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Design a Multi Period Closed-Loop Supply Chain Program to Supply Recycled Products

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Abstract. Over the course of the last decades, closed-loop supply chains (CLSC) and reverse logistics issues have attracted increasing attention owing to strict environmental laws, social responsibilities, economic interests, and customer awareness. Hence, the issue of closed-loop supply chain and reverse logistics has emerged as a field of research in the new era. This issue has received much attention because it allows recyclable products to return to their original cycle. Therefore, this study primarily intends to present a mathematical model for designing a supply chain network for recycled products. The multi-stage and multi-period objective function of the closed-loop supply chain is presented to meet that aim. In this chain,

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dismantling, recycling, and disposal centers are considered. The objective function is to reduce the total cost of the closed-loop supply chain. The results of optimizing the mathematical model demonstrate that this model has the necessary efficiency for use in recycled products.

Keywords: Closed-loop supply chain, Recycled products, Total cost reduction, Reverse logistics

1. Introduction

Recently, closed-loop supply chain (CLSC) and reverse logistics issues have been controversial issues among researchers due to stringent environmental laws, social responsibilities, economic benefits, and customer awareness. In the prevailing era, production companies are under much pressure to produce eco-friendly products and have simultaneously turned to the recovery and collection of returned and used products [1-3]. Therefore, manufacturers have initiated product returns due to economic issues. If these products are repaired or recycled, they can be returned to the production path, which is recognized as CLSC. The financial success of recycling returned products depends on the supply chain operational utility, which requires establishing an efficient infrastructure through designing an optimal and economic network [4-6]. In general, the recovery of returned products can lead to reduced consumption of natural resources, less environmental pollution, and less waste, along with economic benefits and social and cultural considerations [7-9].

Melkote and Daskin made the primary efforts to design an optimal supply chain network by presenting a capacitated facility location/network design problem while taking capacity limitation into account [8]. Also, Aamir aimed to determine the mediating effect of integrated systems on the relationship between supply chain management practices and healthcare performance. Adopting a quantitative methodology, a survey questionnaire administered to 200 respondents was selected through cluster sampling from a target population of 2899 in Punjab. SPSS and AMOS were used for the exploratory and confirmatory factor analyses and structural equation modeling. In a research, Mutha and Pokharel proposed a single-layer and single-period location model to optimize transportation and facility displacement costs [9]. Ambrosino and Scutella developed a dynamic model for a four-layer network under certainty [4]. In the mentioned studies, the forward supply chain was evaluated, meaning that the organizations had no responsibility for the returned products of customers. Increased competitiveness in the environment has forced managers of supply chain affairs to pay more attention to return flows in supply chain design models [2]. In this regard, Flashman et al. believe that purchasing returned products could increase customer return intentions due to economic reasons. In addition, the integrated approach (i.e., simultaneous optimization of the forward and backward networks) can considerably reduce costs compared to the sequential design of both networks [1]. Pishvaee and Farahani showed that the integrated approach can prevent sub-optimality caused by the separate design of advanced and reverse logistics [10]. In research, Lu and Bostel proposed a three-layer network design model, seeking to locate facilities in a reverse logistics network in a way that collection and reconstruction centers could also be considered [7]. Moreover, Pishvaee et al. developed a model that simultaneously took forward and returned flow into account [11]. They presented a bi-objective function to reduce fixed and variable costs and increase network responsiveness.

2. Literature review

Hassanzadeh and Zhang proposed a mixed-integer linear programming model that minimized the total cost [6]. These scholars also investigated the impact of demand and returned uncertainties on the network configuration by stochastic programming (scenario-based). Ramezani et al. presented a stochastic multi-objective model for forward/reverse logistic network design while accounting for quality and responsiveness levels [12]. Aravandan et al. developed a mixed-integer non-linear programming model for CLSC network design with forward and reverse logistics components. The model was solved using Lingo 14 software. Notably, this model forms as a tool to compare future meta-heuristics to check the closeness of their solutions with corresponding optimal solutions. Most studies consider only one product recovery option- i.e., reproduction. Effective reverse logistics implementation requires the design of an appropriate logistics network to perform reverse supply chain activities such as disassembly, recycling, reproduction, repair and disposal. A literature review revealed that transportation and purchasing costs are considered in most presented models, and inventory shortage and maintenance and operational costs are often overlooked. In the actual world, the better the recognition of costs, the more accurate the decisions made by supply chain management. In a research, Zhen et al. presented an integration perspective for developing a green and sustainable CLSC network under uncertain demand [13]. These researchers defined demand by a scenario-based method and applied a Lagrangean relaxation method to solve the model. Li et al. studied the optimization of a hydrogen supply chain network [14]. The mentioned researchers presented a multi-level hydrogen supply chain and reviewed various optimization techniques.

