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An Integrated Optimization Model of Green Supply Chain Network Design with Inventory Management

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Abstract: Supply chain network design and inventory management are both significant for improving the core competitiveness of enterprises. This study investigates the joint optimization problem of facility locations and inventory for assembly manufacturing enterprises' multi-echelon supply chain networks, considering the locations of facilities, the selection of suppliers, transport mode choices, and inventory decisions simultaneously. A corresponding integrated optimization model is proposed, which aims to minimize the total cost, consisting of the fixed open cost of facilities, the inventory cost of the open plants and distribution centers, and the transportation cost of vehicles in the entire supply chain network as well as the cost of CO_2 emissions. Based on the characteristics of the proposed optimization model, a hybrid genetic algorithm embedded with a local search is developed to solve the proposed model. Numerical examples and a case study are provided to illustrate the effectiveness of the proposed model and the corresponding algorithm. The findings show that the model is reasonable and applicable, and hybrid genetic algorithm (HGA) is more efficient than the standard genetic algorithm (SGA). In addition, plants' maximum lead-time has a significant impact on the total cost of the supply chain.

Keywords: green supply chain; network design; joint optimization model; location-inventory; selection of suppliers; transport modes choice; hybrid genetic algorithm

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1. Introduction

In the environment of fierce competition within today's global market, it is significant for most enterprises to improve the corresponding key competitiveness with supply chain management (SCM). SCM aims to decrease the total costs and ensure a quick and effective response to customers by integrating suppliers, core manufacturing enterprises, and third-party logistics [1].The main context of a supply chain management includes the selection of suppliers, network design, production planning, and inventory control as well as transportation and distribution. SCM usually exists in three different flows, logistics, information flow, and capital, among suppliers, plants, distribution centers (DCs), and end customers.

In general, the decision-making problem on SCM is classified into the following three hierarchical levels, i.e., strategic (long term), tactical (medium term), and operational (short terms). The strategic level includes development strategy of supply chain, network design, sales, sourcing channel planning, etc., which covers many years and needs some related approximate and aggregated data. The tactical level, such as the annual operation plan and master production planning, falls between those two extremes with respect to the time horizon and the amount and accuracy of data required. The operational one deals with some short-term decisions, generally within a day and needs transactional data [2].

Tactical or operational decisions are related to inventory control, supplier selection, quantity allocation, the choice of transport mode, vehicle routing and service relationships [3,4].

To deal with the above green supply chain network design with inventory management, it needs optimization theories and methods about supply chain management. The joint optimization problem on location-allocation decisions and inventory control has become a hot research topic, which aims to minimize the total costs of facilities locations, transportation, and inventory. Ventura et al. [5] investigated the supply chain management inventory, which considers the multi-period inventory management with lot-sizing for a single commodity as well as supplier selection and evaluation. Huang et al. [6] found that it is necessary to coordinate and integrate some activities in the supply chain and that selecting and evaluating suppliers effectively is a vital process to build competitive supply chains. Fazayeli et al. [7] investigated the joint optimization problem on location and routing problem by a two-stage method, which considers the selection of transportation mode. Miranda and Garrido [8] proposed a location-inventory model with two novel capacity constraints, of which the first is the warehouse capacity constraint and the second is the inventory capacity constraints with stochastic bound. As we know, freight transportation is a primary contributor to climate change and global warming due to various pollution emissions [9–11].

The traditional supply chain network design mainly focuses on total costs or revenue while the green supply chain network design problem considers the corresponding costs and service efficiency and externalities simultaneously, so as to achieve a sustainable balance between economic, environmental, and social objectives [12,13]. There are a number of studies on green supply chain network design in the literature [14,15]. Li et al. [16] studied an integrated optimization model for the green location-inventory problem for a three-level distribution network, which aims to minimize the total costs and which mainly includes the following components, such as the fixed costs of facilities, hold cost of inventory management, costs of long-haul transportation and distribution, and external cost of CO_2 emissions. Wang et al. [17] explored the green supply chain network design problem and presented a multi-objective optimization model, in which the environmental investment decisions is considered. Mohebalizadehgashti et al. [18] investigated the a green meat supply chain network design problem by a multi-objective approach, which is solved by augmented epsilon-constraint method. Ma et al. [19] applied the game theory to address the sustainable supply chain management with the technology investments and government intervention. Some corresponding management insights on green technology investments for the manufacturer and retailer are obtained.

As mentioned before, supplier selection, location-inventory-allocation, and transportation mode selection are important problems in the strategic decision-making level. To the best of our knowledge, the existing studies integrating supplier selection, facilities location, inventory management, and transport modes selection are still scarce, considering the external cost of CO_2 emissions. To fill this gap, this study investigates the four-echelon green supply chain network design with inventory management by an integrated optimization method, which aims to minimal the total cost of entire supply chain.

Our contributions are summarized as follows. First, an integrated optimization model on a green supply chain network design with inventory management and multiple the selections of suppliers and transport modes is established, which considers the production costs and transport costs simultaneously. Second, an improved hybrid genetic algorithm (HGA) embedded with local search is proposed and examined by some corresponding instances. Finally, some management insights are revealed based on the analysis of simulations results.

The structure of this paper is organized as follows: Section 2 is a literature review, Section 3 describes an integrated optimization model on green supply chain network design and inventory management, and Section 4 gives a hybrid genetic algorithm embedded with local search. Section 5 presents numerical examples and conduct some analyses. The proposed model is applied in a real-world supply chain network design of an electronic equipment assembly company in China in Section 6. A summary of this paper and future research directions is presented in Section 7.

2. Literature Review

There exists a considerable number of studies related to the integrated optimization problem of a supply chain network design with inventory management. The existing research can be classified into three categories according to the corresponding objectives and methodologies: (1) location-inventory problem, (2) location-routing and inventory problem, and (3) green supply chain network design.

The location-inventory problem (LIP) is an extension of the classical facility location problem (FLP), which simultaneously determines the optimal decisions on location, allocation, and inventory. LIP has been widely investigated in recent years. Abdul-Jalbar et al. [20] addressed a multi-echelon inventory distribution problem, which do not allow the (Q,R) inventory policy and the shortages. Ozsen et al. [21] investigated a joint LIP with risk sharing and warehouse capacity constraints. Tsao et al. [22] presented a novel optimization model of the location and inventory problem, which determines the optimal location of the regional distribution centers (RDCs) and rational inventory policies at the RDCs. Bhatnagar et al. [23] addressed the joint optimization problem on transshipment and production schemes for a multi-location production/inventory system. They formulated the corresponding optimization model, and two heuristic algorithms were designed. Fathi et al. [24] investigated the location–inventory problem for supply chain configuration, which considers the stochastic customer demand as well as replenishment lead-time.

As we known, there usually exists a trade-off between transportation cost and inventory one. The integrated optimization problem on location, routing, and inventory has attracted many scholars focuses. A joint optimization model of location–inventory–routing problem (LIRP) deals with to location planning, inventory management, and vehicle routing problems by an integrated approach [25]. Most of existing studies the related LIRP on manufacturing enterprises focus on minimizing the total cost with consideration of the service level and capacity constraints [25–27]. Sadjadi et al. [28] explored a three-level LIRP, which considers the demand and lead-time are both uncertain, following Poisson and exponential distributions, respectively. They applied a queuing approach to solve the above proposed model. Chen et al. [29] studied the integration optimization model of location-routing-inventory problem in food distribution network by two-stage method. An improved hybrid heuristic is proposed, which embedded with genetic algorithm and distance-based clustering approach. Saragih et al. [30] explored the location-inventory-routing problem with inventory decisions within a three-echelon supply chain system and designed a heuristic method to solve the above problem. In the supply chain management, there often exits multiple optimization objectives, such as total costs (or total revenue), customer service level, and environmental external cost. Abbasi et al. [31] addressed the location and routing problem with the considerations of the consolidation hubs disruption risks and product perishability. Ghasemkhani et al. [27] addressed the production-inventory-routing problem on multi-perishable products with uncertain demand, which is solved by a meta-heuristic algorithm, which embedded with imperialist competitive algorithm and self-adaptive differential evolution method. Chavez et al. [32] investigated the location-inventory-routing model of agricultural waste-based biofuel supply chain with stochastic demand with a multi-objective optimization method; a two-phase heuristic method is given.

