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Multi-period Supply Chain Network Design Considering Carbon Emissions, Transportation Methods and Quantity Discounts

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Abstract

Nowadays, competition is constantly intensifying, which is also reflected in the supply chain. For example, in order to be qualified, suppliers will offer discounts to attract customers. Quantity discounting is a real problem in the real world, but the relevant research literature is few, so we propose a mixed integer programming model for quantity discounting problem. This model is based on strategic planning and tactics. It offers a whole-unit quantity discount to suppliers, taking into account the mode of transport and the carbon emissions associated with the production and transport. Emissions. In addition, the model also makes decisions about the opening and expansion of factory warehouses and the production and distribution of goods. The proposed model can be used for strategic and tactical planning when suppliers have supply constraints and quantity discounts. In order to illustrate the application of the model and test the performance of the model, we assume some numerical cases and solve them through CPLEX. The results show that in the case of small and medium scale, the CPLEX solver can obtain high quality solution with short solution time, but in the case of large scale, although the solution quality is high, the solution time is shorter and longer. We can consider designing some heuristic algorithms in the future to reduce the solving time.

Keywords

Supply Chain Network Design; Quantity Discount; Carbon Emission; Mixed Integer Programming Model.

1. Introduction

Supply chain network design is an important part of supply chain management. In recent years, global warming has caused people to pay more and more attention to environmental issues, and carbon emissions, as the main factor leading to climate warming, have aroused widespread concern in society. In recent years, global warming has made people pay more and more attention to environmental issues. As the main factor leading to climate warming, carbon emissions have attracted widespread attention from society.

At the same time, reducing carbon emissions and developing green supply chains have also become hot issues in the research of supply chain management. Therefore, it is of great practical significance to integrate carbon emission into supply chain network design. Lin et al [1] believed that the methods to solve the design problems of green closed-loop supply chain network mainly included optimizing transportation fuel consumption, reducing exhaust gas and carbon dioxide emissions, and strengthening the management of waste materials. Lamba et al. [2] proposed that carbon emission cost control should be one of the criteria for supplier selection, and established a mathematical model.

Quantity discount is an important issue with supply chain management. In real life, suppliers usually offer discounts to attract buyers to buy more products, which is particularly common in sales tactics.

Quantity discount provided by suppliers can not only improve their competitiveness, but also reduce the purchase cost of supply chain. Therefore, it is very important and practical to consider quantity discount in supply chain management. Kheirabadi and Naderi et al. [3] proposed a two-level supply chain network model considering both quantity discount and transportation mode. The linear combination method is adopted in the model to deal with the problem of quantity discount, which is very enlightening for us to deal with quantity discount. However, the paper does not take into account the planning cycle, commodity diversification and other issues.

Supply chain network design is also called supply chain network planning, which is the result of planning various decisions by decision makers.Now that social competition is intensifying, a good plan is very important to the development of the company, especially for those companies that pursue long-term stable development.A good plan should be a comprehensive consideration of multiple levels of decision-making, and then effective planning, rather than just consider a decision-making level.Bender, Hennes and Kalcsics [4] proposed that supply chain network planning can be divided into three levels according to different time ranges: strategic planning, tactical planning and operational planning.

Strategic planning is embodied in long-term planning and corresponds to strategic decision-making; tactical planning is embodied in short-term planning and corresponds to tactical decision-making; operational planning is embodied in daily operations and corresponds to operational decision-making.

In the previous literature, few articles combine strategic planning and tactical planning at the same time, and consider both strategic and tactical decisions. Bashiri, Badri and Talebi [5] considered both strategic planning and tactical planning, and proposed for the first time that the decision-making level should be consistent with the planning time range, and designed a mixed integer programming model for this purpose. In the model, the time of strategic planning and tactical planning are processed separately, and strategic planning and tactical planning are carried out under two time resolutions to ensure the consistency of decision-making level and planning time.

The decision level proposed by Bashiri, Badri and Talebi [5] should be unified with the planning time. This question is very realistic and very important for supply chain planning, because there are some parameters in supply chain planning such as product demand, sales Prices may change every month, and some parameters such as the location and number of facilities may not change for several years.

In the supply chain problem, most of the literatures consider single cycle, few of the literatures consider multi-cycle, and most of the literatures consider quantity discount, carbon emission and other issues respectively for planning and design, and few of the literatures consider multiple factors comprehensively. Rad and Nahavandi [6] proposed a multi-stage, multi-cycle, multi-product, multi-objective green closed-loop supply chain model considering quantity discount, carbon emission and transportation mode, but the paper did not take into account the consistency of decision level and planning time. Based on this, this paper proposes a single-objective mixed integer programming model that simultaneously considers supplier quantity discount, carbon emission and transportation mode choice, and the model simultaneously considers strategic planning and tactical planning, so that the decision level and planning time are unified.

The structure of this paper is as follows: the second section reviews the previous research literature; the third section introduces the background issues of the model; the fourth section describes the proposed model in detail; and the fifth section first uses hypothetical examples to illustrate the application of the model and test the performance of the model. The sixth section draws conclusions and future research directions.The sixth section draws conclusions and future research directions.

2. Literature review

There are many papers on supply chain management, and we have read some relevant literatures, which are mainly divided into two parts. The first part is the research on quantity discount related to supplier selection, and the second part is the research on supply chain network design in decision making and carbon emission.

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2.1 Quantity discount

Quantity discount is closely related to supply chain management in the real world. There are two kinds of quantity discount: progressive quantity discount and whole unit quantity discount.

Lee, Kang and Lai et al. [7] proposed a multi-supplier, multi-period mixed integer programming model considering quantity discount. The quantity discount in the model adopted full-unit quantity discount, and a genetic algorithm was proposed to solve the complex problems of the model.

Crama et al. [8] proposed a nonlinear mixed integer programming model that considered supplier quantity discounts and product substitution. The goal of the model was to minimize the cost, and various methods were proposed to linearize the model, but production capacity was not taken into account in the model.

Arunkumar, Karunamoorthy and Makeshwaraa [9] proposed a multi-objective model of multi-supplier selection with consideration of quantity discount for the quantity discount of suppliers. The defects in supply allocation were considered in the model, and the model was evaluated by simulated annealing algorithm.

In the case of uncertain demand, Ma and Zhang [10] proposed a mixed integer nonlinear programming model considering supplier volume discount, and the model also considered different outsourcing strategies of manufacturers.

Ebrahim, Razmi and Haleh [11] proposed a mathematical model, which not only considered the problem that different suppliers have different types of discounts, but also considered the capacity and demand of suppliers, and proposed a decentralized search algorithm to solve the complex problem of the model.

Ayhan and Kilic [12] adopted the method combining fuzzy analytic hierarchy process (AHP) and mixed integer linear programming to deal with the problem of quantity discount in multi-project and multi-supplier environment. The paper also considered the limitation of the number of suppliers and whether they could maintain long-term cooperative relationship.

Sobhanallahi, Mahmoodzadeh and Naderi [13] proposed a new fuzzy two-stage supply chain supplier selection and order allocation model, which in the second stage, the author of inventory, facility location, transportation route, vehicle scheduling and quantity discount, a multi-objective programming model is put forward, in the end, a case study demonstrates the effectiveness of the model.

Alfares and Turnadi [14] proposed a multi-cycle supplier selection model considering product shortage and quantity discount. The model considered the trade-off between inventory carrying cost and shortage backlog cost. In order to solve large-scale cases, two heuristic algorithms were designed to solve the problem, and the genetic algorithm was the best method to solve the problem.

2.2 Supply chain network design problems

Melo, Nickel and Gama [15] reviewed the literature on facility location in supply chain management and discussed it from the perspectives of strategy, tactics and operations. These literature can help us to deepen our understanding of strategic and tactical decisions.

Thanh, Bostel and Peton [16] this paper proposes a new dynamic model of facility location and design of supply chain, the article not only considering the facility location problem and production allocation problem, but the facilities the extension of the problem, and put forward the warehouse is divided into public and private warehouse warehouse, but the article is standing on the strategic policy level of planning and design, without considering the tactical level.

Bashiri and Hejazi [17] designed a heuristic algorithm to solve the problem that they encountered in [5] that the solving time of large-scale examples was too long, which greatly shortened the solving time of large-scale cases.

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Fattahi, Mahootchi and Husseini [18] proposed to consider price-sensitive requirements in strategic and tactical planning, and designed a mixed integer programming model. The model took into account the consistency of decision making and planning time, and designed a new time modeling method.

Cortinhal, Lopes and Melo [19] proposed a multi-level supply chain network model considering outsourcing opportunities and modes of transportation. Different from previous outsourcing problems, the number of outsourced products in this paper is limited and the warehouse is allowed to purchase a limited number of products from external sources.

Yu, Normasari and Luong [20] proposed a pure integer programming model to solve the problem of facility location in multi-level supply chain. The production rate of the factory was taken into account in the model, and the sensitivity analysis of relevant parameters was made, and it was found that customer demand had the greatest impact on solving this problem.

Khalifehzadeh, Seifbarghy and Naderi [21] put forward a four-level supply chain network model considering customer demand shortage. Another feature of the model is that the reliability of the transportation system is taken into account. The model gives different reliability to different transportation systems.

Ardalan, Karimi and Naderi [22] that customer demand for different choices, which have different needs, and based on this design meet the demand of customers more mode of supply chain model and the model of facility location, distribution strategy and decision-making for the customer demand pattern, finally also designs a Lagrange heuristic algorithm to solve large scale problems.

