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RESEARCH ARTICLE

A location-inventory-routing model for green supply chains with low-carbon emissions under uncertainty

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Abstract
The location-inventory-routing modeling is an integrated and comprehensive approach to the interconnected location planning, inventory management, and vehicle routing problems in supply chain management. Supplier selection and order allocation are critical operational and strategic decisions in green supply chains. Green supply chain management is an environmental approach to sourcing and production that considers sustainability in every supply chain stage. In this study, a novel bi-objective mixed-integer linear programming model is formulated to solve the location-inventory-routing problems in green supply chains with low-carbon emissions under uncertainty. The proposed model is used for supplier selection and order allocation by considering the location priorities, heterogeneous vehicle routing, storage needs, uncertain demand, and backorder shortage. The formulated bi-objective model is solved with a weighted fuzzy multi-objective solution approach coupled with a novel intelligent simulation algorithm to ensure the feasibility of the solution space. We generate and solve different-sized problems to demonstrate the applicability and efficacy of the proposed model.

Keywords Location-inventory-routing · Green supply chain · Low-carbon emission · Mixed-integer linear programming · Fuzzy set theory

Introduction

Supply chain network design is a systematic approach to determining the best combination of facilities, suppliers, and products using mathematical modeling. Supply chain network optimization refers to designing a supply chain network with maximum efficiency (Fathollahi-Fard et al. 2020; Mardan et al. 2019; Sahebjamnia et al. 2018). A supply chain network optimization allows companies to study their supply chain's performance with "what-if" scenarios and develop operational plans based on sound metrics (Karampour et al. 2020; Hajiaghaei-Keshteli et al. 2018). The concept of supply chain efficiency varies according to the decision-makers' belief systems and their modeling preferences (Govindan et al. 2020; Hajiaghaei-Keshteli and Fard 2019; Fathollahi-Fard et al. 2018). Supply chain efficiency in the literature has been studied from different perspectives. Some selected studies stress the importance of cost minimization (Iqbal et al. 2020; Tamannaei and Rasti-Barzoki 2019; Savadkoohi et al. 2018), and some promote the importance of profit maximization (Amin et al. 2017). However, the majority of the studies consider multiple objectives for performance evaluation and efficiency measurement in supply chains (Goodarzian et al. 2020; Mahjoub et al. 2020; Mohammed et al. 2019). Zandkarimkhani et al. (2020) minimized total costs and lost demands simultaneously while maximizing supply chain efficiency. Mardan et al. (2019) minimized the total cost and

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environmental emissions for optimizing the efficiency of the supply chain. Some researchers have considered optimizing the economic, environmental, and social dimensions for this purpose (Zheng et al. 2020; Govindan et al. 2019; Rahimi et al. 2019). The first step in designing an efficient supply chain network is to consider supplier selection and order allocation since suppliers lie at the highest level of the chain and are strongly effective in the supply chain's performance downstream (Kannan et al. 2020; Feng et al. 2019; Safaeian et al. 2019). Distribution planning is another important point in designing an efficient supply chain network (Rastegar et al. 2021; Hsiao et al. 2017). A review of the related literature indicates that there are various types of distribution planning problems. In general, a distribution planning problem can be divided into three categories: distribution allocation, location-allocation, and vehicle routing problems. Combining these problems with other supply chain problems can lead to the emergence of new and applied concepts in the supply chain and pave the way for solving real-world problems. For example, the location-routing problem is an operational-strategic problem that results from combining vehicle routing and location problems in various chains, such as hazardous waste management (Rabbani et al. 2018), healthcare (Veenstra et al. 2018), and plastic (Qazvini et al. 2019). In addition, the integration of location-routing problems into inventory control problems is another problem that has received increasing attention in the literature (Gholipour et al. 2020; Saif-Eddine et al. 2019; Rafie-Majd et al. 2018).

This study's primary goal is to efficiently and effectively solve the location-inventory-routing problems in green supply chains with low-carbon emissions under uncertainty. This goal is accomplished by formulating and solving a bi-objective model with a weighted fuzzy multi-objective solution approach and a novel intelligent simulation algorithm to ensure the solution space's feasibility. The location priorities, heterogeneous vehicle routing, storage needs, uncertain demand, and backorder shortage are considered in different-sized problems to demonstrate the proposed model's applicability and efficacy. The remainder of this paper is organized as follows. Section 2 presents a relevant review of the literature followed by the proposed mathematical model in Section 3. The solution approach and experimental results are presented in Sections 4 and 5, respectively. We apply a real-life problem in Section 6 to demonstrate the applicability and exhibit the efficacy of the propped approach. Sections 7 and 8 are devoted to sensitivity analysis and managerial implications, respectively. Finally, the conclusion is presented in Section 9.

Literature review

The location-inventory-routing modeling is a comprehensive approach to the interconnected supply chain problems in location planning, inventory management, and vehicle routing. Hiassat et al. (2017) presented an integrated location-inventory-routing model to design a supply chain network for perishable products where they used the genetic algorithm to solve their proposed problem. Rafie-Majd et al. (2018) proposed an integrated location-inventory-routing model under uncertainty to design a multi-product multi-period supply chain for perishable products. They used the Lagrangian relaxation algorithm to solve this problem. Tavana et al. (2018) and Vahdani et al. (2018) utilized the location-inventory-routing problem in designing a humanitarian supply chain network. Mixed-integer nonlinear programming (MINLP) model was developed by considering the location-inventory-routing problem for the food supply chain networks (Saragih et al. 2019). They proposed a meta-heuristic algorithm based on simulated annealing to solve large-scale problems. Yavari et al. (2020) developed a resilient supply chain network for perishable products using an MINLP model and integrated location-inventory-routing problems and disruptions in routes. Their model aimed at maximizing the supply chain profit where a meta-heuristic-based genetic algorithm was used to solve the intended problem.

