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A Multiobjective Multiperiod Mixed-Integer Programming Optimization Model for Integrated Scheduling of Supply Chain Under Demand Uncertainty

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ABSTRACT The problem of integrated scheduling of supply chains has a huge impact on operational efficiency and cost effectiveness. Increasing number of the nodes, different time window constraints for customers, and a variety of uncertain scenarios complicate supply chain scheduling. In the study a multi-objective multi-period mixed-integer programming optimization model was developed. We comprehensively considered the effects of demand uncertainty, time window constraints, constraints of node capability, and multi-period and sub-period factors. The conflicting benefit factors, cost and service level are the two optimization objectives. The first objective function aims to minimize the total cost in all periods. The second objective function considers service level by minimizing the material flow of out-of-stock items in all periods to maximize service level. Suppliers' capacity, selection of suppliers, manufacturers' productivity, transaction relationship, sub-period time, inventory capacity and lead time for delivery are also considered. Subsequently the total costs and service levels are normalized, whose sum is the objective function. The problem was transformed into a multi-period non-linear optimization problem. An improved mixed Genetic Algorithm was designed to solve the model. Finally, the practicability of the proposed model and algorithm is demonstrated through its application to an electronics supply chain case study. The results indicate that the proposed model and algorithm can provide a promising approach for fulfilling a multi-objective multi period integrated scheduling plan under uncertain demand scenarios.

INDEX TERMS Integrated scheduling, mixed-integer programming optimization, supply chain, improved mixed genetic algorithm, demand uncertainty.

I. INTRODUCTION

Nowadays, supply chain management (SCM) has become the core of the enterprise management. Exploiting the full potential of SCM is an important guarantee for enhancing the competitiveness of enterprises. Supply, production and distribution are the main operational functions of the supply chain [1]. Integrated scheduling optimization of the raw material supply, product manufacture, and commodity distribution is the key to achieve efficient SCM.

Many works have given a deep insight in the problem of integrated scheduling of supply chain. One of the typical

researches is the integrated scheduling model based on different distribution strategies. Chen [2] studied an integrated production-distribution scheduling problem (IPDSP) in the context of e-commerce supply chains. They classified IPDSP into five categories based on different distribution strategies: immediate delivery to a single customer, batch delivery to a single customer by direct shipping, batch delivery to multiple customers by direct shipping, batch delivery to multiple customers by routing and delivery on a fixed date. Fu *et al.* [3] developed an production-distribution integrated scheduling model based on batch delivery strategy considering the time window constraint of delivery deadline. Chen *et al.* [4] presented a two-stage production-shipment cooperative scheduling model, which solve the problem of

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supply chain scheduling optimization that the same customer order was fulfilled before the deadline.

Moreover, many studies focused on the supply chain uncertainty, based on which the integrated scheduling problem was studied. Ramezani *et al.* [5] presented a mixed-integer programming (MIP) model considering demand uncertainty, capacity constraints, and the supply chain scheduling problem in the flow production environment was solved. Gholizadeh *et al.* [6] proposed a multi-objective stochastic model for sustainable procurement and logistics based on the hybrid uncertainty, considering the constraints of supplier selection, multi-mode transportation, and stochastic demand.

In the study of integrated optimization goal of supply chain, some researchers just considered the expected cost as the objective function. Singh *et al.* [7] designed a scheduling model in which the minimized cost was its optimization goal. It solved the problem of delivering products to customers at the lowest price under the flexible demand. Li *et al.* [8] studied the problem of synchronous scheduling of air transportation and assembly manufacturing in the supply chain of consumer electronic products, using the integer programming method in which the cost was minimized as the optimization goal.

There are also researches on multi-objective optimization for supply chain. Yang *et al.* [9] proposes a two-stage method for a multi-objective supply chain optimization problem under uncertain cost and demand. Then based on the method of AA, the problem becomes an approximating multi-objective mixed-integer programming model. An improved multi-objective biogeography-based optimization (MOBBO) algorithm integrated with LINGO was designed to solve the problem.

However, the constructed models in studies above only described the local features of the supply chain systems. Supply chain integrated scheduling is a complex system problem with multi-objective optimization requirements and time window constraints [10], [11]. In reality, the supply chain is always under uncertainty [12], [13]. The integrated scheduling refers to multi-period. According to different distribution strategies, each period involves different subperiods. Meanwhile, strong constraints should be considered in supplier selection, supply capacity, production capacity, distribution requirements in subperiods, inventory capacity and so on. The models constructed by existing studies do not contain all of these factors.

In this paper, we take the supply chain network of the electronic products in the industrial field as the background, and design a complex supply chain network including the concept of pure network and flow network. It consists of four levels: suppliers, manufacturers, distributors and end retailers. In view of the problem of uncertain demand scenarios, multi-period continuous scheduling and multiple optimization objectives, we constructed a mixed integer programming model. And an improved Mixed Genetic Algorithm (IMGA) was designed to solve the model.

The following problems were mainly solved in this paper: supplier selection strategy and order allocation strategy, production strategy and distribution strategy for manufacturers, distribution strategy and inventory strategy for retailers, which are in a multi-cycle multi-objective complex supply chain network under demand uncertainty.

The contributions and innovations of this paper are as follows:

- 1) A mixed integer programming optimization model for multi-objective multi-period supply chain integrated scheduling under demand uncertainty is formulated.
- 2) An IMGA is proposed to solve the multi-objective nonlinear mixed integer programming problem.
- 3) The mixed coding method of integer and decimal is adopted, and a local search algorithm is introduced to enlarge the search range of optimal solution to prevent the local optimal solution, which reduces the computing burden.

The rest part of the article is organized as follows: The problem is introduced and described in Section II. Then section III built a mixed integer programming model for multi-objective multi-period supply chain under demand uncertainty. Next, an IMGA is designed in Section IV. In Section V, an example is given and the results are analyzed. Finally, Section VI concludes the paper.

II. PROBLEM DEFINITION

This paper proposes a four-level supply chain network design with two attributes of time. As is shown in Fig. 1.

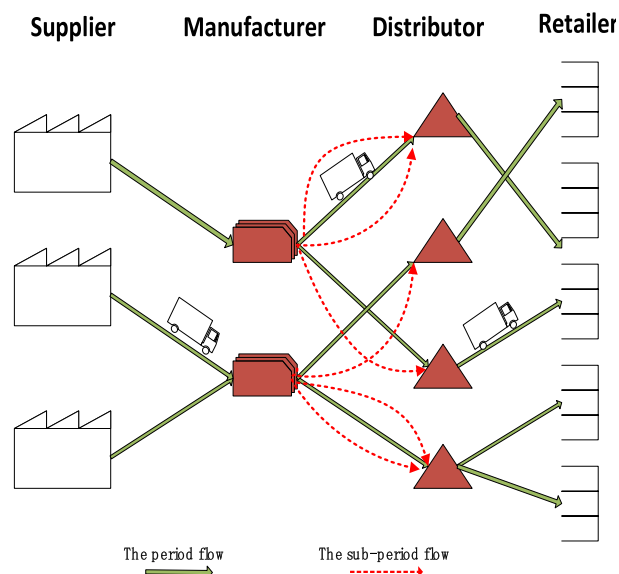


FIGURE 1. Supply chain complex network topology diagram with two attributes of time.