With increasing environmental awareness, the network design problem of green supply chain includes not only economic indexes, but also social environment ones [33,34]. Recently, the green supply chain network design with an inventory and routing problem has attracted the attention of some researchers.

Golpira et al. [35] investigated a robust bi-level optimization for a green supply chain network design problem against uncertainty and environmental. Miranda-Ackerman et al. [36] investigated a green supply network design framework on the processed food industry by heuristic method with clustering. Zhang et al. [37] addressed the green supply chain network for a manufacturing enterprise, which considers the economies of scale about logistics facilities and the external cost of CO_2 emissions. They found that the optimal location of regional distribution centers (RDCs) is affected by the customers' demand and the level of economies of scale on logistics facilities. Moreover, some researchers introduce green technology and government subsidies to promote the development of sustainable supply chain management [38,39]. Zhang et al. [40] considered a green supply chain with one manufacturer and two competing, which aimed to obtain the manufacturer's optimal green technology investment. Ma et al. [19] addressed the sustainable supply chain management considering technology investments and government intervention and proposed the corresponding dynamic game model. They found that a higher emission reduction subsidy encourages green technology investments and increases supply chain members' profits. For a comprehensive review of green supply chain network design problem, interested readers can refer to the references [41–44].

However, our proposed problem differs from the existing studies in the following aspects. First, our proposed model of a green supply chain network design deals with the integrated optimization problem on the locations of facilities, selection of suppliers, transport mode choices, and inventory management. Secondly, we design an improved hybrid GA (HGA) embedded with a local search to solve the proposed problem. Finally, the proposed model and algorithm are suitable for a green supply chain network design of assembly manufacturing enterprises, such as electronics, construction machinery, and automobiles.

3. Problem Description and Model Formulation

3.1. Problem Description

The above proposed problem can be illustrated as a three-echelon supply chain network consisting of suppliers, plants, DCs, and retailers, as shown in Figure 1. In the first-echelon, the selected suppliers provide the raw material to the plants, and the plants fulfill the orders of DCs in the second echelon while the DCs in turn fulfill the demands of retailers in the third echelon. This study investigates the integrated optimization problem of a three-echelon supply chain network design with inventory control and supplier selection and environment concerns, which determines the optimal combined scheme on the locations and inventory decisions for plants and DCs, supplier selection, and transport mode choice simultaneously. The objective of the proposed model aims to minimize the total cost, which consists of the fixed open cost of facilities, the inventory cost of the opened plants and DCs, the transportation cost, and CO_2 emission costs among the entire supply chain network.

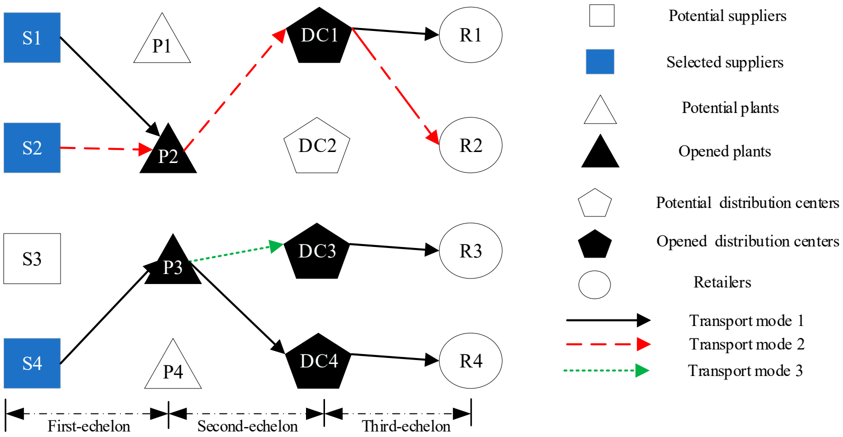


Figure 1. Distribution in the three-echelon supply chain.

In this study, the following key questions about the above green supply chain network with the inventory control and selection of suppliers should be solved:

(1) How to determine the appropriate suppliers among the candidates;

(2) How to determine the optimal number, location of plants, and DCs;
(3) How to develop a reasonable allocation scheme among the suppliers, plants, DCs, and retailers;
(4) How to choose optimal combined transport modes among the entire supply chain network.

3.2. Assumptions

To facilitate the presentation of essential ideas without loss of generality, the following basic assumptions are made:

A1 The demand of each retailer is independent and follows a normal distribution with a known mean and variance;
A2 There are a set of candidate plants and DCs with specific capacities;
A3 There exists several different transport modes with limited capacities among networks, which are pre-defined;
A4 A continuous review inventory method based on (Q,r) inventory policy is adopted in plants and DCs, and economic order quantity (EOQ) purchase strategy is adopted;
A5 A retailer can be served by only one DC, which is also served only by a plant, but a plant can be served by several suppliers;
A6 The shipment incurred between two adjacent nodes are served by only one transport mode, which means that the demands cannot be divided;
A7 The lead-time of suppliers is not permitted to exceed the required maximum lead-time of the plant.

3.3. Notations

Sets:

I: Set of suppliers
J: Set of candidate plants
K: Set of candidate DCs
L: Set of retailers
M: Set of transportation modes

Decision variables:

x_j: Binary variable that takes the value of 1 if plant j is opened, and 0 otherwise
y_k: Binary variable that takes the value of 1 if DC k is opened, and 0 otherwise
t_{ij}^{m}: Binary variable that takes the value of 1 if supplier i is assigned to plant j by transportation mode m, and 0 otherwise
r_{jk}^{m}: Binary variable that takes the value of 1 if plant j is assigned to DC k by transportation mode m, and 0 otherwise
s_{kl}^{m}: Binary variable that takes the value of 1 if DC k is assigned to retailer l by transportation mode m, and 0 otherwise
λ_{ij}: Order quantity from supplier i to plant j

Auxiliary variables:

β_j: Average demand for plant j
V_j: Variance demand for plant j
α_k: Average demand for DC k
U_k: Variance demand for DC k

Retailer parameters:

d_l : Average demand for retailer l
u_l: Variance demand for retailer l

Plant parameters:

F_j: Fixed cost of opening plant j
OC_{ij}: Ordering cost from supplier i to plant j
HC_j: Inventory holding cost per unit at plant j

α: Inventory service level
Z_α : Value of the accumulated standard normal distribution with a probability related to the service level
LT_{ij}^m : Lead-time from supplier i to plant j by transportation mode m
LT_j: Maximum lead-time of plant j
UC_{ij}: Purchase cost per unit from supplier i
P_j: Production cost at plant j
CQ_i: Production capacity of supplier i
CP_j: Capacity at plant j

DC parameters:

f_k : Fixed cost of opening DC k
oc_{jk}: Ordering cost from plant j to DC k
hc_k: Inventory holding cost per unit at DC k
CW_k: Capacity at DC k
lt_{jk}^m: Lead-time from plant j to DC k by transportation mode m

Transportation parameters:

TC_{ij}^m: Transport cost from supplier i to plant j by transportation mode m
RC_{jk}^m: Transport cost from plant j to DC k by transportation mode m
SC_{kl}^m: Transport cost from DC k to customer l by transportation mode m

Other parameters:

E_{ij}^m: Unit CO$_2$ emission of transportation between the arc $(i, j) \in A$ by mode m (kg/t-km)
e_j^p: Unit CO$_2$ emission from handing per unit product in pant, $j \in J$
e_k^d: Unit CO$_2$ emission from handing per unit product in DC, $k \in K$
ϕ: Emission taxes per unit CO$_2$ emission (\$/kg)

3.4. Model Formation

The total cost incurred in the first echelon is denoted as $TC1$.

$$TC1 = \sum_{j\in J} F_j \cdot x_j + \sum_{m\in M}\sum_{i\in L}\sum_{j\in J}\left(\sqrt{2 \cdot OC_{ij} \cdot HC_j} \cdot \sqrt{\beta_j} \cdot t_{ij}^m + Z_\alpha \cdot HC_j \cdot \sqrt{LT_j} \cdot \sqrt{V_j} \cdot x_j + P_j \cdot \beta_j\right) \tag{1}$$

where $TC1$ states the total costs incurred at the first echelon, namely from suppliers to plants, which consists of two parts. The first part is the fixed cost of opening plants while the second part is the total operational cost. The operational cost includes three items, i.e., the ordering cost and holding cost, safety inventory cost, and production cost. Moreover, the first term represents the fixed order and holding inventory costs since each plant uses an EOQ policy, and the second one represents the safety inventory costs for all opening plants [1,8,45].