A multi-objective mixed-integer linear programming (MILP) model for designing a sustainable supply chain network for perishable products was developed by Biuki et al. (2020). Considering the location-inventory-routing problem, they proposed a model to minimize total costs, minimize the destructive environmental effects, and maximize job creation. Some of these studies have gone one step further and considered fuel consumption by vehicles and the resulting pollution in the location-inventory-routing problem. In this regard, Zhalechian et al. (2016) developed a multi-objective model for designing a sustainable closed-loop supply chain by considering the location-inventory-routing problem and fuel consumption under uncertainty. Moreover, an MILP model for designing a green supply chain was presented by Qazvini et al. (2016). They used the concepts of storage and shortage to consider the inventory problem in their model. Their network design also considered the location-routing problem and fuel consumption. Asadi et al. (2018) proposed a stochastic model for designing a biofuel supply chain by considering the location-inventory-routing problem. The purpose of their model was the simultaneous minimization of total costs and CO_2 emissions. They used meta-heuristic algorithms to solve their problem and evaluated their proposed model and algorithms' performance using the algae biofuel chain data. A bi-objective MILP model for green supply chain network design was also suggested by Gholipour et al. (2020). Their model deals with the location of centers, vehicle routing, and inventory control where vehicles' fuel consumption has also been considered in the form of cost in the cost objective function. They benefited from a fuzzy solution to solve their proposed model. Using a bi-objective MILP model, Zandkarimkhani et al. (2020) designed a green supply chain for perishable pharmaceuticals by considering the location-inventory-routing problem under uncertainty. They developed a novel fuzzy goal programming approach to solve multi-objective models under uncertainty. Finally, they validated their proposed model and solution approach using the data of an Avonex prefilled syringe distribution chain.

Kaya and Ozkok (2020) designed a supply chain network for blood distribution using an MINLP model. They studied an integrated location-inventory-routing problem and proposed a novel heuristic for minimizing the overall supply chain costs. Nasr et al. (2021) developed a multi-objective MILP model in a sustainable closed-loop supply chain network by considering a location-inventory-routing problem under uncertainty. Their model aimed to minimize total costs, undesired environmental effects, and lost demands and maximize job opportunities and sustainable supplier purchases. For this purpose, they used a fuzzy goal programming approach to solve their proposed multi-objective model. Yuchi et al. (2021) proposed an MINLP model to design a closed-loop supply chain by considering the location-inventory-routing problem. They considered the amounts of demand and returned products to be uncertain, while their model aimed at minimizing the total supply chain costs. An MINLP model was formulated by Wu et al. (2021) for a supply chain network by considering the location-inventory-routing problem, time window, and fuel consumption. A hybrid meta-heuristic algorithm was used to solve their proposed model.

The development of a supply chain network while considering supplier selection and order allocation and the location-inventory-routing problem with low-carbon emissions reduces harmful environmental effects and cost reduction. This study develops a bi-objective MILP model to design a multi-product, multi-period green supply chain network by considering centers location, heterogeneous vehicle routing problem, backorder shortage, storage for future periods, and uncertain demand. The contributions of this study are fourfold. We (1) develop an MILP model by considering the pollution in integrated location-inventory-routing problems with supplier selection, order allocation, backorder shortage, and storage need under uncertain demand; (2) develop an intelligent simulation algorithm for data generation with the feasible solution space; (3) apply a weighted fuzzy multi-objective solution approach to solve the proposed bi-objective model; and (4) validate the applicability of proposed model using a real-life problem in the automotive parts distribution industry.

Proposed model

This study introduces a multi-objective MILP model for designing a supply chain network with distribution center locations, green vehicle routing, inventory control, supplier selection, and order allocation. The proposed supply chain is a multi-product, multi-period, and multi-echelon network with supply, distribution, and customer levels. A mathematical model considers the supplier scores, purchase price, ordering costs, supplier capacity, and order allocation. The purchased products from suppliers are first shipped to the distribution centers and, then, to the customers using an optimal routing (see Fig. 1). The possibility of storage in distribution centers and shortages have also been considered in the proposed model.

The assumptions considered in the proposed model include

- The possibility of facing a backorder shortage,
- The possibility of storage in the distribution centers for future periods,
- Known locations for the suppliers and customers,
- Unknown locations for the distribution centers,
- Routing between the distribution centers and customers,
- Customer 1 ($a = 1$) is identified as a distribution center,
- Multi-depot type routing problem,
- Heterogeneous and capacitated vehicles,
- Capacitated distribution centers and suppliers,
- Possibility of split-delivery to customers,
- Uncertain demand, and
- Performance evaluation scores for suppliers.

Mathematical model

Indices

i	Supplier
j	Potential distribution center
a, b	Customer
f	Vehicles
m	Product
t	Time period

Parameters

FS_i	The score obtained from performance evaluation for supplier i
ϑ_{mit}^{CP}	The capacity of supplier i for supplying product m in time period t
ϑ_{it}^{FX}	Ordering cost to supplier i in time period t
ϑ_{mit}^{PR}	Purchasing cost of per unit of product m from supplier i in time period t
η_{mjt}^{CP}	The capacity of distribution center j for product m in time period t
η_{j}^{FX}	Establishing the cost of distribution center j

η_{mjt}^{VC}	The processing cost of per unit of product m in distribution center j in period t
η_{mjt}^{HL}	Holding cost of per unit of product m in the distribution center j's warehouse in period t
η_{mjt}^{SH}	Backorder penalty cost per unit of product m in distribution center j in period t
β_f^{CP}	The capacity of vehicle f
β_f^{FX}	Supplying cost of vehicle f
β_f^{FC}	Fuel consumed by vehicle f for per kilometer
ξ_{ja}^{DS}	Distance between distribution center j and customer a
ξ_{ab}^{CS}	Distance between customer a and customer b
ξ_{mat}^{L}	Pessimistic demand of customer a for product m in period t
ξ_{mat}^{U}	Optimistic demand of customer a for product m in period t
ξ_{mat}^{M}	Most possible demand of customer a for product m in period t
μ_{mijt}	Transportation cost of per unit of product m from supplier i to distribution center j in period t
ϖ_m	The volume/weight of product m
β^{FP}	The cost per unit of fuel
BM	A big number

Variables

$\vartheta X_{mit}\begin{cases}1\\0\end{cases}$	If supplier i is selected to purchasing product m in period t Otherwise
$\eta X_j\begin{cases}1\\0\end{cases}$	If distribution center j is established Otherwise
$\beta X_f\begin{cases}1\\0\end{cases}$	If vehicle f is supplied Otherwise
$\beta Y_{fj}\begin{cases}1\\0\end{cases}$	If vehicle f is allocated to the distribution center j Otherwise
$\beta Z_{fabt}\begin{cases}1\\0\end{cases}$	If vehicle f moves from the customer a to customer b in period t Otherwise
$\vartheta\eta_{mijt}$	The amount of product m purchased from supplier i by distribution center j in period t
$\eta\xi_{mjfat}$	The amount of product m shipped from distribution center j to the customer a by vehicle f in period t
ξX_{mjt}	The amount of product m stored in the distribution center j's warehouse in period t
ξY_{mjt}	Amount of facing a shortage for product m in distribution center j in period t
ξZ_{mjt}	Inventory level for product m in the distribution center j's warehouse in period t
θ_{mfat}	Amount of product m in the vehicle f when leaving the location of customer a in period t