Moreover, Haeri et al. provided a multi-objective integrated resilient-efficient model to design a blood supply chain network under uncertainty [15]. They presented a multi-objective mathematical model and carried out the optimization process using a fuzzy technique. Ultimately, Habib et al. proposed a multi-objective mathematical model to design a biodiesel supply chain network [16]. In this regard, the amount of carbon emitted and the total costs were optimized simultaneously. Moreover, a robust optimization approach was applied to deal with the uncertainties in this mathematical model. The present article attempts to develop a comprehensive model for CLSC network design in order to manage product returns and costs by considering a multi-objective and multi-period model that can simultaneously take product recovery activities (e.g., disassembly, recycling and waste disposal) into account. In this model, separation of returned products occurs in the same distribution center in a forward manner, and distribution-separation hybrid facilitation is used for the distribution of products, separation of returned products, and re-distribution of recycled products.[17] Therefore, sharing facilities and resources leads to considerable savings of costs and decreased pollution. In addition, the waste disposal option is considered in the model, which shows a real situation of the supply chain network.

Overall, the subject of closed-loop supply chain and reverse logistics has recently been trending upwards among respective researchers. The supply chain network of the present research can solve many natural problems by considering more recovery options in a dynamic model, in which there are product returns, after-sales services, and the possibility of recycling. Hence, due to the significance of this subject, and since there are no adequate studies on the subject, we aim to more simply design a CLSC network for real-world

problems without loss of generality. The model devised is able to enable integrated decisions of a logistics network design to prevent sub-optimality, stemmed from the sequential design of forward and reverse networks. In the end, some recommendations are made to be considered in future related researches.

3. Statement of the Problem

The present article designs and mathematically models a multi-level and multi-period CLSC network along with stock safety with scarcity conditions. The forward supply chain includes raw material suppliers, plants, distribution centers and customers. On the other hand, the backward supply chain encompasses customers, separation centers (known as distribution centers in this article), recycling centers and disposal centers. The problem includes determining the material flow between each stage in each period of the supply chain while meeting customer demand to minimize the total network cost. The network system (Figure 1) shows the easier design of a reverse logistics network for real-world problems without losing generality. In general, have more advantages in an integrated logistics network, compared to separate distribution and separation centers. In addition, the integration of a given logistics network prevents sub-optimality caused by the sequential design of forward and reverse networks. Product return along with after-sales services and more marketing options exist in the network, and using this strategy can prevent excessive transportation of return products, especially discarded products and deliver products, whether recycled or recovered, directly to the appropriate facilities. All of these are shown in Figure 1. The mentioned return system has a convergent structure from customers to disassembly and disposal centers. This return flow is compressive and based on a percentage of customer demand, in a way that a fixed percentage of products are in reverse flow, and on average, a certain percentage of this flow can be recycled and dismantled or discarded depending on the quality of the returned products.

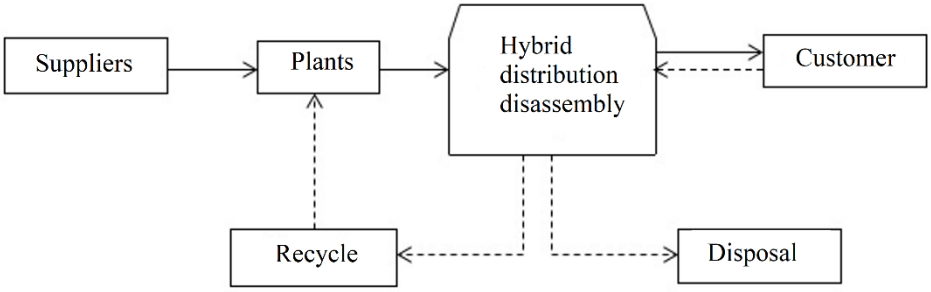


Figure 1. Structure of the studied reverse supply chain network

3.1. Problem Premises

The premises related to the model are, as follows:

- Demand is definite and must be fully satisfied.
- A scheduling horizon is provided for network scheduling.