Similarly, we can obtain the total costs of the second echelon between plants and DCs, denoted $TC2$.

$$TC2 = \sum_{k\in K} f_k \cdot y_k + \sum_{m\in M}\sum_{j\in J}\sum_{k\in K}\sqrt{2 \cdot oc_{jk} \cdot hc_j} \cdot \sqrt{\alpha_k} \cdot r_{jk}^m + \sum_{m\in M}\sum_{j\in J}\sum_{k\in K} Z_\alpha \cdot hc_k \cdot \sqrt{lt_{jk}^m} \cdot \sqrt{U_k} \cdot y_k \tag{2}$$

The first item is the fixed cost of opening DCs. The second item of Equation (2) is the order and holding inventory costs in DCs while the third one is the sum of safe inventory costs incurred in DCs.

Moreover, the total cost of transportation is calculated by Equation (3).

$$TC3 = \sum_{m\in M}\sum_{i\in I}\sum_{j\in J} TC_{ij}^m \cdot \lambda_{ij} \cdot t_{ij}^m + \sum_{m\in M}\sum_{j\in J}\sum_{k\in K} RC_{jk}^m \cdot \alpha_k \cdot r_{jk}^m + \sum_{m\in M}\sum_{k\in K}\sum_{l\in L} SC_{kl}^m \cdot d_l \cdot s_{kl}^m \tag{3}$$

$$TC4 = [(\sum_{m\in M}\sum_{i\in I}\sum_{j\in J} E_{ij}^{m}\cdot\lambda_{ij}\cdot t_{ij}^{m} + \sum_{m\in M}\sum_{j\in J}\sum_{k\in K} E_{jk}^{m}\cdot\alpha_{k}\cdot r_{jk}^{m} + \sum_{m\in M}\sum_{k\in K}\sum_{l\in L} E_{kl}^{m}\cdot d_{l}\cdot s_{kl}^{m}) + (\sum_{j\in J} e_{j}^{p}\cdot x_{j}\beta_{j} + \sum_{k\in K} e_{k}^{d}\cdot y_{k}\alpha_{k})]\cdot\phi \quad (4)$$

Equation (4) represents the CO_2 emission charge cost incurred among the entire supply chain network, including transportation and handling activities in plants and DCs.

$$MinZ = TC1 + TC2 + TC3 + TC4 \quad (5)$$

subject to:

$$\sum_{m\in M}\sum_{k\in K} s_{kl}^{m} = 1 \quad \forall l \in L \quad (6)$$

$$\sum_{m\in M}\sum_{j\in J} r_{jk}^{m} = y_{k} \quad \forall k \in K \quad (7)$$

$$\sum_{m\in M}\sum_{l\in L} d_{l}\cdot s_{kl}^{m} = \alpha_{k} \quad \forall k \in K \quad (8)$$

$$\sum_{m\in M}\sum_{l\in L} u_{l}\cdot s_{kl}^{m} = U_{k} \quad \forall k \in K \quad (9)$$

$$\sum_{m\in M}\sum_{k\in K} \alpha_{k}\cdot r_{jk}^{m} = \beta_{j} \quad \forall j \in J \quad (10)$$

$$\sum_{m\in M}\sum_{k\in K} U_{k}\cdot r_{jk}^{m} = V_{j} \quad \forall j \in J \quad (11)$$

$$\sum_{m\in M}\sum_{i\in I} \lambda_{ij}\cdot t_{ij}^{m} = \beta_{j} \quad \forall j \in J \quad (12)$$

$$\sum_{m\in M}\sum_{j\in J} \lambda_{ij}\cdot t_{ij}^{m} \le CQ_{i} \quad \forall i \in I \quad (13)$$

$$\sum_{m\in M}\sum_{i\in I} \lambda_{ij}\cdot t_{ij}^{m} \le CP_{j}\cdot x_{j} \quad \forall j \in J \quad (14)$$

$$Z_{\alpha}\cdot\sqrt{LT_{j}\cdot V_{j}} + \beta_{j} \le CP_{j}\cdot x_{j} \quad \forall j \in J \quad (15)$$

$$Z_{\alpha}\cdot\sqrt{lt_{jk}^{m}\cdot U_{k}} + \alpha_{k} \le CW_{k}\cdot y_{k} \quad \forall k \in K \quad (16)$$

$$\lambda_{ij} \le CT_{ij}^{m} \quad \forall m \in M \quad (17)$$

$$\alpha_{k} \le CR_{jk}^{m} \quad \forall m \in M \quad (18)$$

$$d_{l} \le CS_{kl}^{m} \quad \forall m \in M \quad (19)$$

$$\sum_{m\in M} t_{ij}^{m} \le 1 \quad \forall i \in I, j \in J \quad (20)$$

$$\sum_{m\in M} r_{jk}^{m} \le 1 \quad \forall j \in J, k \in K \quad (21)$$

$$\sum_{m\in M} s_{kl}^{m} \le 1 \quad \forall k \in K, l \in L \quad (22)$$

$$LT_{ij}\cdot t_{ij}^{m} \le LT_{j} \quad \forall j \in J \quad (23)$$

where Equation (6) states that each customer is served by only one DC. Equation (7) assures us that each DC is served by exactly one plant. Equation (8) and Equation (10) compute the corresponding served average demand by DC k and plant j, respectively. Equation (9) and Equation (11) calculates the total standard deviation of served demand by DC k and plant j, respectively. The purchase amount from each supplier is equal to the quantity demanded by the plant, which is shown as Equation (12).

Equation (13) implies that the supplier's supply capacity cannot exceed its production capacity. Equaretion (14) ensures that the production capacity of plants is not exceeded (only if the plant is open). Equation (15) and Equation (16) imply that the inventory capacity of the plants and DCs cannot exceed their capacities, respectively.

Equations (17)–(19) state that the shipments cannot exceed the corresponding capacities of available transport modes. Equations (20)–(22) ensure that the shipments are served only by one transport mode at each arc among the entire supply chain network. Equation (23) means that the lead-time from the supplier to the plant cannot exceed the plant's maximum lead-time.

4. Solution Algorithm

As a variant of the location-inventory problem (LIP), the proposed problem is also an NP-hard, which faces a great computational challenge to deal with large-size instances with exact solution algorithms [46]. In this regard, a heuristic method or hybrid metaheuristic one are proven as effective methods to solve the above NP-hard problems. A genetic algorithm (GA) is a stochastic global search metaheuristics approach based on evolutionary processes, which is approved as an effective method to solve NP-hard problems [47,48]. In this study, we have designed a hybrid genetic algorithm (HGA) based on standard GA and local search (LS) to solve our proposed problem. The following are some key operations in a hybrid genetic algorithm.

(1) Selection operator

The selection operator is a significant to ensure select good chromosomes from the population. There are some feasible methods, e.g., roulette wheel selection, Boltzmann selection, rank selection, and some others [47]. In this study, we designed a combination method, which is embedded with the roulette wheel selection and optimal individual preservation, so as to choose excellent individuals from their parents. This combination selection strategy can inherit the contemporary optimal individual into the next children individuals [45].