Objective functions

$$
\begin{aligned}
Min\ Z_1 = {} & \sum_{m,i,t}\vartheta_{it}^{FX}\times\vartheta X_{mit}+\sum_{m,i,j,t}\vartheta_{mit}^{PR}\times\vartheta\eta_{mijt}+\sum_j\eta_j^{FX}\times\eta X_j \\
& +\sum_{m,j,f,a,t}\eta_{mjt}^{VC}\times\eta\xi_{mjfat}+\sum_{m,j,t}\eta_{mjt}^{HL}\times\xi X_{mjt}+\sum_{m,j,t}\eta_{mjt}^{SH}\times\xi Y_{mjt} \\
& +\sum_f\beta_f^{FX}\times\beta X_f+\sum_{m,i,j,t}\mu_{mijt}\times\vartheta\eta_{mijt}+\beta^{FP}\times\sum_{f,a>1,b>1,t}\beta_f^{FC} \\
& \times\xi_{ab}^{CS}\times\beta Z_{fabt}+\beta^{FP}\times\sum_{f,j,a>1,t}\beta_f^{FC}\times\xi_{ja}^{DS}\times\beta Y_{fj} \\
& \times\left(\beta Z_{f1at}+\beta Z_{fa1t}\right)
\end{aligned}
\tag{1}
$$

$$Max Z_2=\sum_{m,i,j,t}FS_i\times\vartheta\eta_{mijt} \tag{2}$$

s.t.

$$\xi Z_{mjt}=\xi Z_{mj(t-1)}+\sum_i\vartheta\eta_{mijt}-\sum_{f,a}\eta\xi_{mjfat} \qquad \forall m,j,t>1 \tag{3}$$

$$\xi Z_{mjt}=\sum_i\vartheta\eta_{mijt}-\sum_{f,a}\eta\xi_{mjfat} \qquad \forall m,j,t=1 \tag{4}$$

$$\xi Z_{mjt}=\xi X_{mjt}-\xi Y_{mjt} \qquad \forall m,j,t \tag{5}$$

$$\sum_{j,f,t}\eta\xi_{mjfat}=\sum_t\left(\frac{\xi_{mat}^L+4\times\xi_{mat}^M+\xi_{mat}^U}{6}\right) \qquad \forall m,a \tag{6}$$

$$\sum_j\vartheta\eta_{mijt}\le\vartheta_{mit}^{CP} \qquad \forall m,i,t \tag{7}$$

$$\sum_{f,a}\eta\xi_{mjfat}\le\eta_{mjt}^{CP} \qquad \forall m,j,t \tag{8}$$

$$\sum_{m,a}\eta\xi_{mjfat}\times\varpi_m\le\beta_f^{CP} \qquad \forall j,f,t \tag{9}$$

$$\sum_a\beta Z_{fabt}=\sum_a\beta Z_{fbat} \qquad \forall f,b,t \tag{10}$$

$$\sum_a\beta Z_{fabt}\le 1 \qquad \forall f,b,t \tag{11}$$

$$\eta\xi_{mjfat}\le BM\times\beta X_f \qquad \forall m,j,f,a,t \tag{12}$$

$$\eta\xi_{mjfat}\le BM\times\beta Y_{fj} \qquad \forall m,j,f,a,t \tag{13}$$

$$\eta\xi_{mjfbt}\le BM\times\sum_a\beta Z_{fabt} \qquad \forall m,j,f,b,t \tag{14}$$

$$\sum_j\beta Y_{fj}\le 1 \qquad \forall f \tag{15}$$

$$\vartheta\eta_{mijt}\le BM\times\vartheta X_{mit} \qquad \forall m,i,j,t \tag{16}$$

$$\vartheta\eta_{mijt}\le BM\times\eta X_j \qquad \forall m,i,j,t \tag{17}$$

$$\eta\xi_{mjfat}\le BM\times\eta X_j \qquad \forall m,j,f,a,t \tag{18}$$

$$\sum_f\beta Y_{fj}\le BM\times\eta X_j \qquad \forall j \tag{19}$$

$$\theta_{mfat}+BM\times\left(1-\beta Z_{fabt}\right)\ge\theta_{mfbt}+\eta\xi_{mjfbt} \qquad \forall m,j,f,a,b>1,t \tag{20}$$

$$\theta_{mf1t}\ge\sum_{a>1}\eta\xi_{mjfat} \qquad \forall m,j,f,t \tag{21}$$

The first objective function minimizes total costs. These costs include ordering cost to suppliers, purchasing cost of products from suppliers, the cost of establishing distribution centers, the processing cost of products in distribution centers,

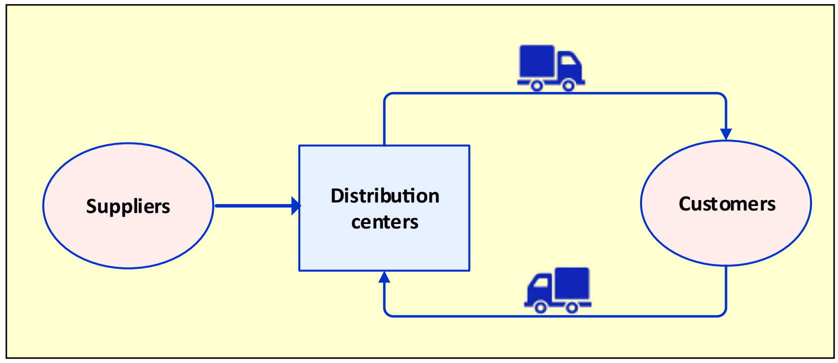


Fig. 1 The proposed supply chain network

holding cost of products in the distribution centers' warehouses, backorder penalty cost, the cost of supplying the vehicles, transportation cost, and fuel costs. The second objective function deals with maximizing orders from worthy suppliers.