- The final product of the plant includes several raw materials prepared from suppliers, and each raw material is used in the final product with a coefficient of use (indicating how much of that substance is needed in the final product).
- Demand is considered different in each period.
- The flow of material and product can only be transferred between two successive layers.
- The capacity of various sections varies in different periods.
- There is only one transportation mode.
- In this thesis, the reverse supply chain includes disassembly, recycling and disposal of used products.
- Separation and distribution centers are in one location since customers can more return the products easily and with greater motivation.

4. Mathematical Modeling

The following sets, parameters and variables are used to model the problem:

4.1. Sets

s: Set of suppliers $s = \{1, \dots, S\}$

f: Set of plants $f = \{1, \dots, F\}$

k: Set of distribution centers (return path of separation center) $k = \{1, \dots, K\}$

m: Set of disposal centers $m = \{1, \dots, M\}$

c: Set of customers $c = \{1, \dots, C\}$

p: Set of raw material $p = \{1, \dots, P\}$

t: Set of time horizon $t = \{1, \dots, T\}$

4.2. Parameters

V_{spt}: Supplier and p raw material capacity in t time

V_f^1: Plant production capacity for production of the product

V_k^2: Capacity of k distributor

D_{ct}: Demand of c customer for the product in t time

A_t: The amount of product return from customer purchase

U_p: Consumption coefficient of p raw material in the product

B_t: The amount of product waste in the distribution or separation sector

W: The amount of product waste after disassembly

C^1_{sfpt}: The cost of delivery of p raw material from s supplier to f plant in t time

C^2_{kft}: The cost of delivery of product from f plant to k distribution center in t time

C^3_{ckt}: The cost of delivery of product from k distribution center to c customer in t time

C^4_{kct}: The cost of return of product from c customer to k distribution center in t time

C^5_{mkt}: The cost of delivery of faulty product from k distribution center to m disposal center in t time

C^6_{fkt}: The cost of delivery of product from k distribution center to f plant in t time

C^7_{pft}: The cost of the conversion of p raw material in f plant in t time

C^8_{pft}, C^9_{kt}, and C^{10}_{ct}: The maintenance cost of p raw material in f plant in t time, the maintenance cost of product in k distributor in t time, and maintenance cost of safety stock of c customer in t time, respectively

C^{11}_{pft}, C^{12}_{kt}, and C^{13}_{ct}: Deficit cost of p raw material in f plant in t time, deficit cost of the product in k distributor in t time, and deficit cost of the product of c customer in t time, respectively

4.3. Variables

Q_{spft}: The number of p raw material delivered from s supplier in t period to f plant.

Q^1_{kft}: The number of products delivered from f plant to k distributor in t time.

Q^2_{ckt}: The number of products delivered from k distributor to c customer in t time.

Q^3_{kct}: The number of products delivered from c customer to k distributor in t time.

Q_{mkt}^{4}: The number of products delivered from k distributor to m disposal center in t time.

Q_{fkt}^{5}: The number of products delivered from k distributor to f plant in t time.

Q_{pft}^{6}: The amount of p raw material produced in f plant in t time.

A_{pft}^{1}: The amount of p raw material inventory in f plant in t time.

A_{kt}^{2}: The amount of product inventory in k distribution center in t time.

A_{ct}^{3}: The amount of c customer safety stock in t time.

B_{pft}^{1}: Deficit rate of p raw material in f plant in t time.

A_{kt}^{2}: Product deficit rate at k distribution center in t time.

A_{ct}^{3}: Product deficit of c customer in t time.