Diabat and Simchi Levi - [23] a green supply chain management optimization model is put forward, the model takes into consideration the transport between factories, warehouses, retailers to produce carbon emissions, by setting the carbon emissions caps to generation of carbon emissions and transportation of the model's goal is fixed operating costs and minimal chemical plant and warehouse facilities, transportation cost between calculated with the reduction of carbon cap assembly would have increased.

Ramudhin and Chaabane et al. [24] is suggested to consider a carbon trading the dual objectives of supply chain network design model, which is consider the enterprise can be in the market for carbon emissions trading, the model of the first goal is to minimize the total cost, the second goal is to minimize carbon emissions produced during production and transportation, and put forward can use carbon conversion factors to integrate the methane and other greenhouse gases to the model.

Nouira and Hammami et al. [25] proposed that product demand is affected by unit carbon emissions, and developed a mixed integer programming model for this.The model takes into account the upstream transport, production processes and downstream transport emissions, and makes decisions about the location of the facility, the selection of suppliers, the selection of transport modes, etc. In addition, different modeling extensions are discussed. The results show that the facility is more suitable to be located closer to the consumers.

Waltho, Elhedhli and Gzara [26] green supply chain of between 2010 and 2017 were reviewed, observed the offset carbon taxes, carbon, carbon, carbon trading and so on four kind of policy influence on supply chain, and analyzes the literature for carbon source, found that with the improvement of environmental awareness, carbon footprint will and cost, the price is as equally important impact on the market of configuration.

Gong, Chen and Lu [27] put forward a double goals to consider carbon supply chain network planning model, the model takes into account the highway, railway, aviation and shipping and so on four kind of different transport modes of different transportation time costs and carbon emissions, the target is to minimize the total costs and carbon emissions, and sensitivity analysis was carried out on the production capacity, the results showed that when the carbon emissions are high, the improvement of productivity of the total cost of the lower the impact is not big.

NZ and Hs et al. [28] put forward a green forward and reverse logistics network design model, which is a multi-objective programming model, and the three objective functions are to minimize the total cost, minimize the carbon emissions and minimize the number of machines in production.In order to verify the effectiveness of the model, the model is applied to the home appliance industry. Finally, sensitivity analysis is used to analyze the impact of demand and cost on the objective function.

Zhen [29] proposed a dual-objective network planning model considering carbon emissions. The planning cycle in the model includes multiple periods, and the different demands of products in different periods are also taken into account, and a Lagrange algorithm is proposed for the model to reduce the solution time.

JL, Lin and Xin [30] will be low carbon policy integration in the coal supply chain network, put forward a sustainable coal supply chain network model, the objective function of the model is to minimize the cost of production, and the upper limit of the carbon, carbon tax and carbon trading and carbon offsets integrated into the constraint conditions, the analysis is compares the four carbon policy influence on supply chain network optimization, and put forward an algorithm to solve the model easy to fall into local optimum in the process of solving problems.

3. Problem Description

Supply chain network design includes four parts: facility location problem, supplier selection, capacity allocation, supply and market allocation.In this paper, supplier selection and facility site selection will be taken as the core issues for planning and design, and the carbon emission, transportation mode selection and production distribution issues in the whole process will be considered at the same time.We consider a multi-commodity and multi-cycle four-level supply chain network as shown in the figure below, which mainly includes four nodes: supplier, factory, warehouse and customer. At the same time, we consider dividing the warehouse into private warehouse and public warehouse. The private warehouse is built and used by the company, while the public warehouse is rented by the company. In subsequent articles, we will refer to private warehouses and factories collectively as facilities

The specific planning of the model in this paper is mainly introduced from the following aspects:

For planning cycle, most of the articles are considering using a single time resolution, will be a big planning cycle divided into multiple small planning cycle planning design, without considering the consistency of decision making and planning time, and this paper reference Kheirabadi and Naderi et al. [3] used the double time resolution in planning and design, at the same time consider strategic planning and tactical planning period.

As for the location of the factory and the private warehouse, we believe that the specific location has been determined at the early stage of the planning, and we only need to choose among the potential locations. Only the public warehouse can be closed, and the factory and the private warehouse shall not be closed until the end of the planning period after they are established. Thanh, Bostel and Peton [16] proposed the warehouse there are private and public warehouse, there is no cost and consider the public warehouse open, the variable cost is higher than private warehouse, but in real life, although the public warehouse has no fixed cost is fixed rent cost, so in this article we think open public warehouse cost, its open cost is far lower than private warehouse fixed construction cost of fixed rent cost, but the public warehouse storage cost is higher than that of common warehouse, these we can pass the data to adjust. With regard to the fixed costs of factories and warehouses during the planning period, we believe that the fixed construction costs and the fixed capacity expansion costs of factories and private warehouses as well as the fixed rental costs of public warehouses are all supported by the external funds in the corresponding planning period and the net income of the previous planning period.

For the ability of factories and warehouses, we believe that only factories and private warehouses have limited ability, public warehouse capacity constraints, only factory production capacity, warehouse storage capacity, only plant operating between maximum utilization and minimum usage, and also considering the factories and private warehouse capacity expansion problem, for example, when the actual construction of the factory area is less than the factory planning area of area can have

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a spare part for capacity expansion in the future.Our ability to extend the way also has carried on the classification, the ability to bring different under different capacity expansion mode selection expanded as a result, factories and private warehouse can only choose one of the ways to choose capacity expansion, and may not be in the first long-term planning, capacity expansion is not reversible, once after capacity expansion, factories and private warehouses will always have the ability to extend state until the end of the planning period.

We stipulated the flow of the product follow from suppliers - factory - warehouse (private and public warehouses) -customers, factory not directly to the products shipped to the customer, regardless of the factory, warehouse product flow between each node can only adopt a mode of transportation between transportation products, if there is no product flows between nodes, will not use any mode of transportation.

For carbon emissions, we divide them into production carbon emissions and transport carbon emissions. The carbon emissions produced by production and transport of enterprises shall not exceed the carbon emissions stipulated by the government.We give carbon emissions a unit cost, through the control of the cost of carbon emissions to control the carbon emissions, so that the company can operate as low as possible carbon emissions, reduce the impact on the environment.

For supplier's ability to supply and the demand of customer, we think that the two belong to the known parameters, and that supplier has not only supply capacity limit, but also to the factory have a lower limit supply, that is to say, each supplier has the biggest supply for the plant capacity limit and the minimum supply restrictions to the factory.

For the selection of suppliers, we adopt the whole-unit quantity discount for processing. In order to maintain the supply stability and reduce the switching cost caused by changing suppliers, we believe that once suppliers are selected to supply in a certain short planning period, they will continue to supply in the next short planning period.

We use the linear combination method proposed by Kheirabadi and Naderi et al [3] to deal with the supplier’s quantity discount problem. We assume that each supplier’s raw material has a corresponding quantity discount quotation and follow piecewise linearity. The discount data has been determined at the beginning of each planning short-term period and remains stable during the planning period. Only in the next planning short-term, the supplier's quantity discount data may change.

We assume that the quantity of the supplier with the price breakdown point (including the origin) is L, the supply of the supplier corresponding to each price breakdown point is $Q_{pr,s,l}$, and the price corresponding to each quantity break point is $PS_{pr,s,l}$. Then these price breakdown points will divide the prices into (L-1) price intervals. We assume that the actual purchase quantity of the factory from the supplier is QR, and the purchase cost is shown in Table 1:

Table 1. Purchase Cost

Purchase Cost	Quantity of raw materials
0	0
$PS_{pr,s,2} \cdot QR$	$0 \le QR \le Q_{pr,s,2}$
$PS_{pr,s,3} \cdot QR$	$Q_{pr,s,2} \le QR \le Q_{pr,s,3}$
⋮	⋮
$PS_{pr,s,l} \cdot QR$	$Q_{pr,s,l-1} \le QR \le Q_{pr,s,l}$

Figure 1 is the supplier's piecewise linear function chart. According to the picture, we can see that with the increase of purchase quantity, the corresponding raw material price will continue to decrease. For the purchase quantity of raw materials, we will use the linear combination method to determine the price range, as shown in the constraints (12) - (19) in the model.

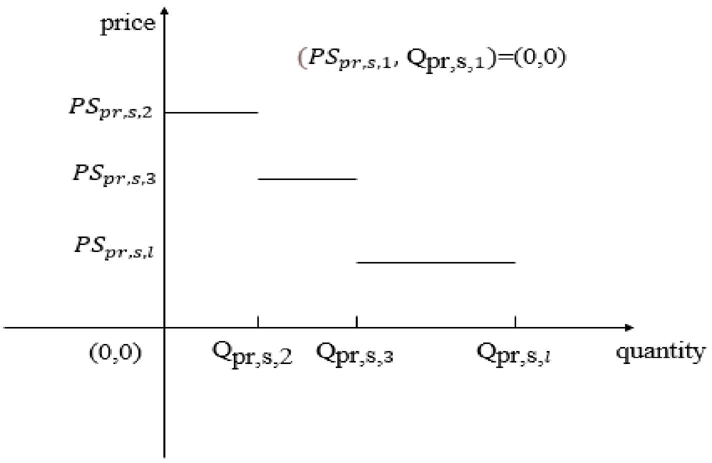

Fig. 1 Supplier piecewise linear function

As for the sources of funds for the construction and expansion of factories and private warehouses, we believe that in the first planning period, all the funds for the construction and expansion of factories and private warehouses come from external investment. In other planning periods after the first planning period, the funds come from the sum of the external investment in the planning period and the accumulated net profit of the previous planning period.