Inventory balance in distribution centers' warehouses is handled by constraints (3) and (4). Constraint (3) establishes the inventory balance for the periods larger than one, and constraint (4) is used for the first period. The relationship between inventory level, storage amount, and shortage amount in each period is defined by constraint (5) for every product in the distribution centers' warehouses. Constraint (6) guarantees to satisfy the backorder demand. This constraint also states that the total delivery to each customer during all periods should be equal to that customer's total demand during all the periods. Not exceeding the suppliers' capacity, distribution centers, and vehicles is represented by constraints (7) to (9), respectively. One of the routing problem conditions is that if a vehicle enters a node, it should leave the node after service delivery. This condition for customers' zones is represented by constraint (10). Another condition in the routing problem is that each vehicle is allowed to visit a customer at most once in any period. This condition is also guaranteed by constraint (11). One of the conditions for product delivery to customers is that the vehicle has already been purchased. In other words, if the vehicle has not been purchased, that vehicle should not be used. Another condition for product delivery to customers is that the purchased vehicle has been assigned to a distribution center. In addition, the third condition for product delivery to customers is that the vehicle visits the customer. These conditions are given in constraints (12) to (14), respectively. Each purchased vehicle should be assigned to one and only one distribution center. This requirement is represented by constraint (15). If the supplier is not selected, it is not possible to purchase from that supplier. This condition is represented by constraint (16). Moreover, based on the location conditions, if a center has not been established, the product flow will not be possible. These conditions, which are related to distribution centers' location, have been considered in constraints (17) and (18). The condition for vehicle allocation to the distribution center is that the distribution center has already been established. Constraint (19) guarantees this condition. Finally, sub-tour elimination has been considered in constraints (20) and (21). These constraints calculate the number of products in the vehicle when leaving the customers' location.

Linearization process

In the first objective function, a nonlinear term has been obtained from the multiplication of two binary variables βY_{fj} and $\beta Z_{\boldsymbol{fabt}}$. The new binary variable of $\beta YZ_{\boldsymbol{fjabt}}$ is defined to linearize this term. This variable is replaced by the multiplication of the two mentioned variables, which is presented as follows:

$$\begin{aligned} Min\ Z_1 = & \sum_{m,i,t} \vartheta_{it}^{FX} \times \vartheta X_{mit} + \sum_{m,i,j,t} \vartheta_{mit}^{PR} \times \vartheta\eta_{mijt} + \sum_{j} \eta_j^{FX} \times \eta X_j \\ & + \sum_{m,j,f,a,t} \eta_{mjt}^{VC} \times \eta\xi_{mjfat} + \sum_{m,j,t} \eta_{mjt}^{HL} \times \xi X_{mjt} + \sum_{m,j,t} \eta_{mjt}^{SH} \times \xi Y_{mjt} \\ & + \sum_{f} \beta_f^{FX} \times \beta X_f + \sum_{m,i,j,t} \mu_{mijt} \times \vartheta\eta_{mijt} + \beta^{FP} \times \sum_{f,a>1,b>1,t} \beta_f^{FC} \\ & \times \xi_{ab}^{CS} \times \beta Z_{fabt} + \beta^{FP} \times \sum_{f,j,a>1,t} \beta_f^{FC} \times \xi_{ja}^{DS} \times \left(\beta YZ_{fj1at} + \beta YZ_{fja1t} \right) \end{aligned} \tag{22}$$

Now the relationship between the two variables and the new variable should be stated. If at least one of the variables is zero, the new variable should also be zero. If both variables have a value of one, the new variable should also take the value of one. These conditions have been guaranteed by using the following relations (Kargar et al. 2020).

$$\beta YZ_{\boldsymbol{fjabt}} - \beta Z_{\boldsymbol{fabt}} - \beta Y_{fj} + 1.5 \geq 0 \forall f, j, a, b, t \tag{23}$$

$$1.5 \beta YZ_{\boldsymbol{fjabt}} - \beta Y_{fj} - \beta Z_{\boldsymbol{fabt}} \leq 0 \forall f, j, a, b, t \tag{24}$$

Multi-objective solution approach

There are many methods for solving the multi-objective model, each of which is used according to the nature of the proposed model. The fuzzy theory approaches are among the most common and efficient methods used to solve multi-objective models under uncertainty. In this regard, the multi-objective solution approach proposed by Shaw et al. (2012) is used in this study. This approach is described as follows:

Step 1: In this step, the lower and upper bounds of objective functions are determined.

Step 2: In this step, the membership functions for the maximization and minimization objective functions are defined using Eqs. (25) and (26), respectively:

$$\mu_{Z_j}^{Max} = \frac{Z_j - Z_j^L}{Z_j^U - Z_j^L} \tag{25}$$

$$\mu_{Z_{j'}}^{Min} = \frac{Z_{j'}^U - Z_{j'}}{Z_{j'}^U - Z_{j'}^L} \tag{26}$$

where Z_j^U and Z_j^L represent the upper and lower bounds for the jth objective function, respectively.

Step 3: In this step, the proposed multi-objective model is converted into a single objective model using Eq. (27).

$$MaxZ^{FZ} = \sum_j w_j \times \lambda_j^{Max} + \sum_{j'} w'_{j'} \times \lambda_{j'}^{Min} \quad \lambda_j^{Max} \le \mu_{Z_j}^{Max} \quad \lambda_{j'}^{Min} \le \mu_{Z_{j'}}^{Min} \quad \sum_j w_j + \sum_{j'} w'_{j'} = 1 \quad \text{System Constraints} \tag{27}$$

Experimental results

The first step in validating the proposed model is data generation. For this purpose, the data will be generated in different sizes using an intelligent simulation pattern. The data simulation procedure is presented in the Appendix. For example, assume the user sets the values i=3, j=3, a=5, f=3, m=2, and t=3. In turn, the model parameters are simulated in proportion to the index values. Table 1 presents an example of the simulated values for the suppliers' capacity.

For instance, the value 8471 in the first row of Table 1 represents the capacity of supplier 1 to supply product 1 in period 1. Eight small and medium-size problems are generated using the pattern presented in the Appendix. The simulated problems are run in GAMS software. Small and medium problems are those that can be solved by GAMS software in less than 3000 s. The values of the indices for the simulated problems are presented in Table 2.

In the following section, the proposed multi-objective model is converted into a single objective one for the eight simulated problems using the multi-objective solution approach proposed by Shaw et al. (2012):

Step 1: In this step, a lower bound and upper bound is determined for the objective functions in each problem by optimizing each objective function independent of the other objective function. The process involves minimizing the first objective function and using the optimal solution as the lower-bound solution for this objective function while a feasible value is determined for the second objective function. This feasible value is considered the lower-bound solution for the second objective function. Similarly, we maximize the second objective function by using the optimal solution as the upper-bound solution for this objective, while a feasible value is determined for the first objective function. This feasible value is considered the upper-bound solution for the first objective function (Nurjanni et al. 2017). The upper bound and lower bound for the objective function in each problem are given in Table 3.