The topological elements of constructed network are defined as follows:

- 1) Nodes and arcs
All the suppliers, manufacturers, distributors and retailers are defined as the nodes of topological

network [14]. And the transaction links of logistics between nodes are defined as arcs [15].

2) Origin- Destination

The suppliers are defined as origins of paths of material flows, and retailers are defined as destinations. These pairs of O- D constitute a supply chain distribution network of logistics [16].

3) Material flow

The material flow in supply chain network consists of the logistics of key components from suppliers to manufacturers, product flow from manufacturers to distributors, and flow from distributors to retailers [17].

4) Two attributes of time

The link flow of supply chain network designed in this paper contains two attributes of time– period attribute and sub-period attribute. The period refers to each cycle in a planning horizon, measured by weeks. The sub-period refers to each cycle in a period, measured by days.

In this paper, the subperiods of the transaction of material flows between nodes and the product batches from manufactures to distributors will be solved by the constructed model.

This paper aims to formulate a mixed integer programming optimization model to solve a multi-objective multiperiod supply chain integrated scheduling problem under demand uncertainty. We define the research question as follows:

1) Supply chain operation model

At the beginning of each period, the uncertain demand is generated by retailers. The orders are received by the selected suppliers, and the material flow of critical parts is transported to the manufacturers. The products are processed by the manufacturers, and then are shipped to the distribution centers in batches [18]. At the centers, one part of the products are held in stock, and the other part as a complete order are delivered to end retailers [19].

2) Order-processing model

At the manufacturers, product orders are not produced as a whole, but rather in a fragmented state, with no labels of end retailers attached [20]. The approach of a complete order delivery is adopted by distributors, and the product flows attach the label of end customers.

3) Manufacturer’s production model

In each sub-period, the manufacturers receive raw materials from different suppliers every day, whose quantity and transport time are different. Each manufacturer arranges production within its capacity, and different manufacturers have different capacity. Therefore, products are processed in batches [21]. And different quantities of finished products are shipped to different distributors each day.

4) Distribution model

The complete orders are rounded up in a period by the distributors, and then distributed to the corresponding

retailer. If the order can’t be rounded up, the products will become inventory within the period, and the cost will be incurred. These stock products will be participated in the distribution of the next period.

Additionally, each retailer is distributed by one distribution center, however, the distribution center can serve different retailers [22].

5) Push-pull junction point

In this paper, the distribution center is set as the push-pull junction point [23]. Pull strategy is adopted by the nodes of upstream, and push strategy is adopted by the downstream.

III. PROBLEM FORMULATION

A. NOTATIONS

1) SETS

TABLE 1. SETS.

$M(m \in M)$	Set of scenarios of demands
$I(i \in I)$	Set of potential suppliers
$T(t \in T)$	Set of periods
$O(o \in O)$	Set of potential manufactures
$J(j \in J)$	Set of potential distributors
$K(k \in K)$	Set of potential retailers

2) PARAMETERS

See Table 2.

3) DECISION VARIABLES

See Table 3.

B. ASSUMPTIONS

1) THE DEMAND OF ORDERS

At the beginning of each period, uncertain demand is generated in the supply chain system, and is independent in each period during the planning horizon [24].

2) TRANSPORTATION MODE, TRANSPORTATION TIME AND ROUTE SELECTION

The influence of transportation mode, transportation time and route selection is not considered in this paper [25].

3) CAPACITY LIMITS

According to a survey on a supply chain system of electronic products in China, there are limitations of supplier capacity, distributor capacity and retailer capacity. And the capacity of each transportation route is not considered.

4) THE INVENTORY

Based on the survey of a supply chain system of electronic products in China, we just consider the distributor inventory, and the inventory quantity is 0 at the beginning of each planning horizon.

TABLE 2. Parameters.

t_0	Start time of the planning horizon
t'_{io}	The subperiod time from supplier i to manufacture o in period t
$t'_{(oj)x}$	The subperiod time of batch x of products from manufacture o to distributor j in period t
t'_{jk}	The subperiod time of the order accumulated by distributor j for retailer k
τ_{jk}	The delivery time from distributor j to retailer k
a_{oj}	The total time of production and shipping from manufacturer o to distributor j
d_k	The latest delivery time of the order for retailer k
c_{pit}	The unit cost of supply for supplier i in period t
c_{iot}^{SD}	The unit cost of shipping from supplier i to manufacture o in period t
c_{ojt}^{SD}	The unit cost of shipping from manufacture o to distributor j in period t
c_{djt}	The unit cost of inventory holding cost at distributor j in period t
b_{mk}	Demand for products in retailer k in scenario m
c_{jkt}^{DR}	The unit cost of transportation from distributor j to retailer k in period t scenario m
g_k	The unit cost of delay penalty for retailer k
h_k	The unit cost of shortage penalty for retailer k
γ	The preference coefficient of supply chain cost and service
Q_{imax}	The maximum capacity of supplier i
a_{io}	The transportation time from supplier i to manufacturer o
$C_{p_o t}$	The maximum capacity of manufacturer o in period t
$I_{jt,max}$	The maximum inventory capacity of distributor j
f_i	The flexibility of supplier i

5) THE SUPPLY CHAIN SERVICE LEVEL

According to a survey on a supply chain system of electronic products in China, in this paper, the supply chain service level is divided into three levels, the descending order and the corresponding mathematical model are as follows:

a: ON TIME DELIVERY

The products will be produced by the manufacturers as soon as the materials are arriving. And then the finished products are shipped to the distribution centers. When the number of products is accumulated to the quantity of the whole order of a retailer, they will be delivered to relevant customers on time.

The service level when the delivery is on time is

$$b_{mk} \sum_{t'_{jk}=0}^{t'_{jk}=d_k-\tau_{jk}} w_{jkt'_{jk}}^{mt}, t'_{jk} \in t$$

TABLE 3. Decision variables.