For the objective function, the traditional supply chain network design generally adopts the minimization of supply chain cost, but the essence of supply chain is to obtain the maximum benefits, so it is more reasonable to use profit maximization as the planning goal. And the current monetary value is not equivalent to the future monetary value, so we will take the first year of planning as the base year, and use the profit present value maximization to evaluate the whole model.

4. Model

4.1 Notations

4.1.1 Sets

M: Set of trategic planning period ($m \in M, m=1,\ldots,M$)

N: Set of tactical planning period ($n \in N, n=1,\ldots,N$)

L: Set of price break points ($l \in L, l = 1, \ldots, L$)

O: Set of facility capacity expansion options ($o \in O$)

S: Set of suppliers ($s \in S$)

I: Set of factories ($i \in I$)

J: Set of warehouses ($j \in J$)

WP: Set of private warehouses ($WP \subset J$)

WH: Set of public warehouses ($WH \subset J$)

C: Set of customers ($c \in C$)

P: Set of products ($p \in P, P = PR \cup PF$)

PR: Set of raw materials ($PR \subset P$, $pr \in PR$)

PF: Set of finished products ($PF \subset P$, $pf \in PF$)

TRS: Set of transportation modes ($tr \in TRS$)

4.1.2 Parameters

INV^m: external investment funds in period m

TR: tax rate

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IR: interest rate

SH: stakeholders' share (%)

$R_{s,pr}^{m,n}$: maximum supply of supplier s for pr in trategic period m and tactical period n

$MO_{s,pr}$: minimum supply of supplier s for pr

MK_i : initial capacity of the factory and private warehouse($i \in I \cup JP$)

NK_i : maximum capacity of the factory and private warehouse($i \in I \cup JP$)

MU_i : minimum utilization rate of the plant($i \in I$)

NU_i : maximum utilization rate of the plant($i \in I \cup JP$)

$D_{c,pf}^{m,n}$: demand of customer c for pf in trategic period m and tactical period n

$B_{pr,pf}$: quantity of pr consumed to produce unit of finished product pf

$WL_{pf,i}$: capacity consumed by factory i to produce a unit of finished product pf

V_{pf} : capacity consumed by warehouse to storage a unit of finished product pf

CK_o : capacity for facility expansion under option o

$A_{i,j}$: transportation times from factory i to warehouse j in one tactical period

PR_{pf} : selling price of a unit pf to customers

CO_i : fixed cost for opening a facility at a potential location i

MC_j : fixed rental costs for opening public warehouses

$CA_{i,o}$: fixed cost for adding capacity option o to facility i

CU_i : fixed cost for operating facility i

$COP_{i,o}$: fixed cost for operating capacity option o at facility i

$CP_{pf,i}$: variable cost of production of a unit of pf at plant i

$CS_{pf,j}$: storage cost of a unit of pf at warehouse j

$CSP_{pr,s,i}^{tr}$:unit transportation cost of transporting pr from s to i using tr transportation modes

$CPW_{pf,i,j}^{tr}$: unit transportation cost of transporting pf from i to j using tr transportation modes

$CWC_{pf,j,c}^{tr}$: unit transportation cost of transporting pf from j to c using tr transportation modes

$PS_{pr,s,l}$: unit price of raw material pr at the price point l of supplier s

$Q_{pr,s,l}$: Quantity corresponding to the l price point of raw material pr in supplier s

$M1$: a very large positive real number

$M2$: a very large positive real number

$M3$: a very large positive real number

$PC_{pf,i}$: carbon emission generated by unit finished product pf produced by factory i

$TC_{pf,i}$: carbon emissions generated by unit product p of transportation when using transportation tr

MC: price per unit of carbon emissions

MCP: The upper limit of production carbon emissions in each tactical period

MCT: The upper limit of transportation carbon emissions between two locations in each tactical period

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4.1.3 Variables

(1) Continuous variables

INC^m : Total profit (pre-tax) in strategic period m

SF^m : cumulative net profit from the first strategic period to period k-1

LC^m : cumulative net profit (after tax) from the first strategic period to period k-1

F : Present value of total profits

$g_{pr,s,i}^{m,n,l} \in [0,1]$: a continuous variable between 0 and 1, which represents the proportion of factory i purchasing from supplier s at the lth price point in the strategic period m and tactical period n, and is used to used to determine the total amount of raw materials pr purchased by factory i from supplier s.

$rc_{pr,s,i}^{m,n,l}$: a continuous variable greater than 0, it represents the total purchase cost of the raw material pr in the strategic planning period m and the tactical period n. The corresponding total purchase quantity should be between the l-1th price breakdown point and the lth price breakdown point. That is said that the total purchase volume should be in the l-1th price intervals.

(2) Boolean variables

$x_i^m = \begin{cases} 0 \\ 1 \end{cases}$ 1 if factory and warehouse opened in strategic period m, 0 otherwise. $\left(x_i^m = 0, \forall m = 0, i \in I \cup J\right)$

$y_{i,o}^m = \begin{cases} 0 \\ 1 \end{cases}$ 1 if factory and private warehouse choose option o for capacity expansion in strategic period m, 0 otherwise. $\left(y_{i,o}^m = 0, \forall m = 0, i \in I \cup JP\right)$

$z_{s,pr}^{m,n} = \begin{cases} 0 \\ 1 \end{cases}$ 1 if supplier s is selected to supply raw materials in strategic period m and tactical period n, 0 otherwise.

$v_{pr,s,i}^{m,n,l} = \begin{cases} 0 \\ 1 \end{cases}$ 1 if the raw material quantity supplied by supplier s to factory i falls within the l-th price intervals in strategic period m and tactical period n, 0 otherwise.

$d_{i,j,tr}^{m,n} = \begin{cases} 0 \\ 1 \end{cases}$ 1 if transport mode tr is used from node i to node j in strategic period m and tactical period n, 0 otherwise.

(3) Integer variables

$f_{p,i,j}^{m,n,tr}$: quantity of product p from location i to j using transportation modes tr in strategic period m and tactical period n.

$q_{i,pf}^{m,n}$: quantity of finished products pf produced by factory i in strategic period m and tactical period n.

$h_{pf,j}^{m,n}$: quantity of finished product pf held in warehouse j at the end of n of strategic m $\left(h_{pf,j}^{m,n} = 0, \forall m = 0\right)$.

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4.2 Objective function

$$F=\sum_{m\in M}\frac{INC^{m}}{(1+IR)^{m-1}}$$

We regard maximizing the net profit of the entire planning period as our planning goal, and considering that the value of currency will change over time, it is more realistic for us to take the present value of the net profit of the entire planning period as the final goal. We set the base year converted to present value as the first year of strategic planning.

4.3 Constriants

$$\sum_{j\in J}\sum_{tr\in TRS} f_{pf,j,c}^{m,n,tr} \leq D_{c,pf}^{m,n} \cdots \forall c\in C, \forall pf\in PF, \forall m\in M, \forall n\in N \quad (1)$$

Constraint (1) represents the demand constraint, because our goal is to maximize profit, so we don't have to meet the needs of customers.This can avoid the situation where the customer has little demand but the company must supply.

$$\sum_{i\in I}\sum_{tr\in TR} f_{pr,s,i}^{m,n,tr} \leq z_{s,pr}^{m,n}\cdot R_{s,pr}^{m,n} \cdots \forall s\in S, \forall pr\in PR, \forall m\in M, \forall n\in N \quad (2)$$

$$\sum_{i\in I}\sum_{tr\in TRS} f_{pr,s,i}^{m,n,tr} \geq z_{s,pr}^{m,n}\cdot MO_{s,p} \cdots \forall s\in S, \forall pr\in PR, \forall m\in M, \forall n\in N \quad (3)$$

Constraints (2) and Constraints (3) restrict the supplier's supply of raw materials.

It indicates that the supplier's supply to the factory should be greater than the supplier's minimum supply, less than the supplier's supply capacity, and only when the supplier is selected, can the raw material be supplied.

$$h_{pf,j}^{m-1,N}+\sum_{i\in I}\sum_{tr\in TRS} f_{pf,i,j}^{m,n,tr}=\sum_{c\in C}\sum_{tr\in TRS} f_{pf,j,c}^{m,n,tr}+h_{pf,j}^{m,n},$$
$$\forall j\in J, \forall pf\in PF, \forall m\in M, \forall n\in N \mid n=1 \quad (4)$$

$$h_{pf,j}^{m,n-1}+\sum_{i\in I}\sum_{tr\in TRS} f_{pf,i,j}^{m,n,tr}=\sum_{c\in C}\sum_{tr\in TRS} f_{pf,j,c}^{m,n,tr}+h_{p,j}^{m,n},$$
$$\forall j\in J, \forall pf\in PF, \forall m\in M, \forall n\in N \mid n\neq 1 \quad (5)$$

Constraint (4) and constraint (5) are the flow conservation constraints of the warehouse.It means that the storage volume of the warehouse at the end of the last tactical period plus the transportation volume from the factory to the warehouse in the current tactical period is equal to the freight volume from the warehouse to the customer in the current tactical period plus the ending storage volume of the warehouse in the current tactical period.