Step 2: In this step, the membership functions of the simulated problems are calculated using Eqs. (25) and (26). These membership functions are shown in Table 4.

Table 1 The simulated values for suppliers' capacity

ϑ_{mit}^{CP}		t		
m	i	1	2	3
1	1	8471	8629	7402
1	2	7555	8281	7443
1	3	8392	7256	7958
2	1	7076	7791	6917
2	2	6999	7522	7629
2	3	7967	7253	7441

Table 2 Sizes of simulated problems

Problem	i	j	a	f	m	t
1	2	2	3	2	1	2
2	2	2	4	2	2	2
3	3	3	5	2	2	2
4	3	3	5	3	2	3
5	3	3	6	3	3	3
6	4	4	6	3	3	3
7	4	4	6	4	3	4
8	4	4	7	4	4	4

Table 3 The lower and upper bounds of objective functions for each problem

Problem	Objective function 1		Objective function 2	
	Lower bound	Upper bound	Lower bound	Upper bound
1	1,049,829,653	1,773,849,679	8292.9	13,290.6
2	1,920,154,386	2,427,852,757	16,364.9	41,543.8
3	2,111,797,753	3,348,241,575	28,903	54,726.8
4	2,433,278,612	4,195,405,552	39,755.7	83,881.8
5	3,372,329,740	6,038,295,163	80,554.4	155,237.7
6	4,058,051,897	6,603,078,898	77,922.2	149,616.5
7	4,666,458,615	8,165,240,779	100462.1	205,903.9
8	6,101,824,196	11,166,989,324	163,762.2	321,954.6

Step 3: In this step, the proposed multi-objective model is converted into a single objective one using Eq. (27). For example, for $w_1 = 0.6$ and$w_2 = 0.4$, problem four is obtained as follows:

$$MaxZ^{FZ} = w_1 \times \lambda_1 + w_2 \times \lambda_2$$
$$\lambda_1 \leq \frac{4195405552 - Z_1}{1762126940}$$
$$\lambda_2 \leq \frac{Z_2 - 39755.7}{44126.1}$$
$$\text{Constraints}(2)\text{to}(24)$$

The optimal values of objective functions and decision variables are obtained by running the single objective model in GAMS software by CPLEX solver. Table 5 shows the optimal values of the objective functions for each of the simulated problems.

As shown in Table 5, the increase in the problem size leads to an increase in its runtime. In other words, as the size of the data increases, the three dimensions of velocity, variety, and volume increase simultaneously. This has a significant effect on the runtime of the problem. Parameters such as the score of suppliers, the capacity of distribution centers and suppliers, raw materials costs, the processing cost of products in the distribution centers, customer demand, holding costs, the penalty for the shortage of products, and shipping costs are effective in the velocity of big data. This problem includes six indices effective in the volume of big data and the number of products, vehicles, customers, distribution centers, suppliers, and periods that influence the variety of big data. Therefore, as the variety dimension increases, the velocity dimension grows dramatically. This means that the data volume grows and big data are generated. As discussed earlier, the volume of the generated data will directly affect the runtime of the proposed model.

Table 4 Membership functions of simulated problems

Problem	Membership function	
	Objective function 1	Objective function 2
1	$\frac{1773849679 - Z_1}{724020026}$	$\frac{Z_2 - 8292.9}{4997.7}$
2	$\frac{2427852757 - Z_1}{507698371}$	$\frac{Z_2 - 16364.9}{25178.9}$
3	$\frac{3348241575 - Z_1}{1236443822}$	$\frac{Z_2 - 28903}{25823.8}$
4	$\frac{4195405552 - Z_1}{1762126940}$	$\frac{Z_2 - 39755.7}{44126.1}$
5	$\frac{6038295163 - Z_1}{2665965423}$	$\frac{Z_2 - 80554.4}{74683.3}$
6	$\frac{6603078898 - Z_1}{2545027001}$	$\frac{Z_2 - 77922.2}{71694.3}$
7	$\frac{8165240779 - Z_1}{3498782164}$	$\frac{Z_2 - 100462.1}{105441.8}$
8	$\frac{11166989324 - Z_1}{5065165128}$	$\frac{Z_2 - 163762.2}{158192.4}$

Table 5 The optimal values of objective functions for each problem

Problem	Objective function 1	Objective function 2	Runtime
1	1,208,636,262	13,290.6	4.683
2	1,937,272,909	25,315.5	8.125
3	2,124,259,788	32,249.7	11.408
4	2,444,607,222	48,262.7	398.418
5	3,672,210,583	102,821.4	583.501
6	4,100,287,411	87,773.2	1024.637
7	4,710,106,354	117,691.7	1673.118
8	6,302,436,448	188,229.9	2461.951

Case study

In this section, the efficacy of the proposed method is studied at Hillman Automotive Parts. Hillman distributes cylinder heads, clutch housings, and water pumps, among others, for Pride and Peugeot. We considered four products for Peugeot 206, including cylinder head (product 1), clutch housing (product 2), valve cover (product 3), and water pump (product 4). We further considered three potential distribution centers operating in four periods; five potential suppliers; seven customers; and six vehicles, including two 3.5-ton, two 4-ton, and two 4.5-ton ISUZU trucks. Detailed case study data are provided through online resources.

We used the weighted fuzzy multi-objective approach presented by Shaw et al. (2012) to convert the multi-objective model into a single-objective model with $w_1 = 0.7$ and $w_2 = 0.3$:

$$MaxZ^{FZ} = 0.7 \times \lambda_1 + 0.3 \times \lambda_2$$
$$\lambda_1 \leq \frac{1796349 - Z_1}{1796349 - 1008683}$$
$$\lambda_2 \leq \frac{Z_2 - 9578.32}{10545.56 - 9578.32}$$
$$\text{Constraints}(2)\text{to}(24)$$

The GAMS software and CPLEX solver was used to run the model and obtain the optimal values of the objective functions and decision variables as follows:

- The value of the first objective function was equal to \$1,016,480, and the value of the second objective function was equal to 10,240.
- Product 1 was purchased from supplier 1, and products 2, 3, and 4 were purchased from supplier 2.
- Distribution center 3 was established.
- Vehicles 1, 5, and 6 were supplied.
- The order of customer visits by vehicles in each period is shown in Table 6.
- The number of products purchased from suppliers 1 and 2 by distribution center 3 in each period is presented in Table 7.

For example, 2384 in the first row of Table 7 represents the quantity of product 1 (cylinder head) purchased from supplier 1 in period 1 transferred to distribution center 3.