4.4. Problem Model

The multi-stage and multi-period objective function of the closed-loop supply chain of the article is presented below:

$$\begin{aligned}\text{Min} & \sum_{\text{s}}\sum_{\text{f}}\sum_{\text{p}}\sum_{\text{t}} Q_{\text{spft}} * \text{C}_{\text{spft}}^{1} + \sum_{\text{c}}\sum_{\text{k}}\sum_{\text{t}} Q_{\text{kft}}^{1} * \text{C}_{\text{kft}}^{2} \\ & + \sum_{\text{c}}\sum_{\text{k}}\sum_{\text{t}} Q_{\text{ckt}}^{2} * \text{C}_{\text{ckt}}^{3} + \sum_{\text{c}}\sum_{\text{k}}\sum_{\text{t}} Q_{\text{kct}}^{3} * \text{C}_{\text{kct}}^{4} + \sum_{\text{m}}\sum_{\text{k}}\sum_{\text{t}} Q_{\text{mkt}}^{4} \\ & * \text{C}_{\text{mkt}}^{5} + \sum_{\text{f}}\sum_{\text{k}}\sum_{\text{t}} Q_{\text{fkt}}^{5} * \text{C}_{\text{fkt}}^{6} + \sum_{\text{f}}\sum_{\text{p}}\sum_{\text{t}} Q_{\text{pft}}^{6} \\ & * \text{C}_{\text{pft}}^{7}\end{aligned} \tag{1}$$

$$+\sum_{f}\sum_{p}\sum_{t} A_{pft}^{1} * C_{pft}^{8} + \sum_{k}\sum_{t} A_{kt}^{2} * C_{kt}^{9} + \sum_{c}\sum_{t} A_{ct}^{3} * C_{ct}^{10} \tag{2}$$

$$+\sum_{f}\sum_{p}\sum_{t} B_{pft}^{1} * C_{pft}^{11} + \sum_{k}\sum_{t} B_{kt}^{2} * C_{kt}^{12} + \sum_{c}\sum_{t} B_{ct}^{3} * C_{ct}^{13}$$

(3)

$$\sum_{\mathrm{f}} Q_{\mathrm{spft}} \leq \mathrm{V}_{spt} \qquad \forall s,p,t \tag{4}$$

$$\sum_{s}\sum_{p} Q_{spft} + \sum_{p} A^{1}_{pf(1-I)} \leq V^{1}_{f} \qquad \forall f,t \tag{5}$$

$$\frac{\sum_s \sum_p Q_{spft}}{u_p} + \sum_p \frac{Q^6_{pf(1-I)}}{u_p} + \sum_p A^1_{pf(1-I)}/u_p + \sum_p \frac{B^1_{pft}}{u_p} = \sum_k Q^1_{kft} + \sum_p A^1_{pft}/u_p \qquad \forall f,t \tag{6}$$

$$\sum_f Q^1_{kft} + A^2_{k(t-I)} \leq V^2_k \qquad \forall k,t \tag{7}$$

$$\sum_f Q^1_{kft} + A^2_{k(t-I)} + B^2_{kt} = A^2_{kt} + \sum_c Q^2_{ckt} + B^2_{k(t-I)} \qquad \forall c,t \tag{8}$$

$$\sum_k Q^2_{ckt} + A^3_{c(t-I)} + B^3_{ct} = D_{ct} + A^3_{ct} + B^3_{c(t-I)} \qquad \forall c,t \tag{9}$$

$$\left(\sum_k Q^2_{ckt}\right) * A_t = \sum_k Q^3_{kct} \qquad \forall c,t \tag{10}$$

$$\sum_c Q^3_{kct} = \sum_m Q^4_{mkt} / B_t \qquad \forall k,t \tag{11}$$

$$\sum_{f} Q_{fkt}^{5} = \sum_{c} Q_{kct}^{3} * (I - B_t) \qquad \forall k, t \tag{12}$$

$$Q_{pft}^{6} = \sum_{k} Q_{fkt}^{5} * u_p * W \qquad \forall p, f, t \tag{13}$$

The objective function includes three sections; the first section shows the delivery costs between different network levels, which are respectively the cost of transfer of raw material from supplier to plants, the cost of delivery from plant to distribution center, the cost of delivery from distribution center to the customer, the cost of return of faulty products to the separation center (distribution), the cost of delivery of the waste product to the disposal sector, the cost of returning the faulty product from the separation center to the plant for disassembly, and the cost of recycling raw materials from a faulty product. The second section shows maintenance costs at different levels of the network, which are respectively the cost of raw material maintenance in the plant, the cost of product maintenance in the distribution center and the cost of product maintenance by the customer. Finally, the third section of the objective function presents the raw material and product deficit costs at network levels, which are respectively the raw material deficit costs in the plant, the product deficit costs in the distribution center and the customer's product deficit costs. In the presented model, phrase [4] is the constraints of supplier capacity limitation, phrase [5] is the constraints of plant capacity limitation for product production, phrase [6] shows the constraints of product and raw material balance in the plant, phrase [7] is the constraints of observing distributor capacity, phrase [8] is the input and output balance of distributor, phrase [9] is the customer's input and output balance, phrase [10] is the balance of faulty products resulting from the product delivered to the customer, phrases [11 & 12] are the constraints of waste disposal, and phrase [13] is the constraints of turning raw materials into products at the plant.

