Han, S, Mo, Y, Chen, L, Luo, Z, Foropon, C and Belal, HM

A Multi-period Closed-loop Supply Chain Network Design with Circular Route Planning

Article

Annals of Operations Research

A Multi-period Closed-loop Supply Chain Network Design with Circular Route Planning

--Manuscript Draft--

Manuscript Number:	ANOR-D-21-02108R1
Full Title:	A Multi-period Closed-loop Supply Chain Network Design with Circular Route Planning
Article Type:	Original Research
Keywords:	Supply Chain Management (T); Closed-loop supply chain network design; Circular transportation mechanism; Routing optimization; Carbon emissions
Corresponding Author:	Zongwei Luo BNU-UIC Institute of AI and Future Networks Zhuhai, CHINA
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	BNU-UIC Institute of AI and Future Networks
Corresponding Author's Secondary Institution:	
First Author:	Shuihua Han
First Author Secondary Information:	
Order of Authors:	Shuihua Han
	Yudi Mo
	Linlin Chen
	Zongwei Luo
	Cyril Foropon
	HM Belal
Order of Authors Secondary Information:	
Funding Information:	Guangdong Science and Technology Department (2021ZDZX3021) — Dr. Zongwei Luo
Abstract:	The routing problem is a critical issue in closed-loop supply chain neatwork design, but it is typically simplified in the literature. In contrast to the traditional approach of a point-to-point delivery between two logistics nodes or a routing problem at the terminal distribution stage in a closed-loop supply chain (CLSC), we propose a multi-period CLSC network that considers circular routing in the network's echelons to reduce empty running. First, we formulate reversible transportation mechanism (RTM) and circular transportation mechanism (CTM), and construct two CLSC network models for a three-echelon supply chain network respectively. The models fully consider backorders, delayed returns, delivery lead time, and carbon emissions cost into the model. Second, a heuristic method with initialization and improvement stages is proposed to tackle the large-scale NP-hard problems, and the local search process is guided via simulated annealing. Third, the model and solution are applied to the real-life case of a toy manufacturer in China. The results show that: compared to RTM, CTM can effectively improve the utilisation of transport vehicles and reduce the number of transport vehicles used in the network; the network operating cost of CTM is significantly less than that of RTM; no matter how the carbon tax on emission will be, the average carbon emission will be reduced under CTM as compared to RTM; the heuristic algorithm we design can efficiently solve large-scale CLSC design problems under both transport mechanisms.

A Multi-period Closed-loop Supply Chain Network Design with Circular Route Planning

Dr. Shuihua Han
Department of Management Science, School of Management,
Xiamen University, Xiamen, China
Email: hansh@xmu.edu.cn

Mr. Yudi Mo
Department of Management Science, School of Management,
Xiamen University, Xiamen, China
Email: myd622@126.com

Ms. Linlin Chen
Department of Management Science, School of Management,
Xiamen University, Xiamen, China
Email: 415949507@qq.com

Dr. Zongwei Luo (corresponding author)
BNU-UIC Institute of AI and Future Networks， Bejing Normal University, Zhuhai, CHINA
Guangdong Key Lab of Interdisplinary Research on Data Science, BNU-HKBU United International College, Zhuhai, CHINA
Email: lzwqhk@outlook.com

Dr. Cyril R.H. Foropon
Montpellier Business School
Montpellier, France
Email: c.foropon@Montpellier-BS.com

Dr. H M Belal
Liverpool John Moores University

Liverpool, Post Code: L3 5UG, UK
Email: H.M.Belal@ljmu.ac.uk

A Multi-period Closed-loop Supply Chain Network Design with Circular Route Planning

Abstract: The routing problem is a critical issue in closed-loop supply chain neatwork design, but it is typically simplified in the literature. In contrast to the traditional approach of a point-to-point delivery between two logistics nodes or a routing problem at the terminal distribution stage in a closed-loop supply chain (CLSC), we propose a multi-period CLSC network that considers circular routing in the network's echelons to reduce empty running. First, we formulate reversible transportation mechanism (RTM) and circular transportation mechanism (CTM), and construct two CLSC network models for a three-echelon supply chain network respectively. The models fully consider backorders, delayed returns, delivery lead time, and carbon emissions cost into the model. Second, a heuristic method with initialization and improvement stages is proposed to tackle the large-scale NP-hard problems, and the local search process is guided via simulated annealing. Third, the model and solution are applied to the real-life case of a toy manufacturer in China. The results show that: compared to RTM, CTM can effectively improve the utilisation of transport vehicles and reduce the number of transport vehicles used in the network; the network operating cost of CTM is significantly less than that of RTM; no matter how the carbon tax on emission will be, the average carbon emission will be reduced under CTM as compared to RTM; the heuristic algorithm we design can efficiently solve large-scale CLSC design problems under both transport mechanisms.

Keywords: Supply Chain Management (T); Closed-loop supply chain network design; Circular transportation mechanism; Routing optimization; Carbon emissions.