(2) Crossover operator

We implement a crossover operation for the two parts of the chromosome. The partially matched crossover (PMX) method is adopted to randomly select two intersections in a chromosome in this study [45,49]. The process of crossover operator is shown as follows:

Step 1: Choose two parent individuals to crossover;
Step 2: Determine the crossover section;
Step 3: Determine the crossover position, namely the columns to be exchanged;
Step 4: Modify the relationship between individual fragments. If there are sections that do not meet the condition, then reconstruct upstream, and the process is similar to the initial solution.

(3) Mutation operator

Mutation changes the gene value of some chromosomes. The mutation operation process is basically similar to the crossover operation. The difference lies in two points: (1) the chromosomes are selected according to a certain probability, and the chromosomes are not necessarily even numbers; (2) the 2-opt algorithm is used for row mutation operations, and other similar parts would not repeat here.

(4) Process of local search

On the basis of determining the optimal individual of each generation by genetic algorithm, the local search operator is used for further optimization. The local search operator is as follows: (i) swap traverses all the elements in the matrix and exchanges them with the elements in another position; (ii) insert indicates that the elements in a row in the matrix are inserted into other different positions in that row; and (iii) 3-opt traverses the rows in the matrix for a 3-opt operator.

(5) Adaptive probabilities of crossover and mutation

The probabilities of a crossover operator and mutation operator have significant effect on the GA's performance, and the unreasonable crossover ratio and mutation ratio will cause the algorithm to fail to converge to the global optimal solution. The improved adaptive crossover ratio and mutation ratio are adapted from Ge et al. [50] and Zhang and Xing [51]. The corresponding probability of a crossover operator (Pc) and that of mutation (Pm) are shown as Equations (24) and (25).

$$p_c = \begin{cases} \frac{k_1(F_{avg}-F')+k_2(F'-F_{\min})}{F_{avg}-F_{\min}} & F' < F_{avg} \\ \frac{k_2(F_{\max}-F')+k_3(F'-F_{avg})}{F_{\max}-F_{avg}} & F' \geq F_{avg} \end{cases} \tag{24}$$

$$p_m = \begin{cases} \frac{k_4(F_{avg}-F)+k_5(F-F_{\min})}{F_{avg}-F_{\min}} & F < F_{avg} \\ \frac{k_5(F_{\max}-F)+k_6(F-F_{avg})}{F_{\max}-F_{avg}} & F \geq F_{avg} \end{cases} \tag{25}$$

where k_1, k_2, k_3, k_4, k_5, and k_6 are the weights of each calculation component. Moreover, k_1, k_2, k_3, k_4, k_5, and k_6 fall in the interval (0, 1) and $k_1 > k_2 > k_3 > k_4 > k_5 > k_6$ [45,51]. $\boldsymbol{F}$ represents the fitness function value of the individual. Moreover, F_{min}, F_{max}, and F_{avg} represent the minimum, maximum, and average values of the current population, respectively.

Algorithm 1 below shows the pseudo-code for the HGA to find a near optimal solution. In order to improve the efficiency of the hybrid genetic algorithm, the local search is performed, whose pseudo-code is shown as Algorithm 2.

Algorithm 1: Hybrid Genetic Algorithm (The pseudo-code for the hybrid genetic algorithm (HGA).

```
Input: Population size (Ps),Max generation (Gen_m), Crossover probability (Pc), and mutation probability (Pm).
Output: the best solution (X,Y,T,R,S)
Begin
g←0;
initialize P(g) by encoding the scheme about location, allocation, inventory, transport mode of the supply chain network;
(X,Y,T,R,S) ← Decode(P(g));
Evaluate P(g) based on the solution (X,Y,T,R,S);
Sort the fitness value of P(g) by an ascending order;
while g <= Gen_m do
    Obtain P1(g) from the parent P(g) by selection operator
    Generate new offspring O(g) from the parent P1(g) by crossover and mutate operator
    Improve O(g) by Iterated Local Search Algorithm
    (X,Y,T,R,S)← Decode(O(g))
    Evaluate O(g) based on the solution (X,Y,T,R,S)
    Sort the fitness value of O(g) by an ascending order
    P(g) ← O(g)//
    g = g + 1;
end
Output the best solution $(X^*,Y^*,T^*,R^*,S^*)$
```

Algorithm 2: Iterated Local Search Algorithm (The pseudo-code for Iterated Local Search).

```
Input: Solution $R(X,Y,T,R,S)$
Output: an improved Solution $\bar{R}(X,Y,T,R,S)$
Begin
Let $\bar{R} = R$ be an initial solution;
while criteria is not met do
    $R_{new}$ = Perturbation(R)
    Evaluate O($R_{new}$) based on the solution $R_{new}$
    if O($R_{new}$)<O($R$) then
        $\bar{R} = R_{new}$
    end
end
Output $\bar{R}$
End
```

5. Computational Experiments

In this section, we first validate our model and compare the computational performance of the proposed hybrid genetic algorithm (i.e., HGA) and standard genetic algorithm (i.e., SGA) by several instances. Moreover, we reveal some managerial insights based on the corresponding analysis.

5.1. Data Input

We considered a four-level supply chain network (i.e., suppliers, plants, DCs, and retailers), which illustrates the above proposed model and solution algorithm. Three alternative transport modes were chosen between suppliers and plants, from plants to DCs, and from DCs to retailers.

To test the computational performance, five instances were generated based on the corresponding parameters shown in Table 1. The proposed hybrid genetic algorithms were coded in MATLAB R2020a. All experiments were conducted on a Lenovo ThinkPad T450 laptop with an Intel Core i5 CPU and 8 GB RAM under the Windows 10 operating system.

Table 1. Parameters to generate the instances.

Parameter	**Notations**	**Range [minimum, maximum]**
Average demand of retailer *l* (unit/day)	d_l	[23, 30]
Demand variance of retailer *l* (unit/day)	u_l	[3, 6]
Production capacity of supplier *i* (unit/day)	CQ_i	[1000, 1200]
Purchase cost per unit from supplier *i* ($)	UC_{ij}	[4800, 4900]
Fixed cost of opening plant *j* ($)	F_j	[100,000, 120,000]
Inventory holding cost per unit at plant *j* ($/day)	HC_j	[1.75, 1.78]
Inventory α service level	α	0.95
Value of the accumulated standard normal distribution with a probability related to the service level	Z_α	1.65
Maximum lead-time of plant *j* (day)	LT_j	[6, 7.5]
Production cost in plant *j* ($/unit)	P_j	[900, 1000]
Capacity at plant *j* (unit/day)	CP_j	[1000, 1200]
Ordering cost from supplier *i* to plant *j* ($/round)	OC_{ij}	[1100, 1500]

Table 1. *Cont.*

Parameter	Notations	Range [minimum, maximum]
Lead-time from supplier *i* to plant *j* by transportation mode *m* (day)	LT_{ij}^{m}	[3, 8]
Fixed cost of opening DC *k* ($)	f_k	[70,000, 80,000]
Inventory holding cost per unit at DC *k* ($/day)	hc_k	[1.44, 1.48]
Capacity at DC *k* ($)	CW_k	[500, 600]
Ordering cost from plant *j* to DC *k* ($/round)	oc_{jk}	[290, 300]
Lead-time from plant *j* to DC *k* by transportation mode *m* (day)	lt_{jk}^{m}	[0.5, 2]
Transport cost from supplier *i* to plant *j* by transportation mode *m* ($)	TC_{ij}^{m}	[90, 1300]
Transport cost from plant *j* to DC *k* by transportation mode *m* ($)	RC_{jk}^{m}	[90, 1300]
Transport cost from DC *k* to customer *l* by transportation mode *m* ($)	SC_{kl}^{m}	[90, 1300]
Unit CO_2 emission from handing per unit product in pant $j \in J$ (kg/t)	e_j^p	[22, 28]
unit CO_2 emission from handing per unit product in DC $k \in K$ (kg/t)	e_k^d	[18, 20]

The numerical experiment tested 5 different instances to compare the HGA with SGA. The crossover rate and mutation rate were set to $p_c = 0.8$ and $p_m = 0.1$ respectively. Moreover, crossover and mutation parameters in HGA were shown as follows, i.e., $k_1 = 0.9$, $k_2 = 0.8$, $k_3 = 0.7$, $k_4 = 0.1$, $k_5 = 0.08$, and $k_6 = 0.06$.