5. Computational Tests

To assess the performance of the proposed model, a problem with different numerical examples is solved in GAMS software using CPLEX on a computer with characteristics of Intel Core 2 Duo (2 MB Cach, 2 GHz) and a 2 GB memory. Table 1 shows the size of generated sample problems, and Table 2 presents the model's parameters randomly selected at specific ranges, all of which follow a uniform distribution. Moreover, values of A_t, B_t, U_1, and U_2 are considered fixed for all problems (0.2, 0.2, 2, and 3, respectively).

Table 1. Sample problems

ID	N						
	Supplier (s)	Plant (f)	Distribution Center (k)	Disposal Center (m)	Customer (c)	Raw Material (p)	Time (t)
M_1	3	2	2	2	5	1	2
M_2	5	6	3	4	8	1	3
M_3	15	8	6	6	20	3	5

Table 2. Network parameter distribution function for sample problems

Parameter	Value	Parameter	Value	Parameter	Value
V_{spt}	round(uniform(200,400))	C^3_{ckt}	round(uniform(5,10))	C^9_{kt}	round(uniform(5,10))
V^1_f	round(uniform(100,200))	C^4_{kct}	round(uniform(5,10))	C^{10}_{ct}	round(uniform(20,50))
V^2_k	round(uniform(100,200))	C^5_{mkt}	round(uniform(5,10))	C^{11}_{pft}	round(uniform(30,50))
D_{ct}	round(uniform(10,30))	C^6_{fkt}	round(uniform(5,10))	C^{12}_{kt}	round(uniform(30,50))
C^1_{sfpt}	round(uniform(5,10))	C^7_{pft}	round(uniform(5,10))	C^{13}_{ct}	round(uniform(30,50))
C^2_{kft}	round(uniform(5,10))	C^8_{pft}	round(uniform(5,10))	W	round(uniform(1,5))

The sample problems presented in Table (1) are solved by the software and the optimal solutions along with their implementation duration are shown in Table (3).

Table 3. Model solution results

ID	Optimal Solution ($)	Implementation Time (hh: mm: ss)
M_1	6569	0:00:09
M_2	15688	0:16:43
M_3	49097	0:17:25

According to Table 3, the time of solving the mathematical model increases in addition to the value of the objective function in case of an increase in the size of the problem. This is due to the increased complexity of the mathematical model and more time required by the optimization software to find the optimal solution. In this thesis, the ratio of changes in the objective function to the changes in demand in the scenarios is compared and analyzed. The schematic representation of these changes is shown in Figure 2.