X_{mit}	Binary variable, 1 if supplier i is selected in period t in scenario m ; 0 otherwise
$Q_{miott'_{io}}^{SD}$	Flow of products from supplier i to manufacturer o in subperiod t'_{io} of period t in scenario m
$Q_{mojtt'_{(oj)x}}^{SD}$	Flow of products of batch x from manufacturer o to distributor j in subperiod $t'_{(oj)x}$ of period t in scenario m
I_{mjt}	Flow of inventory allocated to distributor j in period t in scenario m
$I'_{mj(t-1)}$	Flow of accumulated inventory of distributor j in period $t - 1$ in scenario m
$w_{jkt'_{jk}}^{mt}$	Binary variable, 1 if the order of products of retailer k is completed by distributor j in subperiod t'_{jk} ; 0 otherwise
$Q_{mitt'_i}^{SD}$	The total quantity of material flow provided by supplier i in subperiod t'_i in period t in scenario m
$Q_{mott'_{io}}^{SD}$	The total quantity of material flow received by manufacturer o in subperiod t'_{io} of period t in scenario m
Q_{mot}^{SD}	The total quantity of material flow received by manufacturer o in period t in scenario m
C_1	The total start-up cost of suppliers
C_2	The total raw material cost of suppliers
x	Total number of product batches from manufacturer o to distributor j in period t in scenario m
C_3	The total shipping cost from suppliers to manufacturers
C_4	The total shipping cost from manufacturers to distributors
C_5	The total inventory cost of distributors
C_6	The total shipping cost from distributors to retailers
C_7	The total penal cost of delay
P'	Expected cost of supply chain
S'	Expected service level of supply chain
C_8	The total penal cost of shortage
F	Objective function value

b: DELAYED DELIVERY

If the delivery time from distribution centers to end retailers exceeds the deadline, there will be delayed penalty cost.

The service level when delays occurred is

$$b_{mk} (\sum_{t'_{jk}=0}^{t'_{jk}=t} w_{jkt'_{jk}}^{mt} - \sum_{t'_{jk}=0}^{t'_{jk}=d_k-\tau_{jk}} w_{jkt'_{jk}}^{mt}), t'_{jk} \in t$$

c: NON-DELIVERY

If the products of an order aren't produced by the manufacturers, there will be penalty cost of shortage.

The service level when an order is out of stock is

$$b_{mk}(1 - \sum_{t_{jk}'=0}^{t_{jk}'=t} w_{jkt_{jk}'}^{mt}), t_{jk}' \in t$$

C. MIXED-INTEGER PROGRAMMING MODEL

1) OBJECTIVE FUNCTION

This paper proposes a multi-objective multi-period mixed-integer programming model. Two conflicting factors are considered – the supply chain cost and service level. The objective function in the proposed model is to maximize the service level of multi-period supply chain under demand uncertainty and minimize the expected cost.

The supply chain cost includes start-up cost and raw material cost of suppliers, transportation cost, inventory cost of distributors, penal cost of delay and penal cost of shortage of retailers. For $\forall m, i, j, o, k, t; t'_{io} \in t$, the relevant cost formulas are as follows:

The start-up cost of suppliers is

$$C_1 = \sum_{m=1}^{m=M} P_m \sum_{t=t_0}^{t=T} \sum_{i=1}^{i=I'} c_{it} X_{mit} \tag{1}$$

The raw material cost of suppliers is

$$C_2 = \sum_{m=1}^{m=M} P_m \sum_{t=t_0}^{t=T} \sum_{o=1}^{o=O} c_{pit} Q_{miott'_{io}}^{SD} \tag{2}$$

The total transportation cost from suppliers to manufacturers is

$$C_3 = \sum_{m=1}^{m=M} P_m \sum_{t=t_0}^{t=T} \sum_{o=1}^{o=O} \sum_{i=1}^{i=I'} c_{iot} Q_{miott'_{io}}^{SD} \tag{3}$$

The total transportation cost from suppliers to manufacturers is

$$C_4 = \sum_{m=1}^{m=M} P_m \times \sum_{t=t_0}^{t=T} \sum_{j=1}^{j=J} \sum_{o=1}^{o=O} \sum_{t'_{(oj)_x}=0}^{t'_{(oj)_x}=t} c_{ojt} Q_{mojtt'_{(oj)_x}}^{SD} \tag{4}$$

The total inventory cost of distributors is

$$C_5 = \sum_{m=1}^{m=M} P_m \sum_{t=t_0}^{t=T} \sum_{j=1}^{j=J} c_{djt} (I'_{mj(t-1)} + \sum_{o=1}^{o=O} \sum_{t'_{(oj)_x}=0}^{t'_{(oj)_x}=t} Q_{mojtt'_{(oj)_x}}^{SD} - \sum_{k=1}^{k=K} b_{mk} \sum_{t_{jk}'=0}^{t_{jk}'=d_k - \tau_{jk}} w_{jkt_{jk}'}^{mt}) \tag{5}$$

The total transportation cost from distributors to retailers is

$$C_6 = \sum_{m=1}^{m=M} P_m \sum_{t=t_0}^{t=T} \sum_{k=1}^{k=K} \sum_{j=1}^{j=J} c_{jkt}^{DR} b_{mk} \times \sum_{t_{jk}'=0}^{t_{jk}'=d_k - \tau_{jk}} w_{jkt_{jk}'}^{mt} \tag{6}$$

The penal cost of delay of retailers is

$$C_7 = \sum_{m=1}^{m=M} P_m \sum_{t=t_0}^{t=T} \sum_{k=1}^{k=K} [g_k b_{mk} \times (\sum_{t_{jk}'=0}^{t_{jk}'=t} w_{jkt_{jk}'}^{mt} - \sum_{t_{jk}'=0}^{t_{jk}'=d_k - \tau_{jk}} w_{jkt_{jk}'}^{mt})] \tag{7}$$

The penal cost of shortage of retailers is

$$C_8 = \sum_{m=1}^{m=M} P_m \sum_{t=t_0}^{t=T} \sum_{k=1}^{k=K} [h_k b_{mk} \times (1 - \sum_{t_{jk}'=0}^{t_{jk}'=t} w_{jkt_{jk}'}^{mt})] \tag{8}$$

In Eq. (9), the expected cost of supply chain is calculated by the value that total cost in each period in each demand scenario divides by total demand of retailers.

$$P' = \left(\sum_{n=1}^{n=8} C_n \right) / \left(\sum_{m=1}^{m=M} P_m \sum_{t=t_0}^{t=T} \sum_{k=1}^{k=K} b_{mk} \right) \tag{9}$$

In Eq. (10), the expected service level is calculated by the value that undelaying flow of products divides by the total demand of retailers.

$$S' = \left(\sum_{m=1}^{m=M} P_m \sum_{t=t_0}^{t=T} \sum_{k=1}^{k=K} \sum_{t_{jk}'=0}^{t_{jk}'=d_k - \tau_{jk}} b_{mk} w_{jkt_{jk}'}^{mt} \right) / \left(\sum_{m=1}^{m=M} P_m \sum_{t=t_0}^{t=T} \sum_{k=1}^{k=K} b_{mk} \right) \tag{10}$$

In Eq. (11) and (12), the value of expected cost P' and the value of expected service level S' are normalized. P-bar and P-underline represent the maximum value and minimum value of P' individually, and S-bar and S-underline represent the maximum value and minimum value of S' individually.