Each arc was associated with a different transport mode, which had different cost and unit product cost of CO_2 emissions. The unit CO_2 emission from handing per unit product in plants and DCs was 0.22 kg. The unit CO_2 emission tax was 0.12 $/kg. The unit transport cost and CO_2 emission of different transport modes are shown in Table 2 [10,45].

Table 2. Unit transport cost and CO_2 emissions.

	Highway	Railway	Air Transportation
Unit transport cost ($/t-km)	0.42	0.35	0.50
Unit CO_2 emissions (kg/t-km)	0.283	0.022	2.816
The unit CO_2 emission tax is 0.12 $/kg.			

5.2. Comparison of the Two Algorithms

The numerical experiment tested 5 different scenario groups to compare optimal solution and running time of SGA and HGA. Each group was tested 20 times, and the operation results of the different algorithms are recorded in Table 3.

Table 3. Comparison of computational results reported by SGA and HGA algorithms.

Instances No.	Problem Size (|I|−|J|−|K|−|L|)	Optimal Value		CPU (Sec.)	
		SGA	HGA	SGA	HGA
1	5-3-5-10	1,811,639	1,747,000	2.78	2.85
2	5-3-5-15	2,481,451	2,365,540	3.07	3.14
3	5-3-10-15	2,570,017	2,475,932	8.61	8.74
4	5-5-5-15	2,344,646	2,316,844	8.17	8.28
5	10-3-5-15	2,605,782	2,462,932	7.73	7.84

Note: |I|, |J|, |K|, |L| are the sizes suppliers, plants, DCs, and retails, respectively.

(1) The HGA resulted in the best solution, and the inferior solution and the average objective function value were smaller than those of the SGA, which meant that the HGA could find a higher-quality solution and had better optimization performance.

(2) The running time of the HGA was longer than that of the SGA, but the difference was small. Based on the above comparison analysis, we found that the HGA was more practical for the model.

5.3. Discussion and Analysis

In this section, we address the effects of some significant parameters on the supply chain network and the optimal solution based on Instance 1, which mainly includes the service levels, taxes of carbon emissions, and lead-time of plants.

5.3.1. Effects of Different Service Levels on the Supply Chain Network

First, we investigated the effects of different service levels on the supply chain network and the optimal solution. We vary the values of service level α, from 0.65 to 0.95 and run each scenario 20 times to calculate the corresponding mean values.

Figure 2 shows the change in the relationship of all the costs under different service levels. It can be seen that the total cost, transportation cost, purchase cost, inventory cost, and fixed cost are all increase with the increase of the value of the service level parameter α. Moreover, the purchase cost and transport cost curves will have an obvious increase comparing other costs, which means that the customer service level has a great influence on the purchase cost and transport cost in the supply chain network. Figure 3 shows that the total carbon emission cost is also related to the service level. Specifically, the cost of carbon emission is 8967 under the service level with 0.65, while the corresponding value will increase to 11,268 if the value of service level changes to 0.95.

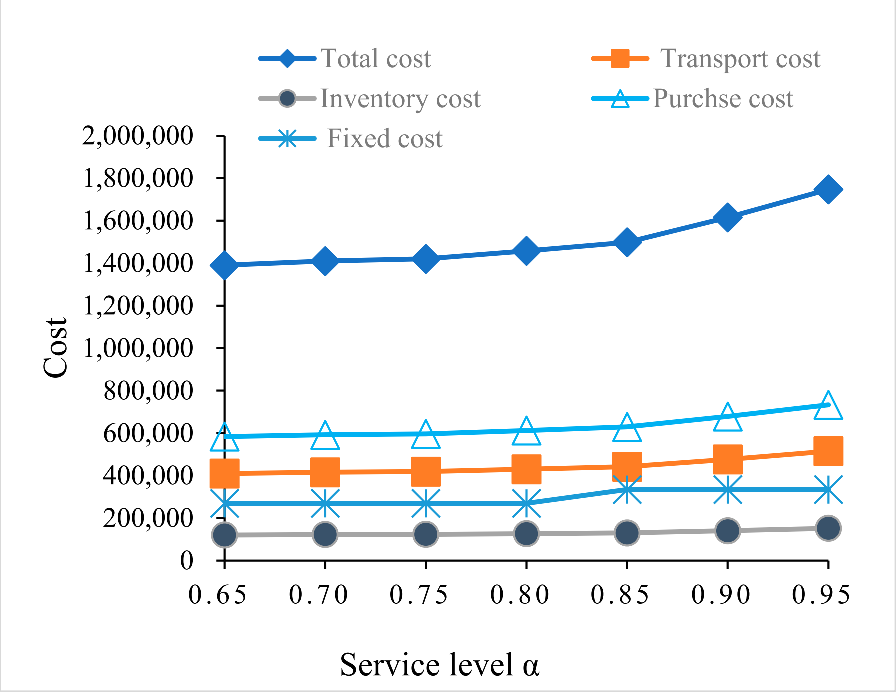


Figure 2. Cost analysis under different service levels.

The above findings reveal two important managerial implications: (1) More frequent purchases and more inventories are needed when the service level is higher, therefore the total cost of the whole supply chain will increase; and (2) enterprises must determine the best customer service level to achieve the lowest total cost in the supply chain.

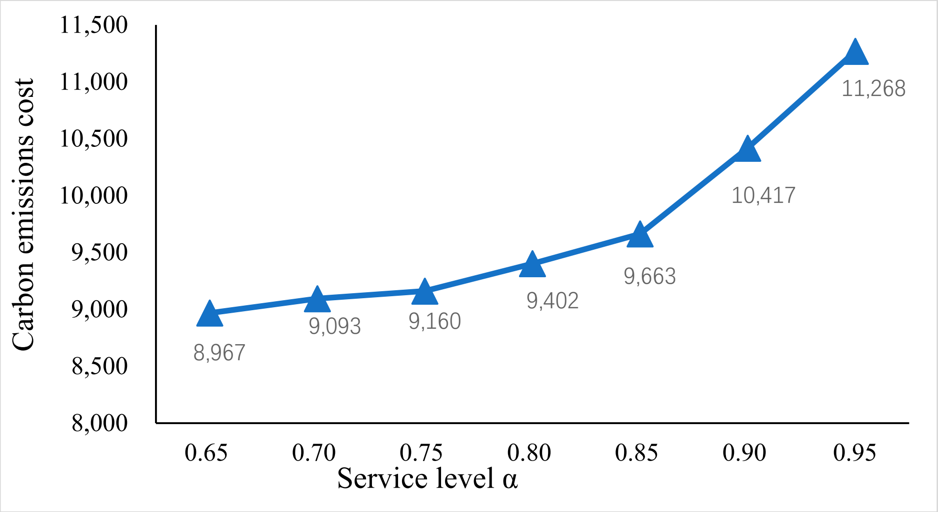


Figure 3. Carbon emission Cost analysis under different service levels.

5.3.2. Effects of Different Carbon Emission Taxes on the Supply Chain Network

Next, we addressed the effects of different carbon emission taxes on the supply chain network. We vary the values of the charging on unit carbon emission taxes from 0.06 to 0.20 \$/kg. Figure 4 shows that the total cost of supply chain will keep a growth trend with the increase of unit CO_2 emission taxes. The transport cost increase fast with the increase of unit CO_2 emission taxes, while it will keep slowly increase after the point of 0.16. The inventory cost keeps the increase trend with the increase of the CO_2 emission taxes. Moreover, we found that the inventory cost keeps the step-shape changes, i.e., increase from 27,000 to 420,000. The open plants and DCs among the candidates are shown as Table 4 under the different unit CO_2 emission taxes. We can see that the number of DCs becomes more with the increase of the CO_2 emission taxes. And we also find that more DCs are open and more green transport modes (e.g., railway) are selected, which ensures to reduce the total cost. This implies that the inventory cost and fixed cost will increase to reduce the corresponding transport cost. So, the CO_2 emission taxes show some significant effect on the supply chain network and transport mode.

