments; $F_1^{\min}$ are $F_1^{\min}$ the lowest values of the first and second objectives among experiments.

b. Sort the distances $dist_{x_i}$, $\forall i$.

which leads to the proposed MOGA in the following.

1. Chromosome representation for initial population: The chromosome in our MOGA implementation is divided into three segments namely **Popen**, **Pcapacity**, and **Ptechnology**, according to the structure of the proposed MOCLSCD model. Each segment is generated randomly.
2. Flow assign and fitness evaluation: The flow assign between two stages depends on the values of the two objectives F_1, F_2. Respectively, the flow with minimum values of F_1, F_2 simultaneously will be assigned firstly. On the point of this view, the proposed ideal-point non-dominated sorting is performed again on the priority of flow assign. The fitness values of F_1 and F_2 are then calculated.
3. Crossover operators: Two-Point Crossover is used to create new offsprings of the three segments **Popen**, **Pcapacity**, and **Ptechnology**.

4. Mutation operators: The mutation operator helps to maintain the diversity in the population to prevent premature convergence.
5. Selection/Replacement strategy: The selection method adopts the $(\mu+\lambda)$ method suggested by Horn et al. (1994) and Deb (2001).
6. Stopping criteria: There are two stopping criteria proposed. Due to the time constraints in the real industry, the first stopping criterion of the proposed MOGA approach is the specification of a maximum number of generations. The algorithm will terminate and obtain the near-optimal solutions once the iteration number reaches the maximum number of generations. In order to search better solutions without time-constraint consideration, the second stopping criterion is the convergence degree of the best solution. While the same best solution has not been improved in a fixed number of generations, the best solution may be convergent and thus the GA algorithm is automatically terminated.

3 Experimental results

This section gives the experimental results. As an example, we implement the MOGA approach on the MOCLSCD model with 4 stages, 4 facilities in each stage, 4 capacity levels, and 4 technology levels. By 200 iterations of MOGA, we obtain the minimum cost 5801020 dollars and carbon emission 6627320 kg.

4 Conclusions

In this work, we firstly proposed a multi-objectives closed-loop supply chain (MOCLSCD) model. Next, a novel multi-objective genetic algorithm (MOGA) with ideal-point non-dominated sorting is used to solve the model.

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