$$f_1 = (P' - P\text{-underline}) / (P\text{-bar} - P\text{-underline}) \tag{11}$$

$$f_2 = (S\text{-bar} - S') / (S\text{-bar} - S\text{-underline}) \tag{12}$$

The objective function in the proposed model is as follows:

$$F = \min\{\gamma f_1 + (1 - \gamma) f_2\} \tag{13}$$

2) CONSTRAINTS

a: THE CONSTRAINT OF SUPPLIER'S CAPABILITY

The constraint of supplier's capability is measured by flexibility coefficient: the amount of raw materials for orders assigned can't exceed the supplier's capacity. As is shown in Equation (14).

$$(1 + f_i) \sum_{o=1}^{o=O} Q_{miott'_{io}}^{SD} \leq Q_{imax} \tag{14}$$

b: THE CONSTRAINT OF SUPPLIER SELECTION

Constraint (15) requires that Xmit is a binary variable. If the material flow supplied by the supplier i takes a positive value, the supplier i is selected, which incurs start-up cost.

$$X_{mit} = \begin{cases} 1 & \text{if } \sum_{o=1}^{o=O} Q_{miott'_{io}}^{SD} > 0 \\ 0 & \text{if } \sum_{o=1}^{o=O} Q_{miott'_{io}}^{SD} = 0 \end{cases} \tag{15}$$

c: THE CONSTRAINT OF FLOW BALANCE AND CONSTRAINT OF SUB-PERIOD TIME FOR SUPPLIERS

Constraint (16) is a balance equation for raw materials flow at supplier i, and ensures that the total shipments that supplier i delivers to manufacturers in sub-period t' is equal to the total

material flow that the corresponding manufacturers receive from supplier i in sub-period t_{io}' .

$$Q_{mit'_i}^{SD} = \sum_{o=1}^{o=O} Q_{miot'_i}^{SD} = \sum_{o=1}^{o=O} \sum_{t'_{io}=0}^{t'_{io}=t} Q_{miot'_i}^{SD} \quad (16)$$

Constraint (17) ensures that supplier i can only deliver once in period t .

$$Q_{mit}^{SD} = Q_{mit'_i}^{SD} \quad (17)$$

Constraint (18) is a balance equation for sub-period time. It ensures that the sub-period time of critical parts shipped to manufacturer o from supplier i is equal to the value that the departure time of the material flow from supplier i plus the transportation time from supplier i to manufacturer o .

$$t'_{io} = t'_i + a_{io}, t'_i, t'_{io} \in t \quad (18)$$

d: THE CONSTRAINT OF PRODUCTION FLOW BALANCE IN SUB-PERIOD AND CONSTRAINT OF CAPACITY FOR MANUFACTURERS

Constraint (19) guarantees that the total material flow from suppliers to manufacturer o in sub-period t_{io}' is equal to the total shipments that the retailers receive from manufacturer o .

$$Q_{i=1}^{i=I'} Q_{miot'_i}^{SD} = Q_{mott'_o}^{SD} = \sum_{j=1}^{j=J} C_{jkt}^{DR} b_{mk} \quad (19)$$

Constraint (20) restricts the production capacity of each manufacturer.

$$Q_{mott'_o}^{SD} \leq C_p \quad (20)$$

e: THE CONSTRAINT OF PRODUCTION FLOW BALANCE IN SUB-PERIOD AND CONSTRAINT OF CAPACITY FOR MANUFACTURERS

Constraint (21) is a balance equation for raw material flow at manufacturer o in period t .

$$t'_{io} + a_{oj} = t'_{(oj)_x}, t'_{io}, a_{oj}, t'_{(oj)_x} \in t \quad (21)$$

f: THE CONSTRAINT OF ORDER ARRANGEMENT FOR DISTRIBUTORS

Constraint (22) denotes the order arrangement constraint at distributor j in period t .

$$\sum_{t'_{jk}=0}^{t'_{jk}=t} w_{jkt'_{jk}}^{mt} \leq 1 \quad (22)$$

g: FLOW BALANCE CONSTRAINT AT DISTRIBUTORS AND TURNAROUND TIME CONSTRAINT

Constraint (23) is a balance equation for products flow at distributor j in period t .

$$I'_{mjt} = I'_{mjt(t-1)} + \sum_{o=1}^{o=O} \sum_{t'_{(oj)_x}=0}^{t'_{(oj)_x}=t} Q_{mojt'_{(oj)_x}}^{SD} - \sum_{k=1}^{k=K} b_{mk} \sum_{t'_{jk}=0}^{t'_{jk}=d_k - \tau_{jk}} w_{jkt'_{jk}}^{mt} \quad (23)$$

Constraint (24) is a balance equation for turnaround time at distributor j in period t .

$$t'_{jk} + \tau_{jk} = t'_k \quad (24)$$

h: THE CONSTRAINT OF INVENTORY CAPACITY FOR DISTRIBUTORS

Constraint (25) restricts the inventory capacity of distributor j in period t .

$$I'_{mjt} \leq I_{j,max}, \forall m, j, t \quad (25)$$

i: NONNEGATIVE CONSTRAINT AND INTEGER CONSTRAINT

Constraints (26)-(27) require that X_{mit} and $w_{jkt'_{jk}}^{mt}$ are binary variables. Constraints (28)-(31) restrict some variables from taking negative values.

$$X_{mit} \in \{0, 1\}, \forall m, i, t \quad (26)$$

$$w_{jkt'_{jk}}^{mt} \in \{0, 1\}, \forall m, k, t, t'_{jk} \quad (27)$$

$$Q_{miot'_i}^{SD} \geq 0, t'_i \in t, \forall m, i, o, t \quad (28)$$

$$Q_{mojt'_{(oj)_x}}^{SD} \geq 0, t'_{(oj)_x} \in t, \forall m, o, j, t \quad (29)$$

$$I_{mjt} \geq 0, \forall m, j, t \quad (30)$$

$$I'_{mjt} \geq 0, \forall m, j, t \quad (31)$$

j: THE CONSTRAINT OF INVENTORY CYCLE FOR DISTRIBUTION CENTER

This paper assumes a period $t = 0$, which denotes that the value of accumulated inventory in period $t = 1$ is 0. At the end of planning horizon, the value of inventory of distribution center j is 0. Constraint (32) restricts the inventory cycle at distribution center j .

$$I'_{mj(t_0-1)} = 0, I'_{mjT} = 0 \quad (32)$$

IV. SOLUTION APPROACH

Genetic algorithm (GA) is adopted to solve the problem in this paper [27]. In order to enhance the local exploratory ability of the algorithm, this paper presents an Improved Mixed Genetic Algorithm (IMGGA): the mixed coding method of integer and decimal is applied in this algorithm. And a Local Search Gridding Arithmetic (LSGA) is adopted to expand the search scope of the optimal solution, and avoid being trapped in a local optimal solution.

A. ENCODING

In this paper, the parameters of the integrated scheduling scheme are mapped to a series of real numbers, which are operated on directly when genetic manipulation is performed [28]. Finally, the real number string is decoded into the parameters of flow distribution scheme.

The encoding is as follows: a supply chain integrated scheduling scheme is encoded as a chromosome made up of a string of y genes, and y represents the number of all parameters contained in the supply chain integrated scheduling scheme within T periods.