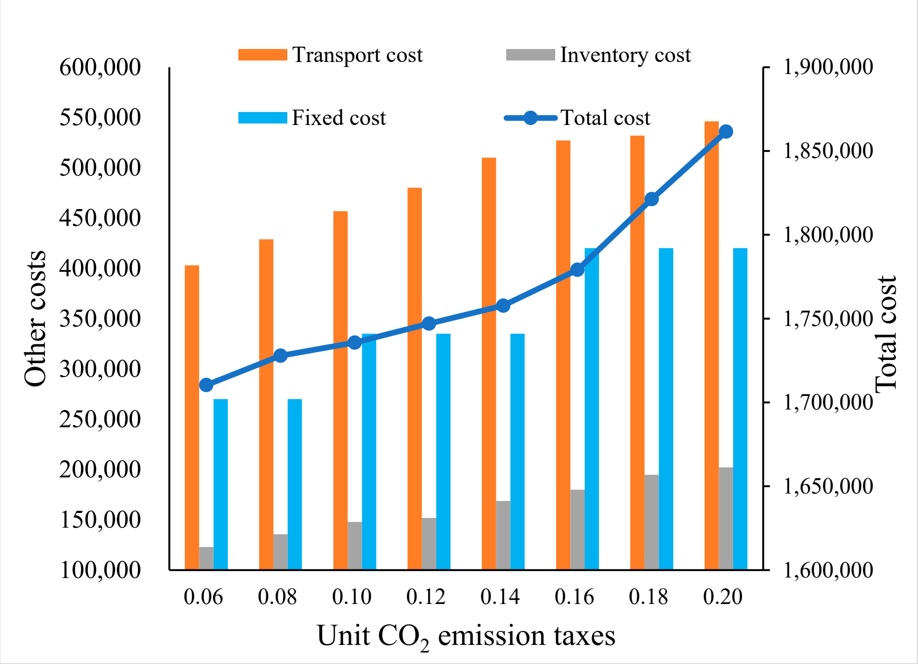


Figure 4. Cost analysis under different unit CO_2 emission taxes.

Table 4. Open plants and DCs under different unit CO_2 emission taxes.

	Unit CO_2 Emission Taxes		
	0.06–00.8	**0.10–0.14**	**0.16–0.20**
The number of open plants	1	1	1
Open plants No.	No. 3	No. 3	No. 3
The number of open DCs	2	3	4
Open DCs No.	No. 2 & 3	No. 2, 3, 4	No. 1, 2, 3, 5

5.3.3. Effects of Different Lead-Time on the Performance of Supply Chain Network

Moreover, we address the effects of different lead-times of plants on the network design of the green supply chain. We vary the lead-time of plants to test the solution algorithm, whose range falls into the interval of [0.5, 1.7]. The other basic input parameters remain unchanged. The maximum lead-time of the plant is adjusted, and the data for each group are run 20 times to obtain the average value. The results are shown in Figure 5.

As shown Figure 5, we find that the total cost will decrease first and then increase with the increase of the maximum lead-time of plants. The total cost of the supply chain will decrease gradually when the maximum lead-time of all plants changes in the range of 0.70 to 1.10. The possible reason is that the factories with less lead-time will receive orders more urgently, so the costs of procurement, transportation and production will increase. However, the total cost of the supply chain network will increase gradually when the maximum lead-time of plants continues to increase from 1.10 to 1.70. This discloses that a large amount of inventory will be accumulated and that the total cost of the supply chain will rise to meet customer needs in time. The optimal maximum lead-time of a plant is near 1.10.

The above findings reveal that the maximum lead-time of plants will have a significant effect on the whole supply network design and its corresponding total cost, and there exists an optimal lead-time for plants.

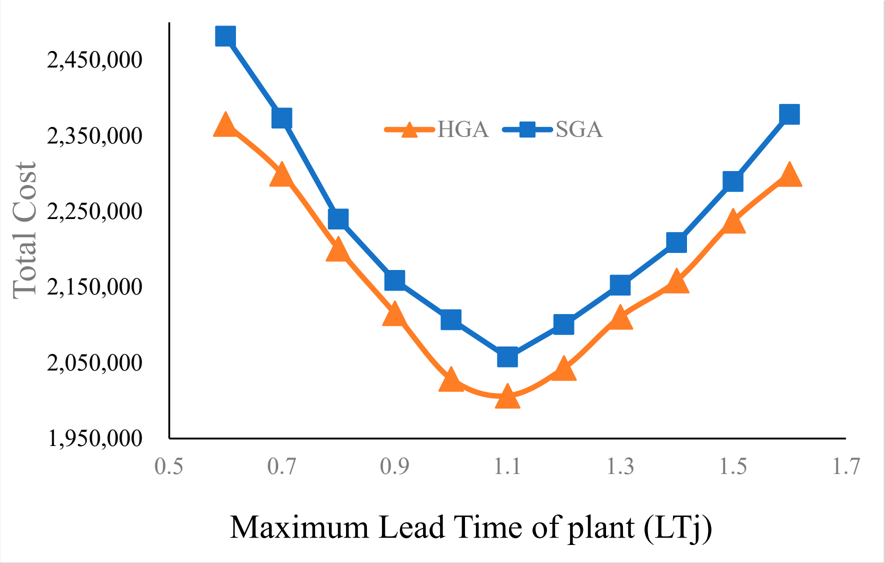


Figure 5. Cost analysis under different maximum lead-times for plants.

6. Case Study

The proposed model and solution algorithm are applied to a real-world supply chain network design of an electronic equipment assembly company, A, in China. The main business of company A covers mobile phones, computers, laptops, and other products. Currently, there are 15 candidate suppliers, 5 assembly plants, 10 distribution centers, and 30 retailers. The distances from suppliers to plants, from plants to DCs, and from DCs to retailers is shown in Tables A1–A5. The demand of retailers is shown in Table 5.

The capacity of the suppliers is shown in Table 6. The other parameters are shown as Tables 7–11.

Table 5. The demand of retailers.

Retailer No.	d_l	u_l	Retailer No.	d_l	u_l	Retailer No.	d_l	u_l
1	19	3	11	39	5	21	39	3
2	31	3	12	33	3	22	25	4
3	26	4	13	13	5	23	36	5
4	26	4	14	13	5	24	54	6
5	38	6	15	19	5	25	23	4
6	26	3	16	22	3	26	34	5
7	28	3	17	18	3	27	29	3
8	28	5	18	45	4	28	26	5
9	16	6	19	39	4	29	23	4
10	28	4	20	21	6	30	53	7

Table 6. The supply capacity of suppliers.

Supplier No.	CQ_i (unit/day)	Supplier No.	CQ_i (unit/day)
1	7000	9	10,000
2	7700	10	9000
3	6000	11	8000
4	5000	12	8000
5	8800	13	9000
6	8000	14	10,000
7	6500	15	9000
8	6600		

Table 7. The operational parameters of assembly plants.

Plant	F_j ($)	HC_j ($/(day•unit))	LT_j (day)	P_j ($/unit)	CP_j (unit/day)
1	140,000	2.27	7.0	20	10,000
2	145,000	2.27	6.0	18	12,000
3	150,000	2.28	7.5	24	15,000
4	140,000	2.30	6.0	18	10,000
5	142,000	2.33	7.5	24	11,000

Table 8. The operational parameters of distribution centers.

No.	f_k ($)	hc_k ($/day. unit)	CW_k (unit/day)
1	80,000	1.97	6000
2	81,500	1.96	5000
3	85,000	1.87	6000
4	80,000	1.90	6000
5	90,000	1.99	9000
6	88,000	1.93	6000
7	86,000	1.94	7000
8	83,000	1.97	6000
9	87,000	1.96	7000
10	81,000	1.96	6000

Table 9. The unit purchasing costs of assembly plants ($/unit).