$$\sum_{s\in S}\sum_{l\in L}\sum_{tr\in TRS} f_{pr,s,i}^{m,n,tr}=\sum_{pf\in PF} B_{pr,pf}\cdot q_{pf,i}^{m,n} \cdots \forall i\in I, \forall pr\in PR, \forall m\in M, \forall n\in N \quad (6)$$

$$q_{pf,i}^{m,n}=\sum_{j\in J}\sum_{tr\in TRS} f_{pf,i,j}^{m,n,tr} \cdots \forall i\in I, \forall pf\in PF, \forall m\in M, \forall n\in N \quad (7)$$

$$\sum_{pf\in PF} W\,L_{pf,i}\cdot q_{pf,i}^{m,n}\leq NU_i\cdot\left(MK_i\cdot x_i^m+\sum_{o\in O} C\,K_o\cdot y_{i,o}^m\right)\cdots \forall i\in I, \forall m\in M, \forall n\in N \quad (8)$$

$$\sum_{pf\in PF} W\,L_{pf,i}\cdot q_{pf,i}^{m,n}\geq MU_i\cdot\left(MK_i\cdot x_i^m+\sum_{o\in O} C\,K_o\cdot y_{i,o}^m\right)\cdots \forall i\in I, \forall m\in M, \forall n\in N \quad (9)$$

$$MK_i\cdot x_i^m+\sum_{o\in O} C\,K_o\cdot y_{i,o}^m\leq NK_i \cdots \forall i\in I\cup JP \quad (10)$$

$$\sum_{pf\in PF} V_{pf}\cdot\left(h_{pf,j}^{m,n}+\sum_{i\in I}\sum_{tr\in TRS}\frac{f_{pf,i,j}^{m,n,tr}}{2A_{i,j}}\right)\leq MK_j\cdot x_j^m+\sum_{o\in O} C\,K_o\cdot y_{j;o}^m \cdots \forall j\in JP \quad (11)$$

Constraint (6) to Constraint (11) are the constraints of factory capacity and warehouse storage capacity.The constraint (6) means that all the raw materials shipped by the supplier to the factory are made into finished products.Constraint (7) means that the finished products produced by the factory will all be transported to the warehouse through various transportation methods, and the factory does not store finished products.Constraint (8) and constraint (9) indicate that the factory should operate between the maximum utilization rate and the minimum utilization rate, where the factory's capacity is the sum of the initial capacity and the expansion capacity.Constraint (10) indicates that the initial

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capacity of the factory and private warehouse plus the expansion capacity cannot exceed the maximum capacity of the factory and private warehouse.Constraint (11) indicates that the storage capacity of a private warehouse cannot exceed the sum of the initial capacity and expansion capacity of the private warehouse.

$$g_{pr,s,i}^{m,n,l} \leq v_{pr,s,i}^{m,n,l} \cdots \forall pr \in PR, \forall s \in S, \forall i \in I, \forall m \in M, \forall n \in N, \forall l \in L \mid l = 1 \tag{12}$$

$$g_{pr,s,i}^{m,n,l} \leq v_{pr,s,i}^{m,n,l} + v_{pr,s,i}^{m,n,l-1}, \forall pr \in PR, \forall s \in S, \forall i \in I, \forall m \in M, \forall n \in N, \forall l \in L \mid 1 < l < L \tag{13}$$

$$g_{pr,s,i}^{m,n,l} \leq v_{pr,s,i}^{m,n,l-1} \cdots \forall pr \in PR, \forall s \in S, \forall i \in I, \forall m \in M, \forall n \in N, \forall l \in L \mid l = L \tag{14}$$

$$\sum_{l=1}^{L-1} v_{pr,s,i}^{m,n,l} = 1 \cdots \forall pr \in PR, \forall s \in S, \forall i \in I, \forall m \in M, \forall n \in N, \forall l \in L \tag{15}$$

$$\sum_{l=1}^{L} g_{pr,s,i}^{m,n,l} = 1 \cdots \forall pr \in PR, \forall s \in S, \forall i \in I, \forall m \in M, \forall n \in N, \forall l \in L \tag{16}$$

$$0 \leq g_{pr,s,i}^{m,n,l} \leq 1 \cdots \forall pr \in PR, \forall s \in S, \forall i \in I, \forall m \in M, \forall n \in N, \forall l \in L \tag{17}$$

$$\sum_{tr \in TR} f_{pr,s,i}^{m,n,tr} = \sum_{l \in L} Q_{pr,s,l} \cdot g_{pr,s,i}^{m,n,l},$$
$$\forall pr \in PR, \forall s \in S, \forall i \in I, \forall m \in M, \forall n \in N, \forall l \in L, \forall tr \in TRS \tag{18}$$

$$rc_{pr,s,i}^{m,n,l} \geq \left(Q_{pr,s,l} \cdot g_{pr,s,i}^{m,n,l} + Q_{pr,s,l-1} \cdot g_{pr,s,i}^{m,n,l-1}\right) \cdot PS_{pr,s,l} - M1 \cdot \left(1 - v_{pr,s,i}^{m,n,l-1}\right),$$
$$\forall pr \in PR, \forall s \in S, \forall i \in I, \forall m \in M, \forall n \in N, \forall l \in L \mid l > 1 \tag{19}$$

Constraint (12) to constraint (18) determine the value of g at each price point, which can be used to calculate which price range of the supplier the total purchase of raw materials is within each tactical period, and to ensure the total purchase of raw materials The volume can only be in one price range.Constraint (19) represents the purchase cost of a certain raw material, which is equal to the purchase amount multiplied by the price, and the constraint guarantees that there is a purchase cost only when the purchase quantity is in the corresponding price range, otherwise the purchase cost will be 0.

$$\sum_{pf \in PF} \sum_{i \in I} P\, C_{pf,i} \cdot q_{pf,i}^{m,n} \leq MCP \cdots \forall m \in M, \forall n \in N \tag{20}$$

$$\sum_{pr \in PR} \sum_{tr \in TR} \sum_{s \in S} \sum_{i \in I} T\, C_{pr,tr} \cdot f_{pr,s,i}^{m,n,tr} \leq MCT \cdots \forall s \in S, \forall i \in I, \forall m \in M, \forall n \in N \tag{21}$$

$$\sum_{pf \in PF} \sum_{tr \in TR} \sum_{i \in I} \sum_{j \in J} T\, C_{pf,tr} \cdot f_{pf,i,j}^{m,n,tr} \leq MCT \cdots \forall i \in I, \forall j \in J, \forall m \in M, \forall n \in N \tag{22}$$

$$\sum_{pf \in PF} \sum_{tr \in TR} \sum_{j \in J} \sum_{c \in C} T\, C_{pf,tr} \cdot f_{pf,j,c}^{m,n,tr} \leq MCT \cdots \forall j \in J, \forall c \in C, \forall m \in M, \forall n \in N \tag{23}$$

Constraint (20) to constraint (23) refers to the carbon emission constraints generated by production and transportation. Among them, constraint (20) refers to the carbon emission constraints of production. In each short planning, the carbon emission generated by plant production is less than the specified upper limit of production carbon emission.Constraint (21) to constraint (23) is the carbon emission constraint of transportation. In each short planning period, the carbon emission from supplier to factory, factory to warehouse, and warehouse to customer is less than the corresponding carbon emission ceiling respectively.

$$\sum_{pr \in PR} f_{pr,s,i}^{m,n,tr} \leq M2 \cdot d_{s,i,tr}^{m,n} \cdots \forall s \in S, \forall i \in I, \forall tr \in TRS, \forall m \in M, \forall n \in N \tag{24}$$

$$\sum_{pf \in PF} f_{pf,i,j}^{m,n,tr} \leq M2 \cdot d_{i,j,tr}^{m,n} \cdots \forall i \in I, \forall j \in J, \forall tr \in TRS, \forall m \in M, \forall n \in N \tag{25}$$

$$\sum_{pf \in PF} f_{pf,j,c}^{m,n,tr} \leq M2 \cdot d_{j,c,tr}^{m,n} \cdots \forall j \in J, \forall c \in C, \forall tr \in TRS, \forall m \in M, \forall n \in N \tag{26}$$

$$d_{s,i,tr}^{m,n} \leq \sum_{pr \in PR} f_{pr,s,i}^{m,n,tr} \cdots \forall s \in S, \forall i \in I, \forall tr \in TRS, \forall m \in M, \forall n \in N \tag{27}$$

$$d_{i,j,tr}^{m,n} \leq \sum_{pf \in PF} f_{pf,i,j}^{m,n,tr} \cdots \forall i \in I, \forall j \in J, \forall tr \in TRS, \forall m \in M, \forall n \in N \tag{28}$$

$$d_{j,c,tr}^{m,n} \leq \sum_{pf \in PF} f_{pf,j,c}^{m,n,tr} \cdots \forall j \in J, \forall c \in C, \forall tr \in TRS, \forall m \in M, \forall n \in N \tag{29}$$

$$\sum_{tr \in TRS} d_{s,i,tr}^{m,n} = 1 \cdots \forall s \in S, \forall i \in I, \forall m \in M, \forall n \in N \tag{30}$$

$$\sum_{tr\in TRS} d_{i,j,tr}^{m,n} = 1 \cdots \forall i \in I, \forall j \in J, \forall m \in M, \forall n \in N \tag{31}$$

$$\sum_{tr\in TRS} d_{j,c,tr}^{m,n} = 1 \cdots \forall j \in J, \forall c \in C, \forall m \in M, \forall n \in N \tag{32}$$

Constraint (24) to constraint (32) restrict the mode of transportation between nodes in the network.Constraints (24)-(26) indicate that when a certain mode of transportation is used to transport between locations, there must be a product flow between locations.Constraints (27)—(28) indicate that when there is no product flow between the two locations, you do not need to choose any constraint method.Constraints (30)—(32) indicate that only one mode of transportation can be used between two locations.