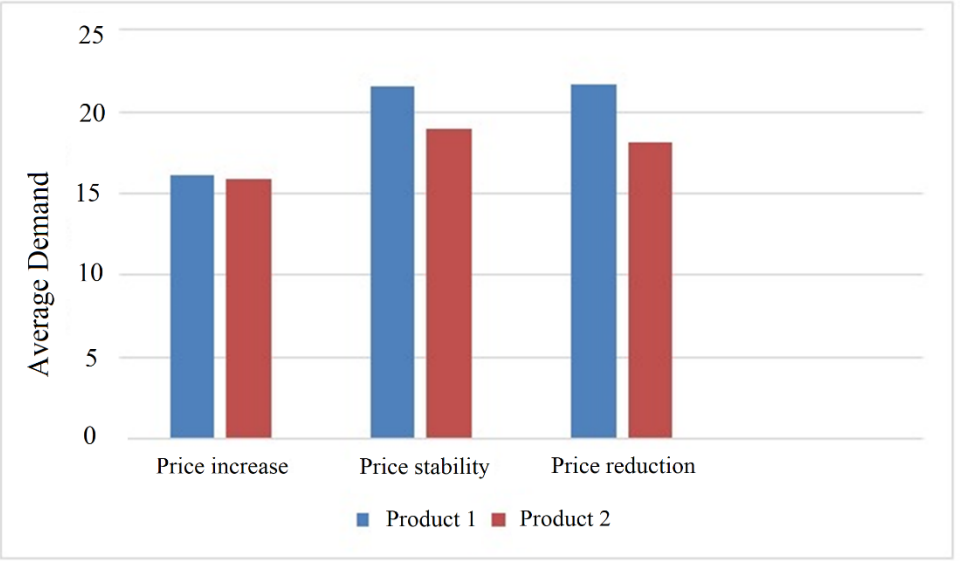


Figure 2. Comparison of fixed and variable cost objective function changes and demand changes

Based on the existing conditions, the objective function of the problem in the second scenario will be reduced by 20% compared to the first scenario with a 21% decrease in demand for the first product and a 15% decrease in demand for the second product. In addition, a comparison of the third scenario to the first scenario shows that a 30% decrease in demand for the first product and a 35% decrease in the demand for the second product will lead to a 30% reduction in the objective function (Figure 3).

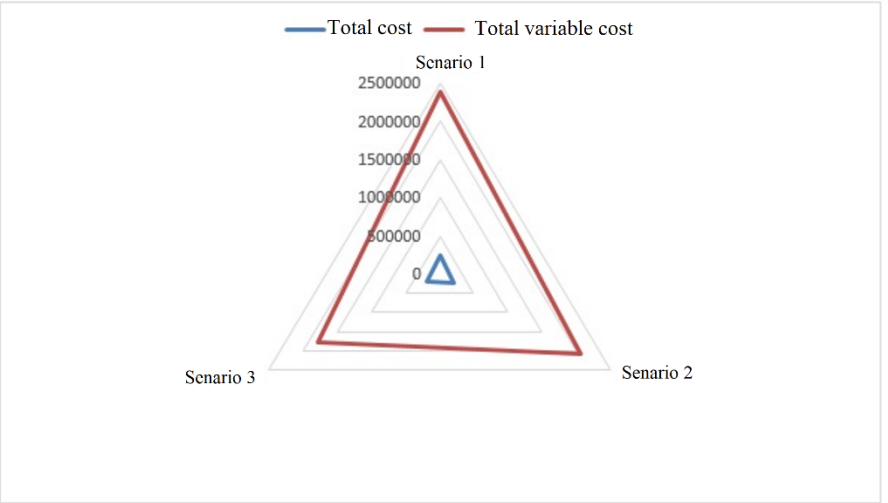


Figure 3. Comparison of fixed and variable cost function

As shown in Figure 3, the variable cost of the supply chain is about 10 times the fixed Cost and the slope changes more as the scenarios change. The fixed cost is applied only once, which is during facility construction. Transportation costs are also lower than carbon dioxide production costs based on the data of the study sample. Therefore, these values are fixed at the points shown in the figure above by considering customer demand estimation and reducing fixed and variable costs and environmental costs. In this regard, the costs calculated in the objective function are calculated separately for scenarios and costs. According to the results, most of the ocosts related to the costs of carbon dioxide emissions are due to internal transportation and the cost of moving goods inside and outside the system. Therefore, it is very important that the facilities are located at the closest distance to each other and customers are at the final priorities at farther distances in the study sample [14-17].

6. Conclusion

This article proposed a multi-level and multi-period CLSC network. The model presented could enable integrated decisions of a logistics network design in order to prevent sub-optimality caused by the sequential design of forward and reverse networks. In addition, hybrid facilitation of separation and distribution was used, which could lead to a considerable reduction of costs and pollution by sharing transportation equipment, infrastructures and human resources. Most previous studies have only considered one option (reproduction) among different product marketing options. The model presented in the current article simultaneously considered marketing activities such as disassembly, recycling and waste disposal options, which could result in the design of an optimal logistics network with fewer costs. In addition, the model showed that different rates of flow of returned products, recycling and disposal could affect the network costs. The model was solved in GAMS software, and computational results demonstrated that as the size of the problem increases, the computational volume increases and the execution time will not be optimal.

In closing, given the fact that a general optimal solution may not exist for all mathematical models, especially very large-scale ones, it is highly recommended that heuristic algorithms be applied in future studies.

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