Supplier No.	Assembly Plant No.				
	1	**2**	**3**	**4**	**5**
1	270	270	270	270	270
2	270	270	270	270	270
3	269	269	269	269	269
4	271	271	271	271	271
5	272	272	27	272	272
6	271	271	271	271	271
7	268	268	268	268	268
8	270	270	270	270	270
9	270	270	270	270	270
10	269	269	269	269	269
11	271	271	271	271	271
12	268	268	268	268	268
13	271	271	271	271	271
14	269	269	269	269	269
15	272	272	27	272	272

The comparison analysis of the current solution to the supply chain network design of company A and optimization is shown in Table 12.

As shown Table 12, the optimized total annual cost of Company A's supply chain network is 4093.17 million dollars, which is an annual savings of 98.76 million dollars compared with the current supply chain network design scheme 4191.93 million dollars. The percent of total cost saving is 2.36%. The fixed cost saved 130.59 million dollars, with a decrease percent of 14.84%. The inventory cost is reduced by 1.36 million dollars, with a saving percent of 12.73%. The procurement and production cost is reduced by 64.74 million dollars, with an optimization of 2.69%. Transportation cost is reduced from 109,07 to 100.04 million dollars, with an decrease of 8.28%. The CO_2 emission cost is reduced from 5.63 to 5.11 million dollars, and the corresponding decrease percent is up to 9.24%.

Table 10. The ordering costs of the assembly plants ($/shift).

Supplier No.	Assembly Plant No.				
	1	**2**	**3**	**4**	**5**
1	700	650	650	700	710
2	645	670	700	660	645
3	700	660	615	665	680
4	660	650	675	630	645
5	550	660	620	655	700
6	630	700	660	605	660
7	675	645	705	700	665
8	605	700	690	645	725
9	660	660	640	700	760
10	675	665	660	660	590
11	690	725	645	670	630
12	640	615	700	660	660
13	750	675	660	645	725
14	695	620	600	660	615
15	690	725	725	695	675

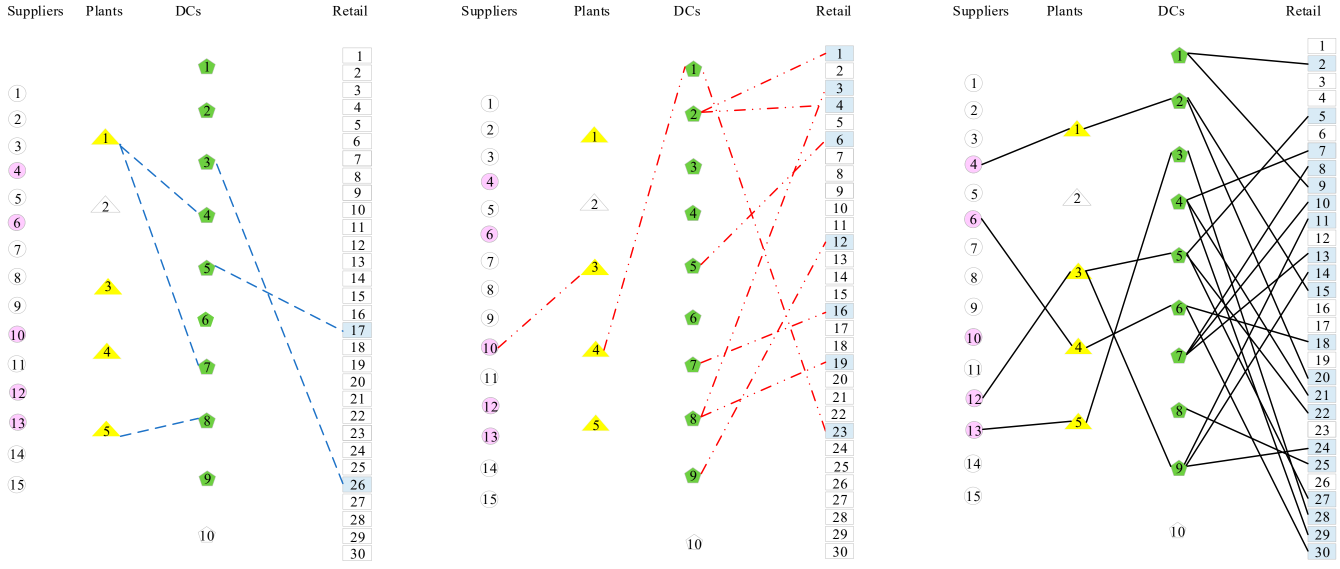
Table 11. The ordering costs of the distribution centers ($/shift).

Supplier No.	**Assembly Plant No.**				
	1	**2**	**3**	**4**	**5**
1	280	288	280	270	270
2	282	276	288	290	282
3	280	300	290	290	280
4	288	290	290	300	288
5	276	290	280	290	276
6	300	300	284	290	290
7	290	290	280	282	290
8	290	290	288	280	300
9	280	276	276	288	290
10	284	300	300	276	290

Table 12. Comparative analysis of the current solution and the optimized solution (Million dollars/year).

	Total Cost	**Fixed Cost**	**Inventory Cost**	**Procurement &Production Cost**	**Transportation Cost**	**CO_2 Emission Cost**
Current solution	4191.93	153.34	10.68	3912.85	109.07	5.63
Optimized solution	4093.17	130.59	9.32	3848.11	100.04	5.11
Cost savings	98.76	22.75	1.36	64.74	9.03	0.52
Saving (%)	2.36%	14.84%	12.73%	2.69%	8.28%	9.24%

The optimization supply chain network design of company A is shown in Figure 6. Since the inventory control methods based on (Q,r) and the economic order quantity (EOQ) purchase strategies are adopted in plants and DCs, the corresponding optimal re-order point and purchase quantities of plants and DCs are shown Tables 13 and 14, respectively.



(a) By Air transportation (b) By Railway (C) by Highway

Figure 6. Optimization supply chain network design.

Table 13. The optimal re-order point and purchase quantities of plants.

Plants	Re-Order Point (unit)	Purchase Quantity (unit)
1	1087	7866
2	-	-
3	1559	11,455
4	923	6172
5	833	6070

Table 14. The optimal re-order point and purchase quantities of DCs.

DCs	Re-Order Point (unit)	Purchase Quantity (unit)
1	259	3017
2	234	3128
3	97	2681
4	96	3304
5	283	3913
6	254	3433
7	105	3424
8	94	3275
9	359	3958
10	-	-

The results show that the proposed optimization model and algorithms in this study significantly reduce fixed inventory costs, transportation costs, and CO_2 emission costs with optimization on the supply chain network design with inventory management. Although the proposed optimization model and algorithms also contribute to reducing procurement and production costs, their impacts are relative limited. The finding reveals that an effective supply chain network design can decease the total cost of supply chains and benefit from reducing CO_2 emissions.

7. Conclusions and Future Work

Achieving low-cost, high-efficiency, and high-service level, the green supply chain has been a hot research topic in recent years. This paper establishes an integrated non-linear programming model, which integrates and optimizes the multi-echelon green sup-ply chain network design with inventory management as well as the selection of suppliers. An improved hybrid genetic algorithm embedded with a local search is presented to solve the above proposed optimization model. To verify the above model and corresponding algorithm, some mathematical experiments and a case study are conducted. By comparing the proposed hybrid genetic algorithm (HGA) and the standard genetic algorithm (SGA), we found that the computational performance of HGA is better than that of SGA.

The following findings are also obtained:

(1) An effective supply chain network design can decease the total cost of the supply chain and benefit from reducing CO_2 emissions;
(2) The service level has the greatest impact on the purchase and holding costs in the supply chain network;
(3) The CO_2 emission taxes show some significant effect on the supply chain network and transport mode;
(4) It is important for enterprises to set a rational maximum lead-time of a plant, which shows a significant effect on the whole supply network design and its corresponding total cost.