- The amount of products delivered to customers from distribution center 3 by vehicles 1, 5, and 6 in each period is reported in Table 8.

  For example, 17 in the first row of Table 8 indicates product 1 is delivered to customer 2 from distribution center 3 by vehicle 1 in period 1.
- The number of products stored in the warehouse at distribution center 3 in each period is reported in Table 9.

  As shown in Table 9, products 1 and 2 are stored in periods 1, 2, and 3. Similarly, products 3 and 4 are purchased in period 4, and the model has determined not to meet the demands for products 3 and 4 in periods 1 to 3 but to meet the total demand in period 4 (the past period).

Table 7 The number of products purchased from suppliers

$\vartheta\eta_{mijt}$			t	
m	i	j	1	4
1	1	3	2384	0
2	2	3	2856	0
3	2	3	0	4020
4	2	3	0	4496

Sensitivity analysis

In this section, the proposed model and solution approach's behavior is examined using scenarios based on changes in objective functions' coefficients. For this purpose, the coefficient of one objective function should increase, and the coefficient of another objective function should decrease simultaneously. It is expected that the value of the objective function does not deteriorate as its coefficient increases and that its value does not improve as its coefficient decreases. The results obtained from the sensitivity analysis using seven scenarios for problem four have been presented in Table 10. Moreover, the trend of changes in the first and second objective functions is depicted in Figs. 2 and 3, respectively. Similarly, the Pareto frontier obtained from the scenarios has been shown in Fig. 4.

According to the results, an increase in each objective function's coefficient does not worsen that objective function's value. Similarly, a reduction in the coefficient of each

Table 6 Order of visiting the customer

Vehicle	Time period	Order of visiting
f=1	t=1	$DC3 \rightarrow customer6 \rightarrow customer2 \rightarrow customer3 \rightarrow customer5 \rightarrow customer4 \rightarrow DC3$
	t=2	$DC3 \rightarrow customer2 \rightarrow customer3 \rightarrow customer4 \rightarrow customer6 \rightarrow customer7 \rightarrow DC3$
	t=3	$DC3 \rightarrow customer2 \rightarrow customer6 \rightarrow customer4 \rightarrow customer3 \rightarrow customer7 \rightarrow customer5 \rightarrow DC3$
	t=4	$DC3 \rightarrow customer3 \rightarrow customer5 \rightarrow customer7 \rightarrow customer6 \rightarrow customer2 \rightarrow DC3$
f=2	t=1	$DC3 \rightarrow customer3 \rightarrow customer6 \rightarrow customer7 \rightarrow customer5 \rightarrow customer4 \rightarrow customer2 \rightarrow DC3$
	t=2	$DC3 \rightarrow customer2 \rightarrow customer3 \rightarrow customer7 \rightarrow customer5 \rightarrow customer4 \rightarrow DC3$
	t=3	$DC3 \rightarrow customer2 \rightarrow customer6 \rightarrow customer7 \rightarrow customer4 \rightarrow customer5 \rightarrow DC3$
	t=4	$DC3 \rightarrow customer2 \rightarrow customer6 \rightarrow customer5 \rightarrow customer3 \rightarrow DC3$
f=3	t=1	$DC3 \rightarrow customer2 \rightarrow customer6 \rightarrow customer7 \rightarrow customer3 \rightarrow customer4 \rightarrow customer5 \rightarrow DC3$
	t=2	$DC3 \rightarrow customer3 \rightarrow customer5 \rightarrow customer4 \rightarrow customer6 \rightarrow DC3$
	t=3	$DC3 \rightarrow customer2 \rightarrow customer6 \rightarrow customer5 \rightarrow customer3 \rightarrow customer4 \rightarrow customer7 \rightarrow DC3$
	t=4	$DC3 \rightarrow customer2 \rightarrow customer7 \rightarrow customer6 \rightarrow customer3 \rightarrow customer4 \rightarrow customer5 \rightarrow DC3$

Table 8 The number of products delivered to customers by vehicles

$\eta\xi_{mjfat}$				t			
m	j	f	a	1	2	3	4
1	3	1	2	17	3	44	0
1	3	1	3	0	0	57	0
1	3	1	4	0	107	291	0
1	3	1	5	0	0	2	0
1	3	1	6	88	29	0	0
1	3	5	2	44	0	248	0
1	3	5	3	0	1	0	0
1	3	5	4	1	29	0	0
1	3	5	5	0	77	103	0
1	3	5	6	0	0	139	56
1	3	5	7	0	386	0	0
1	3	6	3	0	83	232	7
1	3	6	4	0	4	0	0
1	3	6	5	1	72	137	0
1	3	6	6	0	0	124	0
1	3	6	7	0	0	0	2
2	3	1	2	484	0	0	0
2	3	1	3	0	436	10	0
2	3	1	4	2	0	0	0
2	3	1	7	0	0	54	0
2	3	5	3	32	0	0	0
2	3	5	4	0	0	4	0
2	3	5	5	460	0	0	0
2	3	5	6	1	0	0	0
2	3	5	7	160	0	0	0
2	3	6	3	0	2	0	0
2	3	6	4	15	483	0	0
2	3	6	6	435	2	0	0
2	3	6	7	267	0	0	9
3	3	1	3	0	0	0	625
3	3	1	5	0	0	0	712
3	3	1	7	0	0	0	552
3	3	5	2	0	0	0	662
3	3	5	3	0	0	0	61
3	3	5	6	0	0	0	537
3	3	6	4	0	0	0	626
3	3	6	6	0	0	0	103
3	3	6	7	0	0	0	142
4	3	1	3	0	0	0	720
4	3	1	5	0	0	0	40
4	3	5	5	0	0	0	724
4	3	5	6	0	0	0	772
4	3	6	2	0	0	0	756
4	3	6	4	0	0	0	748
4	3	6	7	0	0	0	736

Table 9 The number of products stored in the warehouse at distribution center 3

ξX_{mjt}		t		
m	j	1	2	3
1	3	2233	1442	65
2	3	1000	77	9

objective function does not improve its value. Therefore, it can be argued that the proposed model and solution approach's behavior and performance are reasonable, and, thereby, the obtained results are confirmed.