$$z_{s,pr}^{m,n-1} \leq z_{s,pr}^{m,n} \cdots \forall s \in S, \forall i \in I, \forall pr \in PR, \forall m \in M, \forall n \in N \tag{33}$$

$$\sum_{pr\in PR} z_{s,pr}^{m,n} = 1 \cdots \forall s \in S, \forall m \in M, \forall n \in N \tag{34}$$

$$\sum_{c\in C} \sum_{pf\in PF} f_{p,j,c}^{m,n} \leq x_j^m \cdot M3 \cdots \forall j \in J, \forall m \in M, \forall n \in N \tag{35}$$

Constraint (33) means that once a supplier is selected, the supplier will continue to supply raw materials in the next tactical period. Constraint (34) means that each supplier can only supply one type of raw material Constraint (35) means that only open warehouses can ship products to customers.

$$y_{i,o}^m \leq x_i^m \cdots \forall i \in I \cup JP, \forall o \in O \tag{36}$$

$$x_i^{m-1} \leq x_i^m \cdots \forall i \in I \cup JP \tag{37}$$

$$y_{i,o}^{m-1} \leq y_{i,o}^{m} \cdots \forall i \in I \cup JP, \forall m \in M \tag{38}$$

$$\sum_{o\in O} y_{i,o}^m \leq 1 \cdots \forall i \in I \cup JP \tag{39}$$

$$\sum_{o\in O} y_{i,o}^m \leq 1 - (x_i^m - x_i^{m-1}) \cdots \forall i \in I \cup JP, \forall m \in M \tag{40}$$

$$\begin{pmatrix} \sum_{o\in O} C\,A_{i,0} \cdot (x_i^m - x_i^{m-1}) + \sum_{j\in JH} M\,C_j \cdot x_j^m \\ + \sum_{i\in I\cup JP} \sum_{o\in O} C\,A_{i,o} \cdot \left(y_{i,o}^m - y_{i,o}^{m-1}\right) \end{pmatrix} \leq INV^m + LC^m \cdots \forall m \in M \tag{41}$$

Constraint (36) means that only open factories and private warehouses can expand capacity. Constraint (37) means that once factories and private warehouses are opened, they will remain open until the end of the planning period. Constraint (38) means that the expansion part of the factory and warehouse cannot be closed. Constraint (39) indicates that factories and warehouses can only choose one method for capacity expansion. Constraint (40) means that in the first strategic period, the newly opened factories and private warehouses cannot be expanded. Constraint (41) indicates that the fixed costs required for the opening of factories and warehouses and the expansion of factories and private warehouses are all derived from the external investment in each strategic period plus the after-tax net profit of the previous strategic period.

$$INC^m = \sum_{n\in N} \sum_{j\in J} \sum_{pf\in PF} \sum_{c\in C} \sum_{tr\in TR} P\,R_{pf,c} \cdot f_{pf,j,c}^{m,n,tr} \tag{42}$$

$$- \sum_{i\in I\cup JP} C\,O_i \cdot (x_i^m - x_i^{m-1}) \tag{43}$$

$$- \sum_{j\in JH} M\,C_j \cdot x_j^m \tag{44}$$

$$- \sum_{i\in I\cup jP} \sum_{o\in O} C\,A_{i,0} \cdot \left(y_{i,o}^m - y_{i,o}^{m-1}\right) \tag{45}$$

$$- \sum_{i\in I\cup JP} \left(CU_i \cdot x_i^m + \sum_{o\in O} C\,OP_{i,0} \cdot y_{i,o}^m\right) \tag{46}$$

$$- \sum_{n\in N} \sum_{pf\in PF} \sum_{i\in I} C\,P_{pf,i} \cdot q_{pf,i}^{m,n} \tag{47}$$

$$- \sum_{n\in N} \sum_{pf\in PF} \sum_{j\in W} C\,S_{pf,j} \cdot \left(h_{pf,j}^{m,n} + \sum_{i\in I} \sum_{tr\in TR} \frac{f_{pf,i,j}^{m,n,tr}}{2A_{i,j}}\right) \tag{48}$$

$$- \sum_{pr\in P_R} \sum_{s\in S} \sum_{i\in I} \sum_{n\in N} \sum_{tr\in TR} f_{pr,s,i}^{m,n,tr} \cdot CSP_{pr,s,i}^{tr} \tag{49}$$

$$- \sum_{pf\in PF} \sum_{i\in I} \sum_{j\in J} \sum_{n\in N} \sum_{tr\in TR} f_{pf,i,j}^{m,n,tr} \cdot CPW_{pf,i,j}^{tr} \tag{50}$$

$$- \sum_{pf\in P_F} \sum_{j\in j} \sum_{c\in C} \sum_{n\in N} \sum_{tr\in TR} f_{pf,j,c}^{m,n,tr} \cdot CWC_{pf,j,c}^{tr} \tag{51}$$

$$-\sum_{pr\in P_R}\sum_{s\in S}\sum_{i\in I}\sum_{EL}\sum_{n\in N} r\, c_{pr,s_1 i}^{m,n,l} \tag{52}$$

$$-\sum_{pf\in PF}\sum_{i\in I}\sum_{n\in N} P\, C_{pf,i}\cdot q_{pf,i}^{m,n}\cdot MC \tag{53}$$

$$-\sum_{pr\in P_R}\sum_{tr\in TR}\sum_{s\in S}\sum_{i\in I}\sum_{n\in N} T\, C_{pr,tr}\cdot f_{pr,s,i}^{m,n,tr} \tag{54}$$

$$-\sum_{pf\in PF}\sum_{tr\in TR}\sum_{i\in I}\sum_{j\in J} T\, C_{pf,tr}\cdot f_{pf,i,j}^{m,n,tr}\cdot MC \tag{55}$$

$$-\sum_{pf\in PF}\sum_{tr\in TR}\sum_{j\in J}\sum_{c\in C} T\, C_{pf,tr}\cdot f_{pf,j,c}^{m,n,tr}\cdot MC \tag{56}$$

$$SF^m=\sum_{m=1}^{M} Inc^m\ ,\forall m\in M \tag{57}$$

$$LC^m=(1-TR)(1-SH)\cdot SF^m,\forall m\in M \tag{58}$$

The total profit is obtained by subtracting the cost from the total income, which is the pre-tax profit. Constraint (42) represents the total income in the strategic period m. Constraint (43) represents the fixed cost of opening a factory and private warehouse, constraint (44) represents the fixed cost of opening a public warehouse, Constraint (45) represents the fixed cost of opening the factory and private warehouse expansion, Constraint (46) represents the fixed costs of operating factories and private warehouses and the fixed costs of operating factories and private warehouses, Constraint (45) represents the variable cost of producing the product,constraint (48) represents storage cost, constraint (49) represents transportation cost from supplier to factory, and constraint (50) represents transportation from factory to warehouse Cost, constraint (51) represents the operating cost from the warehouse to the customer, constraint (52) represents the purchase cost of raw materials, constraint (53) represents the cost of carbon emissions from production, and constraint (54) represents represents the carbon emission cost of transportation between suppliers and factories. Constraint (55) represents the carbon emission cost of transportation between factories and warehouses, and constraint (56) represents the carbon emission cost of transportation between warehouses and customers, Constraint (57) represents the cumulative net income from the first period to the m-1th period, Constraint (58) represents the cumulative net income after deducting taxes and shareholder dividends from the first period to the m-1th period.

$$d_{i,j,tr}^{m,n}\in\{0,1\},\forall i\in S\cup I\cup J,\forall j\in I\cup J\cup C,\forall tr\in TR,\forall m\in M,\forall n\in N \tag{59}$$

$$x_i^m, y_{i,o}^m\in\{0,1\},\forall s\in S,\forall i\in I\cup JP,\forall j\in I\cup JP,\forall o\in O,\forall m\in M,\forall n\in N \tag{60}$$

$$z_{s,pr}^{m,n}, v_{pr,s,i}^{m,n,l}\in\{0,1\},\forall pr\in PR,\forall s\in S,\forall i\in I,\forall m\in M,\forall n\in N,\forall l\in L \tag{61}$$

$$g_{pr,s,i}^{m,n,l}\in[0,1],\forall pr\in PR,\forall s\in S,\forall i\in I,\forall m\in M,\forall n\in N,\forall l\in L \tag{62}$$

$$f_{p,i,j}^{m,n,tr}\geq 0,\forall p\in P,\forall i\in S\cup I\cup J,\forall j\in I\cup J\cup C,\forall m\in M,\forall n\in N,\forall tr\in TR \tag{63}$$

$$q_{i,pf}^{m,n}\geq 0,\forall i\in I,\forall pf\in PF,\forall m\in M,\forall n\in N \tag{64}$$

$$h_{\mathrm{pf},j}^{m,n}\geq 0,\forall pf\in PF,\forall j\in J,\forall m\in M,\forall n\in N \tag{65}$$

$$rc_{pr,s,i}^{m,n,l}\geq 0\cdot\forall pr\in PR, s\in S, i\in I,\forall m\in M,\forall n\in N,\forall l\in L \tag{66}$$

Constraints (59) to (61) require that these variables are binary.Constraints (62) Require variable to be continuous.Constraints (63) to (66) require that these variables from taking non-negative values.