In each period, the encoding consists of three parts: the first part is integer coding, represented the material flow of each link, the subperiod time and inventory flow; the second is decimal encoding, represented the link weight; the third is integer coding, represented the distribution scheme from distributors to retailers.

B. THE INITIAL POPULATION

According to the prior knowledge of a supply chain integrated scheduling scheme, the distribution range of the optimal solution is determined, and the initial population is generated in this range. Generated a certain number of individuals randomly, the initial population is generated [29]. N is the population size, j is the length of the chromosome, and the initial population is an $N \times j$ binary matrix.

C. THE EVALUATION FUNCTION

The objective function is defined as the evaluation function. The higher the value of individual fitness function is, the higher the survival rate is. The method that the survival rate of individuals is proportional to the value of the fitness function is chosen by the selection strategy of genetic algorithm in this paper [30].

D. THE GENETIC OPERATORS

1) THE SELECTED OPERATORS

The method of stochastic universal selection based on the value of individual fitness is adopted in this paper. We adopt the approach of rank-based fitness assignment based on linear ordering to calculate the fitness value. The higher the fitness value is, the higher the probability of being selected is. The probability of the selected operator is 10% [31].

2) THE CROSSOVER OPERATOR

The method of single-point crossover is adopted for the crossover operator [32]. A crossover point k of genomic string is set randomly according to the crossover probability. The range of the value of crossover point k is $[1, N - 1]$. k is as the boundary, the anterior and posterior part of which swaps between two individuals. And new chromosomes are formed. The odd row and the next even row are selected to swap. If the number of rows of the parent matrix is odd, then the last line is not selected to swap.

3) THE MUTATION OPERATORS

The algorithm steps of mutation operator are as follows:

Step1: Calculate the supply chain integrated scheduling scheme of paternal chromosomes. Assumed that the scheduling scheme is $x = (x_1, x_2, \dots, x_q)$, for $k = 1$, the daughter chromosome is equal to the father chromosome.

Step2: With a mutation rate p_m , each gene is mutated. If the value of gene is greater than p_m , then the value of the situ gene code remains unchanged. Otherwise, the mutation is operated, and output the scheduling scheme of offspring.

4) THE LOCAL SEARCH OPERATORS

β is the number of chromosomes produced by local search. We let $\beta = N \times 10\%$. The algorithm is designed as follows:

Step1: Let $k = 1$, $N_e = \emptyset$, \emptyset represents the empty sets.

Step2: If $k \leq \beta$, then turn to step 3, otherwise, turn to step5.

Step3: Select a demand scenario randomly, and coded as $m_e \in \{1, 2, \dots, m\}$. Change the value of gene coding of link flow under the demand scenario m_e randomly, and a new scheme N_k is got.

Step4: Insert N_k into N_e , let $k = k + 1$, turn to step2.

Step5: Choose the best chromosome from N_e , and that's the chromosome x' according to the local search.

5) THE PROCESS OF ALGORITHM

Therefore, the process of IHGA is as follows:

Step1: Initialization. Let $t = 0$, the initial population $P(0)$ is produced. Calculate all the fitness values in the population.

Step2: Selection. According to the algorithm of selection operator, a group of offspring $P(t)$ is selected from $P(0)$ with a selection probability p_f .

Step3: The crossover operators. According to the algorithm of crossover operator, the method of single-point crossover is adopted and a set of offspring $P'(t)$ is obtained from $P(t)$.

Step4: The mutation operators. According to the mutation operator algorithm, a set of offspring $P''(t)$ is obtained from $P'(t)$.

Step5: The fitness value. Calculate all the fitness values in the population $P''(t)$.

Step6: The local search operators. According to the algorithm of local search operator, a group of offspring $P'''(t)$ is selected from $P''(t)$, with a selection probability p_h .

According to the algorithm of selection operator, a group of offspring $P(t)$ which consists of N chromosomes is selected from $P'''(t)$. The elite retention strategy is adopted for the union of $P'''(t)$ and $P(t)$, and the next generation $P(t + 1)$ is obtained.

Step7: If the number of iterations reaches the threshold, the program terminates, otherwise, let $t = t + 1$, and turn to step2.

The process of algorithm is shown in Fig. 2.

V. NUMERICAL RESULTS AND DISCUSSION

A. CASE DESCRIPTION

In this section, we take a domestic electronic product supply chain network as an application example. And the proposed model and algorithm are adopted to solve a realistic problem of multi-objective multi-period supply chain integrated scheduling under demand uncertainty. The supply chain topology network with all possible center locations and transportation channels is shown in Fig.3. It consists of nine suppliers, four manufacturers, three regional distributors and twelve end retailers.

Based on historical sales data, three demand scenarios are considered in this paper: $m = 1$ represents daily demand scenario, $m = 2$ represents the demand scenario of peak season,

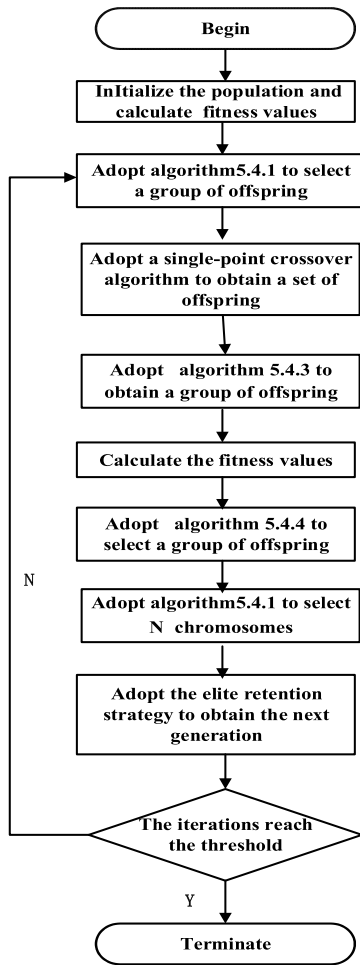


FIGURE 2. Flow chart of an improved hybrid genetic algorithm.

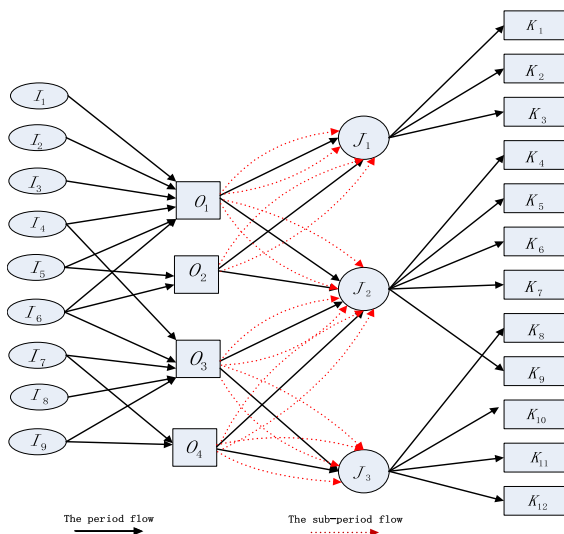


FIGURE 3. Supply chain network topology diagram of electronic products with two attributes of time.

and $m=3$ represents the off-season. The planning horizon is one month, and per period is one week. Table 4 shows the results of supply chain terminal demand for four periods and three scenarios.