Managerial insights

This study highlights the importance of integrating strategic and operational decisions in supply chain network design when considering environmental and economic factors. Suppliers constitute one of the most critical components of sustainable supply chains. Failure to strategically select suppliers can increase undesirable environmental effects and impose enormous costs on the chain. In addition, failure to consider operational factors such as facility location, vehicle routing, and inventory planning in the supply chain network design leads to increased costs and carbon emissions. This study aimed to improve the supply chain's strategic and operational plans while implementing practical and mathematically sound decisions within the network. Demand uncertainty can disrupt supply chain networks and lead to increased costs and emissions. In this research, the fuzzy set theory was used to govern uncertain demand and its adverse effects on the chain's performance. The model proposed in this study can be used as a decision support system to assist managers and make informed and effective decisions such as supplier selection, optimal purchasing, product flow, storage requirements, vehicle procurement, vehicle routing, and facilities location planning.

Table 10 Results obtained from the sensitivity analysis of coefficients of objective functions

Scenario	w_1	w_2	Objective function 1	Objective function 2
1	0.7	0.3	2,435,006,736	47,635.8
2	0.65	0.35	2,440,694,711	47,866.5
3 (Problem 4)	0.6	0.4	2,444,607,222	48,262.7
4	0.55	0.45	2,567,200,384	50,163.6
5	0.5	0.5	2,767,492,119	50,738.4
6	0.45	0.55	2,973,846,233	51,873.5
7	0.4	0.6	3,367,384,829	53,111.2

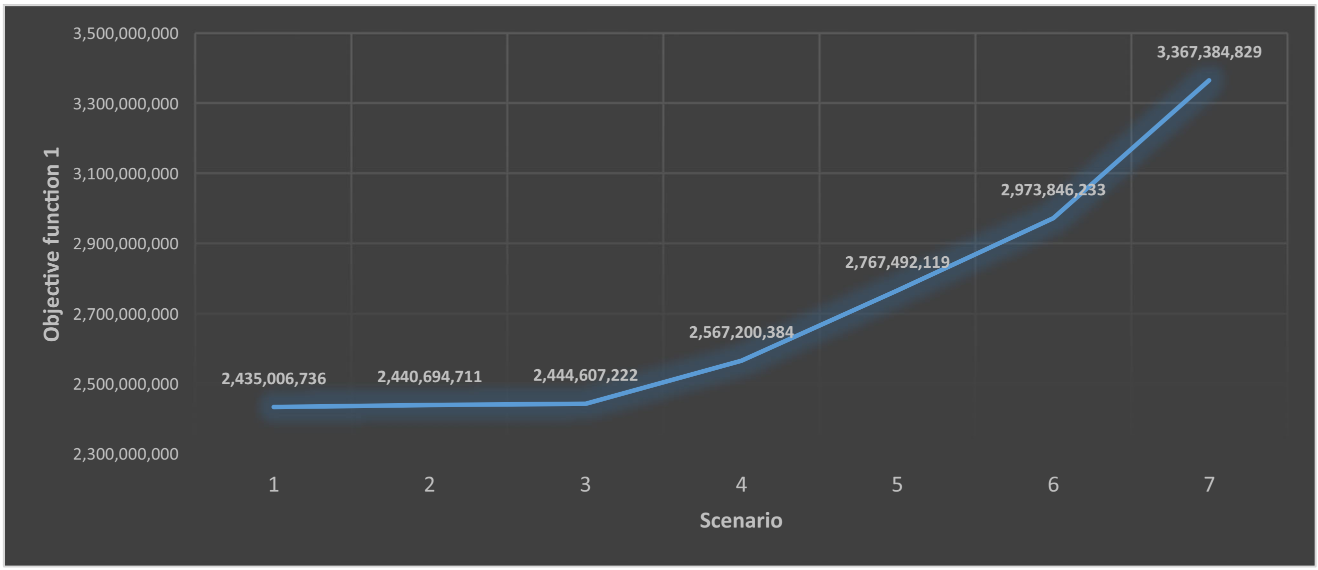


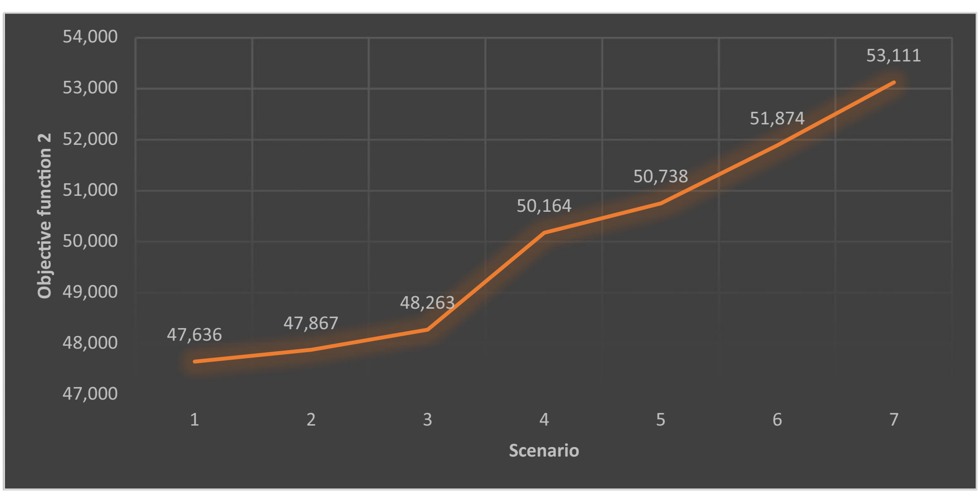
Fig. 2 Change trend of the objective function for different scenarios

Conclusion

This study presents a novel bi-objective MILP model for integrating strategic decisions (i.e., supplier selection, vehicle procurement, and location planning) and operational decisions (i.e., storage planning, vehicle routing, product flow management, and order allocation) in sustainable supply chains. The proposed model is designed to efficiently and effectively solve the location-inventory-routing problems in green supply chains with low-carbon emissions under uncertainty. A weighted fuzzy multi-objective solution approach is proposed to solve the bi-objective MILP problem formulated in this study. In addition, a simulation algorithm with feasible solution space is introduced for data generation. The performance and effectiveness of the proposed model were evaluated in the automotive industry using simulated problems. Finally, a sensitivity analysis with several scenarios was conducted to study the robustness of the models and the objective functions' behavior. The sensitivity analysis results confirmed the efficacy of the proposed model and the solution approach.

The supplier's score in this study is considered a predetermined parameter. We invite researchers to study this score in future research through multi-criteria decision-making approaches from economic, circularity, and social perspectives. The location-inventory-routing problem considered in this study is an NP-hard problem. We suggest developing an efficient meta-heuristic algorithm to solve large-size instances of this problem since GAMS software is incapable of solving them.