5. Calculation test

5.1 Model application

We have designed a simple example with a strategic period of 2 years and a tactical period of 4 quarters to illustrate the application of the model, and we assume that there will be an annual external investment of US$10,000 for the construction and expansion of factories and private warehouses during the planning period. Some parameters are shown in Table 2, and other parameters are shown in the appendix.

Table 2. Model parameters

A long planning period	2	The customer	2
Short planning period	4	The raw materials	2
supplier	2	Finished goods	2
The factory	2	Price point quantity	5
Private warehouses	2	Capacity to choose	2
Public warehouse	2	The mode of transportation	2

The detailed discount data of the supplier is shown in Table 3-Table 10.

Table 3. Supplier quantity discount

Points	m=1 n=2							
	$Q^{m,n}_{pr1,s1,l}$	$PS^{m,n}_{pr1,s1,l}$	$Q^{m,n}_{pr1,s2,l}$	$PS^{m,n}_{pr1,s2,l}$	$Q^{m,n}_{pr2,s1,l}$	$PS^{m,n}_{pr2,s1,l}$	$Q^{m,n}_{pr2,s2,l}$	$PS^{m,n}_{pr2,s2,l}$
1	0	0	0	0	0	0	0	0
2	4500	7	4300	7	4250	7	4300	6
3	8500	5	7800	5	7500	6	8000	5
4	12000	4	9800	4	9800	4	10000	4
5	15000	3	14000	3	13000	2	14000	3

Table 4. Supplier quantity discount

Points	m=1 n=2							
	$Q^{m,n}_{pr1,s1,l}$	$PS^{m,n}_{pr1,s1,l}$	$Q^{m,n}_{pr1,s2,l}$	$PS^{m,n}_{pr1,s2,l}$	$Q^{m,n}_{pr2,s1,l}$	$PS^{m,n}_{pr2,s1,l}$	$Q^{m,n}_{pr2,s2,l}$	$PS^{m,n}_{pr2,s2,l}$
1	0	0	0	0	0	0	0	0
2	5000	6	4200	6	4300	6	4500	7
3	8400	5	8000	5	7750	5	8200	5
4	11000	4	11500	4	10000	4	10000	3
5	16000	3	15000	3	12500	2	13500	2

Table 5. Supplier quantity discount

Points	m=1 n=3							
	$Q^{m,n}_{pr1,s1,l}$	$PS^{m,n}_{pr1,s1,l}$	$Q^{m,n}_{pr1,s2,l}$	$PS^{m,n}_{pr1,s2,l}$	$Q^{m,n}_{pr2,s1,l}$	$PS^{m,n}_{pr2,s1,l}$	$Q^{m,n}_{pr2,s2,l}$	$PS^{m,n}_{pr2,s2,l}$
1	0	0	0	0	0	0	0	0
2	4600	7	4500	7	4400	8	5000	7
3	8000	4	8200	5	7800	7	8800	6
4	13000	3	12000	3	9700	5	12500	5
5	15500	2	15500	2	13500	3	14500	3

Table 6. Supplier quantity discount

Points	m=1 n=4							
	$Q^{m,n}_{pr1,s1,l}$	$PS^{m,n}_{pr1,s1,l}$	$Q^{m,n}_{pr1,s2,l}$	$PS^{m,n}_{pr1,s2,l}$	$Q^{m,n}_{pr2,s1,l}$	$PS^{m,n}_{pr2,s1,l}$	$Q^{m,n}_{pr2,s2,l}$	$PS^{m,n}_{pr2,s2,l}$
1	0	0	0	0	0	0	0	0
2	4800	7	4400	6	4500	6	4800	6
3	8800	5	8125	5	7600	5	9000	5
4	12500	4	11500	3	9600	4	12500	4
5	14500	3	16000	2	14000	2	15000	2

Table 7. Supplier quantity discount

Points	m=2 n=1							
	$Q^{m,n}_{pr1,s1,l}$	$PS^{m,n}_{pr1,s1,l}$	$Q^{m,n}_{pr1,s2,l}$	$PS^{m,n}_{pr1,s2,l}$	$Q^{m,n}_{pr2,s1,l}$	$PS^{m,n}_{pr2,s1,l}$	$Q^{m,n}_{pr2,s2,l}$	$PS^{m,n}_{pr2,s2,l}$
1	0	0	0	0	0	0	0	0
2	5000	6	4500	7	4500	8	4600	7
3	8000	5	8000	5	8000	6	7800	5
4	12000	4	12000	4	9600	4	10000	4
5	16000	2	15500	2	13500	2	14000	3

Table 8. Supplier quantity discount

Points	m=2 n=2							
	$Q^{m,n}_{pr1,s1,l}$	$PS^{m,n}_{pr1,s1,l}$	$Q^{m,n}_{pr1,s2,l}$	$PS^{m,n}_{pr1,s2,l}$	$Q^{m,n}_{pr2,s1,l}$	$PS^{m,n}_{pr2,s1,l}$	$Q^{m,n}_{pr2,s2,l}$	$PS^{m,n}_{pr2,s2,l}$
1	0	0	0	0	0	0	0	0
2	5200	6	4300	6	4300	6	4600	6
3	8400	5	8300	5	7800	5	8200	4
4	13000	4	12500	3	9800	4	12500	3
5	15500	3	16000	2	14000	2	15000	2

Table 9. Supplier quantity discount

Points	m=2 n=3							
	$Q^{m,n}_{pr1,s1,l}$	$PS^{m,n}_{pr1,s1,l}$	$Q^{m,n}_{pr1,s2,l}$	$PS^{m,n}_{pr1,s2,l}$	$Q^{m,n}_{pr2,s1,l}$	$PS^{m,n}_{pr2,s1,l}$	$Q^{m,n}_{pr2,s2,l}$	$PS^{m,n}_{pr2,s2,l}$
1	0	0	0	0	0	0	0	0
2	4800	7	4800	6	4450	7	4700	6
3	8600	5	8225	5	7600	5	8000	5
4	13000	4	11500	4	10000	4	13500	4
5	15500	2	15000	2	14000	2	14550	3

Table 10. Supplier quantity discount

Points	m=2 n=4							
	$Q^{m,n}_{pr1,s1,l}$	$PS^{m,n}_{pr1,s1,l}$	$Q^{m,n}_{pr1,s2,l}$	$PS^{m,n}_{pr1,s2,l}$	$Q^{m,n}_{pr2,s1,l}$	$PS^{m,n}_{pr2,s1,l}$	$Q^{m,n}_{pr2,s2,l}$	$PS^{m,n}_{pr2,s2,l}$
1	0	0	0	0	0	0	0	0
2	4600	7	4600	6	4550	7	4800	7
3	9000	4	8350	5	7500	5	8300	5
4	14000	3	13000	3	9870	3	12500	4
5	17000	2	17500	2	13500	2	16000	2

Through calculation, for the problem of supplier selection, the solution we get is that in the first strategic period, supplier 1 supplies raw material 2 and supplier 2 supplies raw material 1, and in the second strategic period, Supplier 1 supplies raw material 1, and supplier 2 supplies raw material 2. The detailed results have been shown in Table 11.

Table 11. Reasonable supplier selection plan

Supplier	Raw material	Strategic period	Tactical period			
			1	2	3	4
S1	PR1	1	×	×	×	×
S1	PR2	1	✓	✓	✓	✓
S2	PR1	1	×	×	×	×
S2	PR2	1	✓	✓	✓	✓
S1	PR1	2	✓	✓	✓	✓
S1	PR2	2	×	×	×	×
S2	PR1	2	×	×	×	×
S2	PR2	2	✓	✓	✓	✓

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Through calculation, we can also know the supplier's supply cost and the discount provided by the supplier when purchasing raw materials.The detailed situation is shown in Table 12.

Table 12. Supplier selection and discount plan

(Strategic period, Tactical period)	Supplier (Plant$^{raw\ material}$)	Cost	Price interval
(1, 1)	S1(I1^{PR2})	29724	2
	S1(I2^{PR2})	28704	2
	S2(I1^{PR1})	21500	2
	S2(I2^{PR1})	21500	2
(1, 2)	S1(I1^{PR2})	24770	2
	S1(I2^{PR2})	23920	2
	S2(I1^{PR1})	21000	2
	S2(I2^{PR1})	21000	2
(1, 3)	S1(I1^{PR2})	34678	2
	S1(I2^{PR2})	33488	2
	S2(I1^{PR1})	18921	1
	S2(I2^{PR1})	23920	2
(1, 4)	S1(I1^{PR2})	24770	2
	S1(I2^{PR2})	23920	2
	S2(I1^{PR1})	22000	2
	S2(I2^{PR1})	22000	2
(2, 1)	S1(I1^{PR1})	19374	1
	S1(I2^{PR1})	25730	2
	S2(I1^{PR2})	26590	2
	S2(I2^{PR2})	25730	2
(2, 2)	S1(I1^{PR1})	26000	2
	S1(I2^{PR1})	23448	1
	S2(I1^{PR2})	21272	2
	S2(I2^{PR2})	20584	2
(2, 3)	S1(I1^{PR1})	24000	2
	S1(I2^{PR1})	25730	2
	S2(I1^{PR2})	26590	2
	S2(I2^{PR2})	25730	2
(2, 4)	S1(I1^{PR1})	20468	2
	S1(I2^{PR1})	20584	2
	S2(I1^{PR2})	26590	2
	S2(I2^{PR2})	25730	2

According to Table 12, we can see that the purchase of raw materials mainly falls in the second price range, and a few fall in the first price range. This shows that under the stimulation of price discounts, factories tend to buy more raw materials to reduce purchases. cost.