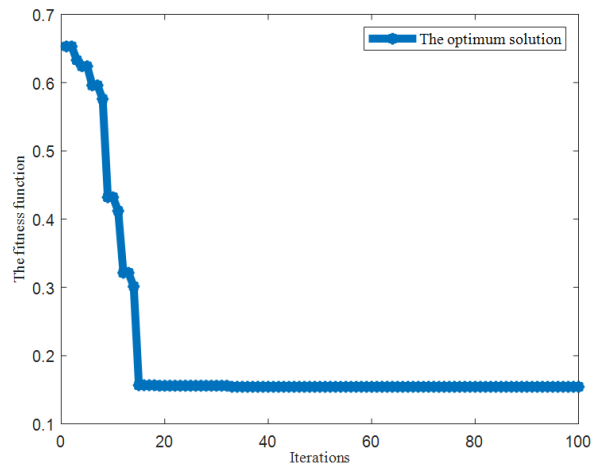


FIGURE 4. The convergence process curve of IHGA ($\gamma = 0.5$).

Table 5 presents the data of the start-up cost and maximum capacity for suppliers, unit cost of raw materials, and the flexibility coefficient. The data of the maximum production capacity of manufacturers, the unit cost of inventory and maximum inventory capacity of distributors is shown in Table 6. In Table 7, the sub-period time of transport time between nodes is presented. Table 8 presents the latest delivery time and the unit cost of penalty for retailers.

B. RESULTS AND DISCUSSION

In this paper, an IHGA is adopted to solve the problem. The parameters are set as follows: the initial population size is $N = 100$, crossover rate $p_c = 0.1$, mutation rate $p_m = 0.1$, the local search rate $p_h = 0.5$, the selection rate $p_f = 0.1$. The computing time of the algorithm program is 120s. Therefore, the optimal solution can be obtained in a short time and the performance of the algorithm is good. For $\gamma = 0.5$, the iterative convergence process of the algorithm is shown in Fig. 4.

Fig. 4 shows that the value of the objective function is convergent and tends to be stable within 100 iterations in the process of optimization. Therefore, the algorithm proposed in this paper has good convergence, and can provide a satisfactory solution for the model. Fig. 3.4 shows the integrated scheduling scheme of the supply chain in the scenario $P_m = 0.5$ in the first period, when $\gamma = 0.5$.

Fig. 5 shows that all suppliers are started in the first period. After manufactured, products are shipped to different distributors in batches. The manufacturer O_1 supplies to distributor J_1 twice; manufacturer O_2 supplies to distributor J_2 for 3 times; manufacturer O_3 supplies to distributor J_3 for 3 times in the subperiod of the third day, the fourth day and the fifth day separately; distributor J_3 also receives products from manufacturer O_4 for 2 times separately in the subperiod of the third day and the fifth day; the stock holding values of J_1 , J_2 and J_3 are respectively 699,600 and 160. The requirements of 12 supply chain terminal retailers are all met, with no shortages or delays occurred.

TABLE 4. Forecast data of supply chain terminal demand.

b_{mtk}	m=1 ($P_m = 0.5$)				m=2 ($P_m = 0.2$)				m=3 ($P_m = 0.3$)			
	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4
K_1	400	450	460	440	600	650	620	640	200	250	200	200
K_2	600	610	580	590	850	860	830	850	300	320	350	340
K_3	700	750	730	760	1000	950	980	900	400	420	450	400
K_4	1000	900	950	980	1600	1500	1600	1400	500	550	530	540
K_5	500	550	570	540	1000	1100	950	980	200	220	230	250
K_6	650	640	600	620	1100	1000	1100	950	400	400	420	410
K_7	800	790	750	810	1400	1500	1400	1300	550	530	540	550
K_8	870	900	880	860	1200	1100	1200	1000	600	600	580	620
K_9	1300	1200	1110	1400	1500	1400	1500	1450	850	830	820	810
K_{10}	1100	1200	1100	1000	1500	1400	1500	1500	780	750	720	760
K_{11}	1000	1000	970	950	1400	1500	1300	1300	700	720	730	750
K_{12}	700	750	760	730	1200	1300	1200	1250	550	600	620	640

TABLE 5. The cost and capacity data of suppliers.

	t	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9
c_{it}	1	4800	5900	6200	5300	5000	4600	6700	4000	4400
	2	4900	5800	6100	5200	5100	4700	6600	3900	4500
	3	4800	5900	6000	5300	5100	4800	6500	4200	4400
	4	4900	5900	6100	5400	5000	4700	6600	3800	4300
c_{pit}	1	21	25	28	24	23	19	30	15	17
	2	20	26	28	25	22	19	28	15	16
	3	21	25	27	23	23	18	29	14	16
	4	21	25	27	24	22	18	30	13	17
Q_{itmax}	1	850	1300	1500	1100	900	800	1600	650	720
	2	870	1200	1400	1100	920	810	1500	660	720
	3	860	1300	1400	1100	950	800	1600	670	740
	4	860	1300	1400	1000	900	800	1500	680	720
f_{li}		0.6	0.40	0.30	0.45	0.55	0.63	0.20	0.7	0.65

TABLE 6. The cost and capacity data for manufacturers and distributors.

	t	O_1	O_2	O_3	O_4	J_1	J_2	J_3
C_{pot}	1	5000	2500	5500	2000			
	2	1534	1420	3500	2000			
	3	2000	1420	3500	2500			
	4	3000	1200	5500	2000			
c_{ajt}	1					5	12	7
	2					6	11	8
	3					4	12	7
	4					5	13	6
$I_{jt,max}$	1					700	1200	500
	2					650	900	850
	3					660	1200	900
	4					680	1250	800

C. SENSITIVITY ANALYSES

1) SENSITIVITY ANALYSES WITH RESPECT TO DIFFEREN γ
 To capture the sensitivity of the optimal strategy to the variations of γ , we let γ vary from 0.1 to 10 with an increment

0.1 in the following set of experiments. In the process of the variation of γ , the corresponding expected service level S' and expected cost P' under different demand scenarios are illustrated respectively in Fig. 6 and Fig. 7.

TABLE 7. The sub-period time of transport time between nodes.

	O_1	O_2	O_3	O_4	J_1	J_2	J_3	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9	K_{10}	K_{11}	K_{12}	
I_1	1	3	2	2																
I_2	2	2	2	1																
I_3	2	1	2	3																
I_5	2	1	3	1																
I_6	3	2	2	2																
I_7	2	1	1	1																
I_8	2	3	2	1																
I_9	1	3	3	2																
O_1					1	1	2													
O_2					2	2	1													
O_3					2	1	1													
O_4					1	2	1													
J_1								2	4	2	4	4	2	3	5	2	3	3	3	3
J_2								3	3	3	2	3	2	5	3	2	5	2	2	2
J_3								3	5	2	3	3	3	2	2	2	4	2	2	2
J_4								2	3	2	2	2	2	4	5	2	2	3	2	2

TABLE 8. The latest delivery time and the penalty cost per unit for retailers.