Fig. 3 Change trend of the second objective function for different scenarios



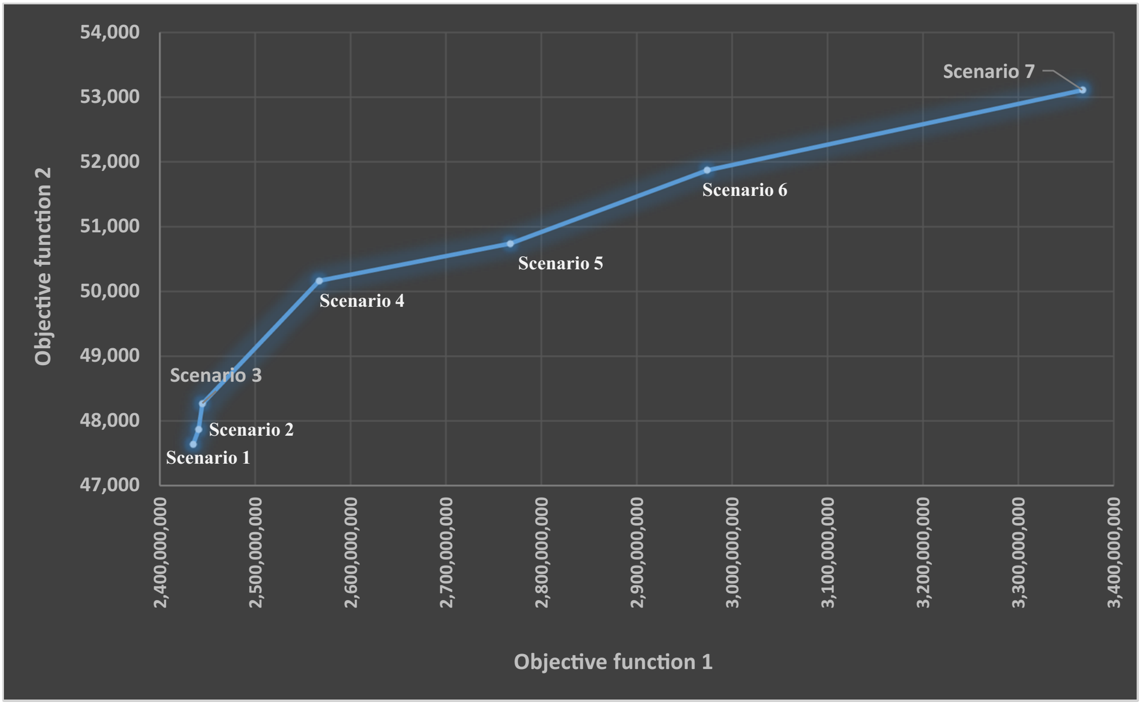


Fig. 4 Pareto frontier obtained from sensitivity analysis of coefficients of objective functions

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Authors' contributions M.T.: conceptualization; methodology; formal analysis; writing—original draft; writing—review and editing; visualization. H.T.: supervision; investigation; data curation. M.A.: investigation; validation; data curation. R.L.**:** investigation; data curation; software. H.M.: conceptualization; writing—review and editing; visualization.

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Declarations

Ethics approval Not applicable

Consent to participate Not applicable

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Declaration of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Data simulation model

Indices		
i	The user should determine the number of suppliers	
j	The user should determine the number of distribution centers	
a	The user should determine the number of customers	
f	The user should determine the number of vehicles	
m	The user should determine the number of products	
t	The user should determine the number of time periods	
Parameters		
FS_i	$Uniform(w,u)$	$w=0.4, u=0.8$
ξ_{mat}^{M}	$loop(m,$ $loop(a>1,$ $loop(t,$ $\xi_{mat}^{M} = Round(uniform(w,u));$ $);$ $);$ $);$	$w=2800, u=3000$
ξ_{mat}^{L}	$Round(Uniform(w,u)\times\xi_{mat}^{M})$	$w=0.9,\ u=0.95$
ξ_{mat}^{U}	$Round(Uniform(w,u)\times\xi_{mat}^{M})$	$w=1.05, u=1.1$
ϖ_m	$Uniform(w,u)$	$w=0.4, u=0.5$
ϑ_{mit}^{CP}	$Round(Uniform(w,u)\times\frac{\sum_{a}\xi_{mat}}{card(i)})$	$w=1.8, u=2.2$
ϑ_{it}^{FX}	$Round(Uniform(w,u))$	$w=5\times10^{6}, u=6\times10^{6}$
ϑ_{mit}^{PR}	$Round(Uniform(w,u))$	$w=1.25\times10^{4}, u=1.35\times10^{4}$
η_{mjt}^{CP}	$Round(Uniform(w,u)\times\frac{\sum_{a}\xi_{mat}}{card(j)})$	$w=1.8, u=2.2$
η_{j}^{FX}	$Round(Uniform(w,u))$	$w=5.5\times10^{8}, u=6\times10^{8}$
η_{mjt}^{VC}	$Round(Uniform(w,u))$	$w=700, u=800$
η_{mjt}^{HL}	$Round(Uniform(w,u))$	$w=400, u=500$
η_{mjt}^{SH}	$w\times\eta_{mjt}^{HL}$	$w=100$
β_{f}^{CP}	$Round(Uniform(w,u)\times\frac{\sum_{m,a,t}\xi_{mat}\times\varpi_m}{card(f)\times card(t)})$	$w=1.8, u=2.2$
β_{f}^{FX}	$Round(Uniform(w,u))$	$w=1.4\times10^{8}, u=1.5\times10^{8}$
β_{f}^{FC}	$Uniform(w,u)$	$w=0.14, u=0.18$
μ_{mijt}	$Round(Uniform(w,u))$	$w=500, u=600$
β_{pgt}^{PR}	$Round(uniform(w,u))$	$w=4000, u=4500$
ξ_{ja}^{DS}	$loop(j,$ $loop(a>1,$ $\varphi\alpha_{oq} = Round(Uniform(w,u));$ $);$ $);$	$w=50, u=80$
ξ_{ab}^{CS}	$loop(a,$ $loop(b,$ $if(b>a,$ $\xi_{ab}^{CS} = Round(Uniform(w,u));$ $else\,if(a>b,$ $\xi_{ab}^{CS} = \xi_{ba}^{CS};$ $else$ $\xi_{ab}^{CS} = c;$ $);$ $);$ $);$ $);$	$w=25, u=40, c=0$
β^{FP}	3000	

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