In the model, we also made decisions about the mode of transportation among suppliers, factories, warehouses, and customers. We considered two different modes of transportation. The choice of transportation method is affected by unit transportation cost and carbon emissions. In this example, the reasonable transportation solution is shown in Table 13.

According to the table 13, we can see that most of the locations use the first mode of transportation for transportation, and only a few locations use the second mode of transportation. This is the result of the combined effect of unit transportation costs and carbon emissions.

Table 13. Transportation plan

(Strategic period, Tactical period)	Origin	Destination	Product	Transportation mode
(2, 1) (2, 2) (2, 3), (2, 4)	S1	I1	PR1	1
(2, 1) (2, 2) (2, 3), (2, 4)	S1	I2	PR1	1
(1, 1) (1, 2) (1, 3) (1, 4)	S2	I1	PR1	1
(1, 1) (1, 2) (1, 3) (1, 4)	S2	I2	PR1	1
(1, 1) (1, 2) (1, 3) (1, 4)	S1	I1	PR2	1
(1, 1) (1, 2) (1, 3) (1, 4)	S1	I2	PR2	1
(2, 1) (2, 2) (2, 3), (2, 4)	S2	I1	PR2	2
(2, 1) (2, 2) (2, 3), (2, 4)	S2	I2	PR2	1
(1, 1) (1, 2) (1, 3) (1, 4), (2, 1) (2, 2) (2, 3), (2, 4)	I1	W3(H)	PF1	1
(1, 1) (2, 2) (2, 3)	I1	W4(H)	PF1	1
(1, 3) (1, 4), (2, 1) (2, 3), (2, 4)	I2	W1(P)	PF1	1
(1, 1) (1, 2)	I2	W1(P)	PF1	2
(1, 1) (1, 2) (1, 3) (1, 4), (2, 1) (2, 2) (2, 3), (2, 4)	I2	W4(H)	PF1	1
(1, 1) (1, 2) (1, 3) (1, 4), (2, 1) (2, 2) (2, 3), (2, 4)	I1	W1(P)	PF2	2
(1, 1) (1, 2) (2, 2)	I2	W1(P)	PF2	2
(1, 4)	I2	W4(H)	PF2	1
(1, 3), (2, 1) (2, 4)	W1(P)	C2	PF1	1
(1, 1) (1, 2) (1, 3) (1, 4), (2, 1) (2, 2) (2, 3), (2, 4)	W3(H)	C2	PF1	1
(1, 1) (1, 2) (1, 3) (1, 4), (2, 1) (2, 2) (2, 3), (2, 4)	W4(H)	C1	PF1	1
(1, 2) (1, 4)	W4(H)	C2	PF1	1
(1, 1) (1, 2) (1, 3) (1, 4), (2, 1) (2, 2) (2, 3), (2, 4)	W1(P)	C1	PF2	2
(1, 3), (2, 1) (2, 4)	W1(P)	C2	PF2	1

Table 14. Factory production plan

Plant	Finished product	Strategic period	Tactical period			
			1	2	3	4
I1	PF1	1	1823	1723	226	1923
I1	PF2	1	570	2541	2141	265
I2	PF1	1	1908	1808	2392	2008
I2	PF2	1	2573	1335	2573	2573
I1	PF1	2	654	754	2251	554
I1	PF2	2	2089	118	518	2394
I2	PF1	2	484	584	-	384
I2	PF2	2	-	1238	-	-

Table 14 shows the production plan of the calculation example during the entire planning period. From the table, we can see that factory 2 stopped producing PF1 in strategic period 2 and tactical period 3, and factory2 stopped producing PF2 in strategic period 2 and tactical period 1,3,4.In other strategic and tactical periods, the factory has been in production.

Table 15. Factory and warehouse openning plan

Strategic period	Plant		Warehouse			
	I1	I2	WP1	WP2	WH1	WH2
1	✓	✓	✓	×	✓	✓
2	✓	✓	✓	×	✓	✓

Table 16. Facilities expansion options

Option	Strategic period (m=1)				Strategic period (m=2)			
	I1	I2	WP1	WP2	I1	I2	WP1	WP2
O1	×	×	×	×	×	×	×	×
O2	×	×	×	×	✓	✓	×	×

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Table 15 is the opening plan of the factories and warehouses. As can be seen from the table, only the second private warehouse was closed, while the other factories and warehouses remained open throughout the planning period. Table 16 shows expansion plans for factories and private warehouses. According to the table, we can see that only the second factory chooses to expand the capacity, and the factory chooses the second option for capacity expansion.

Table 17. Warehouse storage plan

Warehouse	Product	Strategic period	Tactical period 1	2	3	4
WP1	P1	1	445	491	-	437
WP1	P1	2	-	-	1034	-

Table 17 is the storage plan of the warehouse. As shown in the table, the products will be stored in the first private warehouse during the planning period. Products will not be stored in the third quarter of the first year and the first, second and fourth quarters of the second year. .The product PF1 is stored in the first, second, and fourth quarters of the first year and the third quarter of the second year, and the largest amount of products stored in the third quarter of the second year.

Table 18. Distribution plan

Origin	Destination	(Strategic period, Tactical period) (1, 1)	(1, 2)	(1, 3)	(1, 4)	(2, 1)	(2, 2)	(2, 3)	(2, 4)
Supplier1	Plant1	4954	4954	4954	4954	3229	5200	4800	2924
	Plant2	4784	4784	4784	4784	5146	3908	5146	5146
Supplier2	Plant1	4300	4200	2703	4400	5318	5318	5318	5318
	Plant2	4300	4200	4784	4400	5146	5146	5146	5146
Plant1	WP1	654	754	2251	554	2089	118	518	2394
	WP2	-	-	-	-	-	-	-	-
	WH1	1677	1723	226	1923	570	1880	1849	265
	WH2	146	-	-	-	-	661	292	-
Plant2	WP1	929	630	786	454	821	1238	1034	655
	WP2	-	-	-	-	-	-	-	-
	WH1	-	-	-	-	-	-	-	-
	WH2	1463	1762	1606	1571	1714	1335	1539	1918
WP1	C1	1138	1338	1947	938	1976	1356	518	1864
	C2	-	-	1581	-	1409	-	-	2219
WP2	C1	-	-	-	-	-	-	-	-
	C2	-	-	-	-	-	-	-	-
WH1	C1	-	-	-	-	-	-	-	-
	C2	1677	1723	226	1923	570	1880	1849	265
WH2	C1	1609	1623	1606	1554	1714	1996	1831	1918
	C2	-	139	-	17	-	-	-	-

Table 18 is the distribution plan of the product. According to the table, during the planning period, both suppliers have raw materials shipped to two factories. Products from factory 1 are shipped to WP1, WH1, WH2, and products from factory 2 are shipped to WP1 and WH2. WP1 and WH2 serve customer C1. WP1, WH1, WH2 serve customer C2. Since the private warehouse 2 (WP2) is not opened, there is no product flow between WP2 and the factory and customers.

5.2 Numerical Analysis

In order to evaluate the performance of the model, we divided the problems into three categories: large, medium, and small, and conducted group experiments. There are a total of 8 (p1-p8) groups in the experiment, of which three small experiments (S) were carried out, namely p1, p2, p3, and the

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medium experiments (M) were carried out in three groups, namely p4, p5, p6, and large experiments. (L) Two groups were conducted, p7 and p8 respectively. These examples are solved using CPLEX software, which runs on an eight-core 2.10GHz processor with 8GB of RAM. The strategic period of the experiment we designed is five years, and each strategic period has four tactical periods, representing the four quarters of each year. Detailed experimental data settings are shown in Table 19 and Table 20.

Table 19. Experimental data

Class	Problem	Strategic period	Tactical period	Supplier	Plant	Customer	product	Option
S	P1	5	4	2	2	2	2	2
	P2	5	4	3	3	4	2	2
	P3	5	4	5	4	6	2	2
M	P4	5	4	7	5	10	3	3
	P5	5	4	9	6	12	3	3
	P6	5	4	10	7	14	3	3
L	P7	5	4	16	10	22	3	3
	P8	5	4	18	10	26	3	3

Table 20. Experimental data

warehouse		Raw material	product	Trans mode	Investment in each strategic period				
private	hire				1	2	3	4	5
2	1	2	2	2	10000	8000	10000	8000	8000
2	1	2	2	2	10000	8000	10000	8000	8000
2	2	2	2	2	10000	8000	10000	8000	8000
3	2	3	3	2	10000	20000	10000	20000	10000
3	3	3	3	2	10000	20000	10000	20000	10000
4	3	3	3	2	10000	20000	10000	20000	10000
6	4	3	3	2	10000	20000	10000	20000	10000
7	3	3	3	2	10000	20000	10000	20000	10000

We conducted a total of eight sets of experiments. During the entire experiment, we recorded the solution time, optimal gap, and the number of variables and constraints for each set of experiments, and we set the upper limit of the experimental solution time to 2 hours. The optimal gap refers to the gap between the best feasible solution and the optimal solution, and is used to evaluate the quality of the CPLEX solver. The specific formula is as follows:

$$\text{Gap}=\frac{\text{Best Possible Solution-Final Solution}}{\text{Best Possible Solution}}\times 100\%$$

Table 21. Computational results for instances

Class	Problem	Variable	Binary variable	Integer variable	Other variable	constraint	CPU(s)	GAP(%)
S	P1	4521	1425	1480	1616	6020	0.56	0.00
	P2	9096	2840	2640	3616	11655	1.34	0.00
	P3	19036	5900	5120	8016	23610	11.66	0.03
M	P4	48206	13390	13800	21016	56600	62.95	0.01
	P5	72751	20175	20160	32416	84625	426.56	0.01
	P6	95211	26315	26880	42016	109875	683.91	0.01
L	P7	208916	57700	55200	96016	239240	6126.22	0.01
	P8	237051	65435	63600	108016	270665	>2h	NFS

Table 21 is the calculation result of the case,According to the table, we can see that the small-scale experiment solution time is small, the minimum is 0.56s, and the optimal gap is 0. That is to say, it is relatively easy for us to find the optimal solution for the small-scale data.The minimum solution time of the medium-sized experiment is 62.95s, the maximum solution time is 683.91s, and the optimal

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gap is controlled at 0.01%. This shows that the quality of the CPLEX solver in the medium-sized experiment is very high, and it can almost be considered as the optimal solution. The solution time of the first set of data of the large-scale experiment is 6162.22s, and the optimal gap is 0.01%. Although the solution time of the second set of data is more than two hours, the optimal gap has been reduced to 1.60% at the 916.50 second, and the optimal gap is reduced to 1.60% in the 7200th. The optimal gap in seconds is 0.1%, which is very close to the optimal solution and meets the solution requirements, indicating that CPLEX can find relatively high-quality solutions for large-scale experiments.