	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9	K_{10}	K_{11}	K_{12}
d_k	6	8	6	7	7	6	7	9	6	7	6	6
g_k	2.4	1.7	2.2	2.1	1.7	2.4	2.1	1.7	1.8	1.7	2.4	1.9
h_k	5.1	3.8	4.0	4.6	3.9	4.8	4.0	4.9	4.2	3.8	3.6	3.8

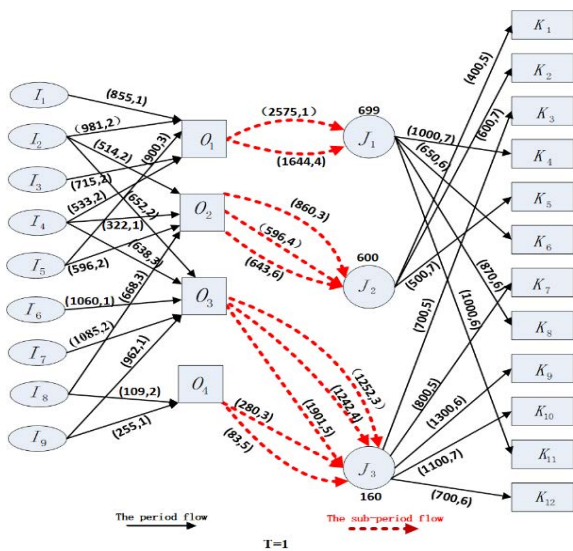


FIGURE 5. Multi-objective multi-period integrated scheduling diagram of uncertain supply chain ($\gamma = 0.5, P_m = 0.5$).

As shown in Fig.6, when $\gamma = 0$, the service preference is only considered by decision makers, and the value of expected service level S' is high in all scenarios. When $\gamma = 1$, and the cost preference is only considered, and the value of

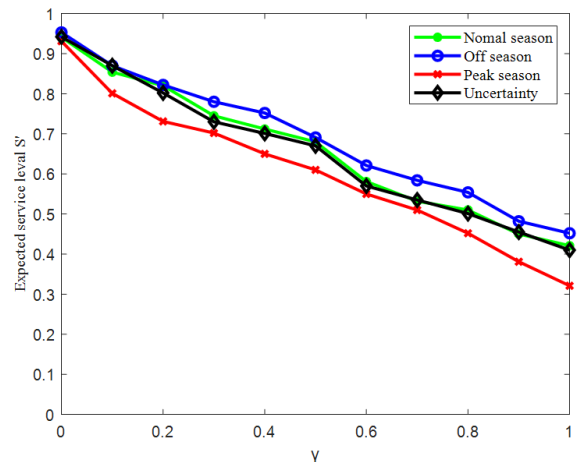


FIGURE 6. The variations of relevant expected service level S' with respect to parameter γ .

expected service level S' reaches the minimum in all scenarios. In Fig. 6, the expected service level S' in the off-season is the highest for the same value γ in different demand scenarios. When γ changes from 0 to 1, there is few differences of the expected service level between the uncertain demand scenario and the normal scenario, and both curves show a downward trend in a winding fashion. Above results show

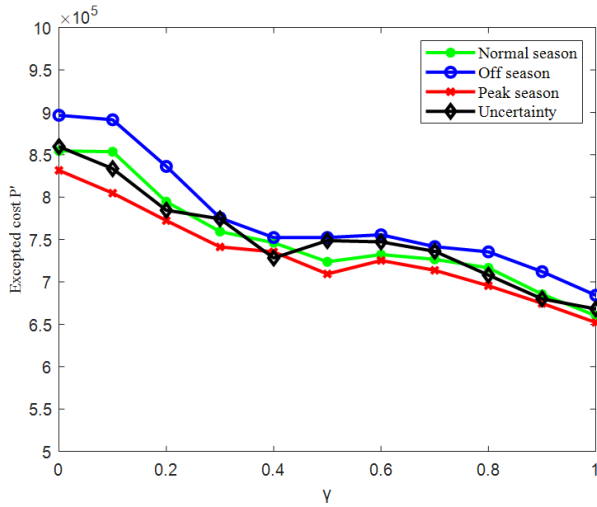


FIGURE 7. The variations of relevant expected cost P' with respect to parameter γ .

that, the supply chain system can fulfill the requirements well regardless of the off-season or the peak season, and it has excellent operational capability.

Fig. 6 also shows that when the value of γ increases, the expected service level in the uncertain demand scenario tends to decrease, and the expected service level in peak season scenario tends to decrease markedly. These results show that it is necessary to expand supply chain capacity for peak season demand.

As is shown in Fig.7, when $\gamma = 0$, the value of expected cost level P' reached the maximum. When $\gamma = 1$, the value of expected cost level P' reached the minimum in all scenarios. When the value of γ increases, and the decision of integrated scheduling focuses on the cost preference, the expected cost tends to decrease. It shows that when the value of service preference is increased, the expected cost will be reduced in any demand scenario.

When $\gamma \leq 0.2$, the expected cost P' for the same value γ in different demand scenarios is compared. It shows that the ordinate values of the curves vary greatly in each different demand scenario. This is because when the optimization objective focuses on the service preference, the emphasis on the cost optimization decreases synchronously. When $\gamma \geq 0.8$, the difference between the ordinate values of the curves of different demand scenarios becomes smaller. This is because when the optimization objective focuses on the cost preference, the emphasis on cost optimization increases.

When $\gamma \in [0.2, 0.8]$, compared the expected cost P' for the same value γ in different demand scenarios, the curves under different scenarios show a winding fashion. When $\gamma = 0.5$, compared the expected costs between the off-season scenario and the peak season scenario, the cost in the peak season is low. It is related to supply chain performance, penalty cost of out of stock and penalty cost of delay.

In view of the point above, we provide cost distribution diagram under various demand scenarios in Fig. 8.

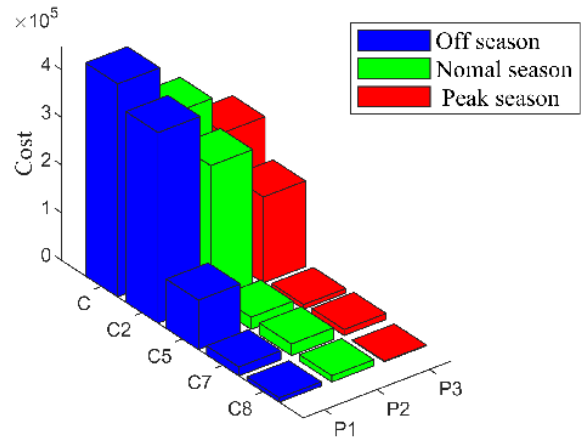


FIGURE 8. The Cost distribution diagram of multi-period multi-objective supply chain under uncertain demand ($\gamma \geq 0.5$).