Future research directions are listed as follows:

(1) Establishing an uncertain robust multi-echelon supply network considering the determination of customer requirements and procurement lead-time;

(2) Considering a flexible supply network to combine multi-source supply with supply interruption;

(3) Designing heuristic or meta-heuristic algorithms to solve the model to obtain better solutions.

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Appendix A

Table A1. Distance from suppliers to plants by different transport modes (km).

Plants No.	Suppliers No.														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
By Highway															
1	223	210	218	213	212	213	210	230	210	230	233	210	213	210	220
2	200	213	210	230	233	213	210	230	210	230	233	233	210	230	233
3	200	213	210	230	233	210	218	213	212	213	210	233	233	210	230
4	230	225	215	222	233	220	228	210	230	230	233	208	210	230	227
5	233	232	210	230	233	210	218	210	212	213	210	225	233	210	225
By Railway															
1	300	320	380	370	380	380	370	380	380	300	410	380	360	340	335
2	330	320	380	380	370	380	380	300	410	380	380	380	370	355	350
3	330	370	380	380	310	345	315	325	300	310	360	380	310	340	335
4	330	320	380	380	370	370	380	380	300	310	380	380	370	355	350
5	380	310	345	315	325	300	300	360	380	380	380	370	355	340	335
By Air transportation															
1	393	397	410	411	393	408	411	400	416	397	410	411	393	402	416
2	397	410	402	396	397	397	398	413	411	398	411	393	408	411	401
3	416	408	411	400	416	416	402	396	397	397	416	416	402	396	397
4	402	396	402	402	402	4004	397	410	402	397	397	398	413	398	397
5	398	398	413	411	398	398	398	398	413	411	411	398	411	393	411

Table A2. Distance from plants to DCs by different transport modes (km).

Plants No.	**DCs No.**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
By Highway										
1	367	273	284	277	275	277	273	299	273	299
2	260	277	273	299	303	277	273	299	273	299
3	260	277	273	299	303	273	284	277	275	277
4	299	293	280	288	303	286	297	273	299	299
5	303	301	273	299	303	273	284	273	275	277
By Railway										
1	390	416	494	481	494	494	481	494	494	390
2	429	416	494	494	481	494	494	390	533	494
3	429	481	494	494	403	449	410	423	390	403
4	429	416	494	494	481	481	494	494	390	403
5	494	403	449	410	423	390	390	468	494	494
By Air transportation										
1	511	516	533	535	511	531	534	520	541	516
2	517	533	522	514	517	517	518	537	535	518
3	541	531	534	520	541	541	522	514	517	517
4	522	515	523	522	522	5205	517	533	522	517
5	518	518	537	535	518	518	518	518	537	535

Table A3. Distance from plants to DCs by highway (km).

Suppliers No.	**DCs No.**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	178	289	329	277	296	295	164	185	153	175
2	200	280	244	294	303	218	243	152	299	170
3	336	180	299	216	289	314	200	313	381	189
4	221	388	324	334	341	277	191	295	303	313
5	281	279	313	227	250	165	238	249	151	276
6	310	327	212	353	255	333	311	232	380	338
7	270	157	220	318	303	160	347	292	220	175
8	280	297	327	254	366	201	365	283	333	286
9	233	390	373	378	223	291	221	261	279	385
10	232	301	349	314	238	381	283	306	356	251
11	302	384	244	255	357	218	395	298	311	360
12	194	258	364	374	232	221	348	225	314	211
13	268	301	391	251	233	350	302	229	359	390
14	330	264	260	268	298	363	278	264	291	214
15	236	229	243	328	217	217	348	366	293	250
16	197	379	269	209	380	370	368	385	349	202
17	211	336	301	296	568	215	240	302	258	276
18	162	240	354	392	265	215	253	338	396	350
19	238	398	337	325	337	328	225	392	276	322
20	169	345	246	203	397	382	359	373	376	289
21	277	295	269	339	396	360	291	370	232	331
22	183	320	343	234	278	388	266	201	231	358
23	398	380	279	329	211	216	261	245	283	232
24	294	219	207	281	242	234	213	208	372	397
25	209	236	379	294	217	368	372	276	282	388
26	296	201	341	689	324	286	378	366	360	334
27	347	311	247	211	253	273	397	282	318	337
28	307	331	250	366	265	318	324	208	226	300
29	268	282	243	257	317	357	357	385	242	227
30	333	242	264	388	364	333	389	340	330	228

Table A4. Distance from plants to DCs by Railway (km).

Suppliers No.	DCs No.									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	196	268	362	305	326	325	180	204	168	193
2	220	308	268	323	333	240	267	167	329	187
3	370	198	329	238	318	345	220	344	361	208
4	243	359	356	367	375	305	210	281	333	344
5	309	307	344	250	275	182	262	274	166	304
6	341	360	233	388	270	366	342	255	418	372
7	297	173	242	350	333	176	382	321	242	193
8	308	327	360	279	403	221	402	311	366	315
9	256	429	410	416	245	320	243	287	307	424
10	255	331	384	345	262	419	311	337	392	276
11	332	422	268	281	393	240	435	328	342	396
12	213	284	400	411	255	243	383	248	345	232
13	295	331	430	276	256	385	332	252	395	429
14	363	290	286	295	328	399	306	290	320	235
15	260	252	267	361	239	239	383	403	322	275
16	217	417	296	230	418	407	372	424	384	222
17	232	370	331	326	625	237	264	332	284	304
18	178	264	389	431	292	237	278	438	436	385
19	262	438	371	358	371	361	248	333	304	354
20	186	380	271	223	437	420	395	410	414	318
21	305	325	296	373	436	396	320	407	255	364
22	201	352	377	257	306	427	293	221	254	394
23	369	418	279	329	211	216	261	245	283	232
24	323	241	228	309	266	257	234	229	409	437
25	230	260	417	323	239	405	409	304	310	427
26	326	221	667	758	356	315	416	403	396	367
27	382	342	247	232	278	300	437	310	350	371
28	338	364	250	403	292	350	356	229	249	330
29	295	310	243	283	349	393	393	424	266	250
30	366	266	264	427	400	366	428	374	363	251

Table A5. Distance from plants to DCs by Air transportation (km).

Suppliers No.	DCs No.									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	231	376	428	360	385	384	213	241	199	228
2	260	364	317	382	394	283	316	198	389	221
3	437	234	389	281	376	408	260	407	426	246
4	287	424	421	434	443	360	248	332	394	407
5	365	363	407	295	325	215	309	324	196	359
6	403	425	276	459	319	433	404	302	494	439
7	351	204	286	413	394	208	451	380	286	228
8	364	386	425	330	476	261	475	368	433	372
9	303	507	485	491	290	378	287	339	363	501
10	302	391	454	408	309	495	368	398	463	326
11	393	499	317	332	464	283	514	387	404	468
12	252	335	473	486	302	287	452	293	408	274
13	348	391	508	326	303	455	393	298	467	507
14	429	343	338	348	387	472	361	343	378	278
15	307	298	316	426	282	282	452	476	381	325
16	256	493	350	272	494	481	439	501	454	263
17	274	437	391	385	658	280	312	393	335	359
18	211	312	460	510	345	280	329	517	515	455

Table A5. *Cont.*

Suppliers No.	DCs No.									
	1	2	3	4	5	6	7	8	9	10
19	309	517	438	423	438	426	293	394	359	419
20	220	449	320	264	516	497	467	485	489	376
21	360	384	350	441	515	468	378	481	302	430
22	238	416	446	304	361	504	346	261	300	465
23	389	494	363	428	274	281	339	319	368	302
24	382	285	269	365	315	304	277	270	484	516
25	272	307	493	382	282	478	484	359	367	504
26	385	261	684	896	421	372	491	476	468	434
27	451	404	321	274	329	355	516	367	413	438
28	399	430	325	476	345	413	421	270	294	390
29	348	367	316	334	412	464	464	501	315	295
30	433	315	343	504	473	433	506	442	429	296

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