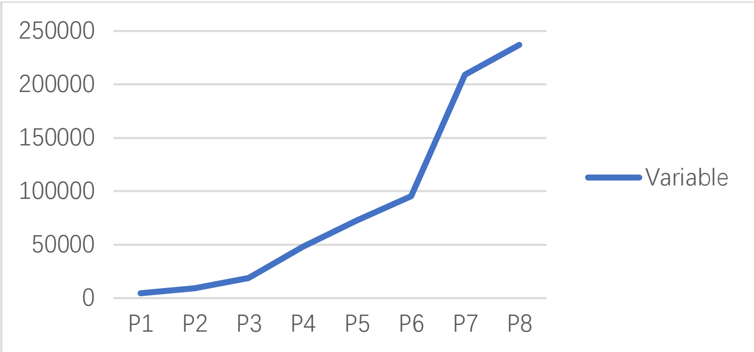

Fig. 2 Increasing trend of variables

Figure 2 shows the change in the number of variables in each tactical period during the experiment. From the figure, we can see that as the experimental data becomes larger, the total amount of variables also increases.

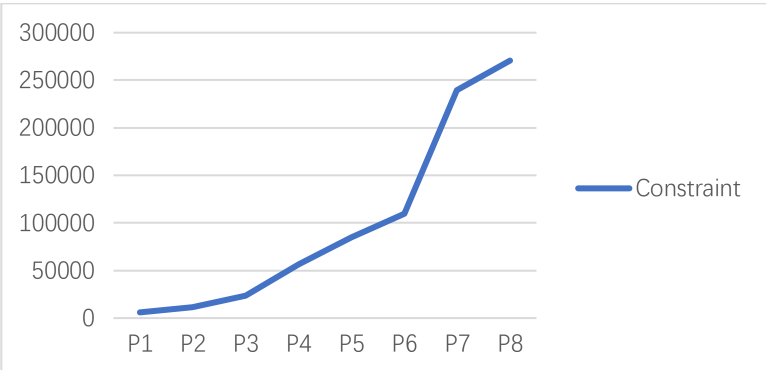

Fig. 3 Trend of the total number of constraints

Figure 3 shows the change in the total amount of constraint conditions. Through this figure, we can see that as the experimental data becomes larger, the number of constraint conditions is also increasing.

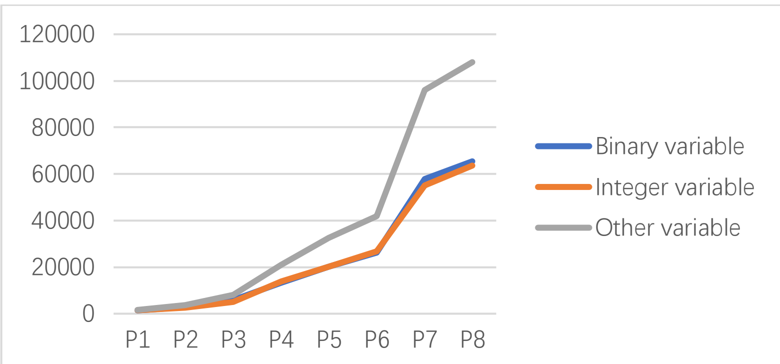

Fig. 4 Trend of various variables

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Figure 4 shows the changing trends of integer variables, binary variables, and other variables during the experiment. From the figure, we can see that the changing trends of integer variables and binary variables are very close, and the two broken lines almost coincide. On the whole, the number of each variable in the experiment shows an upward trend as the data becomes larger.

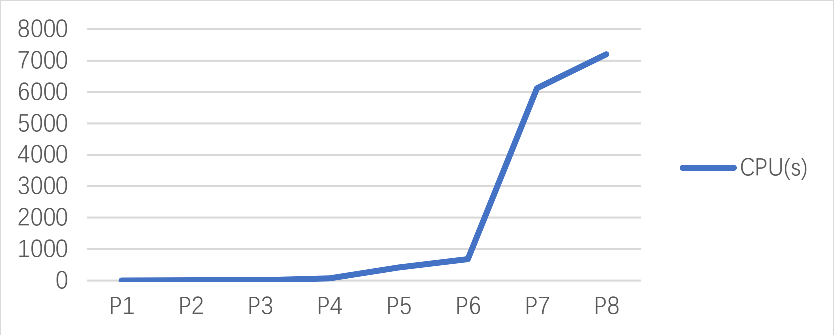

Fig. 5 Trend of CPU time

Figure 5 shows the trend of the experimental solution time. Through this figure, we can see that as the data becomes larger, the constraints and the number of variables are also increasing, and the solution time becomes longer and longer. It shows that the larger the data, the longer the solution time.

6. Conclusions

Considering the two time resolutions of strategic planning and tactical planning, this paper proposes a multi-period dynamic four-level supply chain network model that considers supplier quantity discounts, transportation methods, and carbon emissions.The proposed model includes not only the location of factories and warehouses, but also the expansion of factories and warehouses. In order to be more realistic, we limit the source of expenses for factory and warehouse expansion to accumulated net income.

The model in this paper makes decisions on the selection of suppliers, the location of factories and warehouses, the amount of product transportation between various locations, and the choice of transportation methods.These decisions are made on the basis of considering both strategic planning and tactical planning, because strategic planning and tactical planning are inseparable. We also design strategic planning and tactical planning in different time dimensions, taking into account the consistency of decision level and time.For example, the starting and closing of factories and warehouses are strategic planning, which develops and changes in the time unit of year, while suppliers may change once every quarter due to the change of discount. Therefore, it is more practical to deal with strategic planning and tactical planning in different time units respectively. In addition, considering strategic planning and tactical planning in different time dimensions is conducive to company decision-makers to make high-quality decisions.

In this paper, a small hypothetical example is used to illustrate the application of the model, and small, medium and large scale examples are designed to analyze and evaluate the solution time.Through experiments, we found that for small and medium-sized examples, the CPU time of the model is small, and some of them can obtain the optimal solution. But as the data keeps getting bigger, the CPU time keeps increasing, especially for large-scale cases, the CPU time exceeds two hours. Although the solution time for large cases is longer, the quality of the solution is relatively high.

There are still many incomplete considerations in the article. For the model proposed in this article, we can also consider constructing a more realistic transportation cost function to reduce transportation costs. You can also consider the choice of different production technologies in the production process to reduce production costs and improve model.In addition, for the solving time of large-scale problems, we can consider developing some heuristic algorithms to solve them. This is the next problem to be studied.

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Appendix

Parameters	Data
IR	0.05
TR	0.25
SH	0.30
$R_{s,pr}^{m,n}$	$Interger\ U(10000{,}20000)$
$MO_{s,p}$	500
MK_i	$Interger\ U(500{,}1000)$
NK_i	$Interger\ U(1000{,}1500)$
MU_i	0.1
NU_i	0.9
$D_{c,pf}^{m,n}$	$Interger\ U(2000{,}4000)$
$B_{pr,pf}$	$Interger\ U(1{,}3)$
$WL_{pf,i}$	$Interger\ U(1{,}4)$
V_{pf}	$Interger\ U(1{,}3)$
CK_o	$Interger\ U(200{,}500)$
$A_{i,j}$	$Interger\ U(10{,}15)$
PR_{pf}	$Interger\ U(80{,}100)$
CO_i	$Interger\ U(1000{,}2000)$
$CA_{i,o}$	$Interger\ U(1000{,}1500)$
CU_i	$Interger\ U(1000{,}1500)$
$COP_{i,o}$	$Interger\ U(100{,}300)$
$CP_{pf,i}$	$Interger\ U(10{,}20)$
$CS_{pf,j}$	$Interger\ U(2{,}10)$
$CSP_{pr,s,i}^{tr}$	$Interger\ U(1{,}3)$
$CPW_{pf,i,j}^{tr}$	$Interger\ U(1{,}3)$
$CWC_{pf,j,c}^{tr}$	$Interger\ U(1{,}3)$
M1	1000000
M2	1000000
M3	20000
$PC_{pf,i}$	$Interger\ U(1{,}3)$
$TC_{p,tr}$	$Interger\ U(1{,}3)$
MC	1
MCP	1000000
MCT	1000000

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