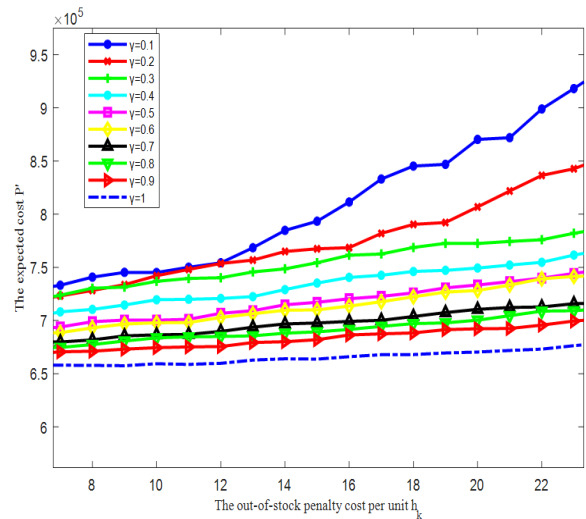


FIGURE 9. The variations of relevant expected cost P' with respect to parameter h_k .

Fig. 8 shows that little penalty cost and little delay cost is beard by the end retailers under the peak season scenario. So there's few differences between peak the cost of season scenario and that of off-season scenario. It shows that the supply chain network is resilient enough to meet the demand of peak season. Compared to the off-season, the inventory cost in peak season is small. And this is the reason that the inventory cost in peak season scenario is lower than that in the off-reason, which shows in Fig. 7.

2) SENSITIVITY ANALYSES WITH RESPECT TO DIFFERENT h_k
To capture the sensitivity of the optimal strategy to the variations of parameter h_k , we let h_k vary from 5 to 25 with an increment 1. In the variation process of h_k , the corresponding expected service level S' and expected cost P' under different demand scenarios are illustrated respectively in Fig.9 and Fig. 10.

Fig. 9 shows that the expected cost increases as the penalty cost of stockout increases. The larger the value of γ is, the

more slowly the curve escalates, and the smaller the value of expected cost which has the same out-of-stock penalty cost is. It shows that when the unit cost of out-of-stock penalty increases, the changes of unit cost have less effect on the expected cost with the increase of the value of γ . Therefore, increasing the value of γ can smooth out the effect of the unit cost of out-of-stock penalty on the expected cost.

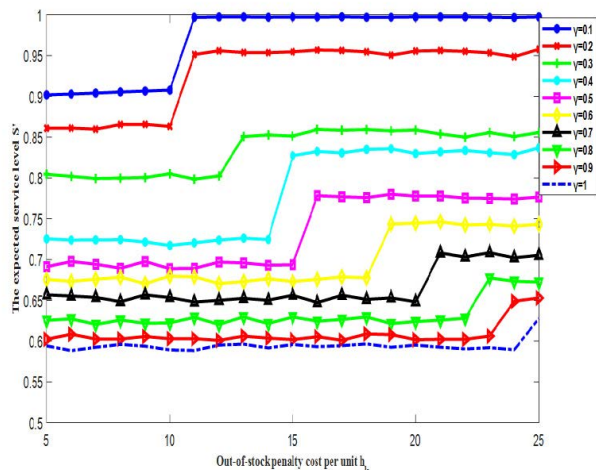


FIGURE 10. The variations of relevant expected service level S' with respect to parameter h_k .

Fig. 10 shows that the value of expected service level increases with leaps and bounds when the value of h_k increases. The value of expected service level increases, with the slope gradually decreasing. Then the value increases dramatically, and at last the slope decreases again. Finally, the value of the expected service level remains constant.

As is shown in Fig.10, curves with larger values of γ are located in the lower half of the coordinate plane. It shows that the larger the value of γ is, the smaller the value of expected service level which has the same out-of-stock penalty cost is. The larger the value of γ is, the more flat the curves which have increased drastically are, and make the abrupt points of the values of unit penalty cost of stockout move to the right. So the increase of the value of γ can smooth out the effect of unit penalty cost of stockout on the expected service level.

VI. CONCLUSION AND FUTURE RESEARCH

This paper investigated a novel optimization problem in supply chain integrated scheduling. We considered the demand uncertainty, multi-objective optimization, and the continuous planning of multiple periods in a planning horizon. A mixed integer programming model for multi-objective multi-period supply chain integrated scheduling optimization under demand uncertainty was constructed, with minimizing supply chain cost and maximizing service level as the optimization objectives.

This study focused on optimizing the supply chain integrated scheduling strategy, and generated the supply plans

for suppliers, the production and distribution plans of each sub-period for manufacturers, and the distribution and inventory plans of each sub-period for distributors in each period and each demand scenario. Then an IMGA was designed in order to find an exact-optimal/near-optimal solution. The practicability of the proposed model and algorithm was demonstrated through its application in solving an integrated scheduling problem of an electronic supply chain network.

At the end, sensitivity analysis was done for the preference coefficient γ and for out-of-stock penalty cost parameter h_k . The results indicate that:

- 1) When γ changes from 0 to 1, there is few differences of the expected service level between the uncertain demand scenario and the normal scenario. This means that the supply chain system is resilient, and can fulfill the requirements well both in the off-season scenario and in the peak season scenario.
- 2) When $\gamma = 0.5$, compared the expected cost of the off-season with that of the peak season, the cost in the peak season is low. The reason is that little penalty cost and delay cost is beard by the end retailers under the peak season scenario, meanwhile, the inventory cost is lower than that of the off-reason.
- 3) The changes of unit shortage cost have less effect on expected cost with the increase of the value of γ . Therefore, the increase of the value of γ can smooth out the effect of unit out-of-stock cost on the expected cost.
- 4) The abrupt points of the values of out-of-stock penalty cost move to the right with the increase of the value of γ . It indicates that the increase of the value of γ can smooth out the effect of unit out-of-stock cost on the expected service level. Therefore, the parameter value of the unit out-of-stock penalty cost is appropriate to be set in the range of abrupt points to improve the service level of supply chain.

The model and algorithm constructed in this paper can provide the decision support for supply chain integrated scheduling based on the multi-objective multi-period optimization under demand uncertainty. Meanwhile, as the current model is not fully applicable to all the operation scenarios, there are many related issues that should be further investigated.

- 1) The proposed model in this paper is only applied on the uncertain demand scenario. In actual operation scenarios, supply chain faces many uncertainty scenarios, for example, the cost uncertainty, the uncertainty of the node capability, etc. The problem of supply chain integrated scheduling optimization under these uncertainty scenarios needs to be further studied.
- 2) In this paper, we just take the supply chain cost and service level as the optimization objectives. The supply chain benefit, efficiency and other factors can be considered as the optimization category to improve the practicality of the model in the further study.

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