1. Introduction

The design of good supply chain networks is a hot topic in supply chain management. Companies (e.g., Toyota) have tried vendor-managed inventory to eliminate the bullwhip effect. Further, vendor-managed inventory has facilitated the study of the inventory–routing problem, which integrates inventory management, vehicle routing and scheduling decisions (Coelho et al., 2013). And as manufacturers (e.g., P&G) and retailers (e.g., Wal-Mart) join supply chains and participate in the production coordination and distribution process, the problem of locating distribution warehouses is incorporated into the supply chain network design decision. In addition, appropriate inventory decisions are important for improving the performance of supply chain operations. It can improve customer service levels and reduce operational costs, especially for perishable products (Daskin et al., 2002). No matter how complicated the traditional supply chain network design problem is, the objective is mainly to minimize production and operation costs and add economic value, but it often ignores the impact of business operations on the environment (Xu, 2013). The product life cycle includes not only design, procurement, production and sales but also recycling and remanufacturing (Yao & Askin, 2019). Recycling and remanufacturing can not only alleviate environmental pollution (Yolmeh & Saif, 2021) but also generate profits (Zhalechian et al., 2016). Many countries and regions have already introduced requirements and enacted regulations to enhance product recycling and reduce environmental pollution (Fu et al., 2021; Georgiadis & Besiou, 2010). Accordingly, academics have been paying attention to the closed-loop supply chain network design (CLSCND) problem.

As a practical matter, the design of a closed-loop supply chain (CLSC) network requires the full consideration of various elements to maximize the network's operability and practicability. Similar to traditional supply chain network design, CLSCND needs to consider the operational capacity of logistics facilities and equipment (Keyvanshokooh et al., 2016; Yuchi et al., 2021), backorders (Rahimi et al., 2017), delivery lead times (Ramezani et al., 2014) and so on. In addition, CLSCND also needs to consider sustainability (Rahimi et al., 2017) and delayed returns. For example, Rahimi et al. (2017) considered the operational capacity of logistics equipment, backorders and sustainability. Ramezani et al. (2014) fully considered the operational capacity of logistics facilities and delivery lead times. Therefore, further study of CLSCND that integrates various practical elements to enhance operability and practicability is of great significance. However, solving CLSCND as an NP-hard problem that integrates these practical elements is a great challenge.

Most CLSCND studies have not considered the routing problem. They simplified product delivery to a point-to-point process between logistics nodes, resulting in trucks returning empty, which seriously increases a company's operating costs and environmental pollution. Therefore, some of the literature has fully combined the routing problem and other strategic and tactical decision problems to study CLSCND. For example, some authors (Yuchi et al., 2021; De and Giri, 2020; Johari and Hosseini-Motlagh, 2019; Guo et al., 2018; Deng et al., 2016; Zhalechian et al., 2016) designed a three-echelon CLSC network model of manufacturers, distribution centers, recycling centers and customers to solve the location–routing–inventory problem (Yuchi et al., 2021; Validi et al., 2020; Deng et al., 2016; Guo et al., 2018; Asgari et al., 2017;

Zhalechian et al., 2016) and routing–scheduling problem (De & Giri, 2020). The above researches on the design of CLSC networks considering routing optimization have all optimized the operating costs of the networks from different perspectives, including transportation costs, facility location costs, inventory costs, penalty costs, inspection costs, and disposition costs. In addition, some of the literature reduced vehicle carbon emissions in the transport stage by constructing carbon emission (Zhalechian et al., 2016) and carbon cost (De & Giri, 2020) objectives. However, there are some gaps in these CLSC models: first, they ignore the differences between recycling centers and distribution centers and set recycling centers inside distribution centers, which is not in line with reality; second, the routing problem is limited to the terminal distribution stage, ignoring the routing problems within different echelons of a CLSC network; third, most are single-period models, which is not helpful for the daily operations of CLSC networks. Therefore, when designing a CLSC network by combining the routing problem and other strategic and tactical decision problems, it is very important to consider the differences between recycling centers and distribution centers, the hierarchical nature of CLSC networks and the guidance for daily operations, all of which are significant for improving the operational performance of a CLSC network.

Combining the current real-life practice and identified the shortcomings of academic research, our research motivation is mainly from the logistics operations within CLSC networks: First, the effectiveness of a CLSC network design is closely related to the consideration of different practical elements. Compared to traditional supply chain network design, the CLSC need to consider not only the operational capacity of logistics facilities and equipment, backorders, delivery lead times but also sustainability and delayed returns. Therefore, we hope to integrate these realistic elements of logistics to design CLSC networks and enhance the practicability and operability of CLSC networks. Second, in reality, the transportation business in CLSC networks is lack of routing decisions, especially in the upstream stage of the CLSC. This leads to a large number of empty running vehicles, seriously increasing the network operating costs and environmental pollution. Therefore, we hope to address the routing problem at different echelons of the CLSC network based on the existing research, so as to reduce the empty running of vehicles. Third, global warming has prompted governments to focus on carbon emissions and introduced various policies related to carbon emissions, resulting in the need to consider carbon emissions in the operation of CLSCs. Therefore, we hope to further expand the carbon reduction target, so as to reduce carbon emissions from logistics operations.

According to the above research gaps and research motivations, this paper designs a multi-period, three-echelon, closed-loop location–inventory–routing supply chain network model. The objective is to consider the economics of business operations and the sustainability of social development, and the model constraints consider realistic elements such as the operational capacity of logistics facilities and logistics equipment, backorders, delayed returns and delivery lead time. In addition, this paper provides a new heuristic algorithm solution by combining local search and simulated annealing (SA) algorithms. The results show that: 1) compared to RTM, CTM can effectively improve the utilisation of transport vehicles and reduce the number of transport vehicles used in the network; 2) the network operating cost of circular transportation mechanism (CTM) is significantly less than that of reversible transportation mechanism (RTM), and this improvement mainly comes from the transportation business; 3) no matter how the carbon tax on emission will be, the average carbon emission will be reduced under CTM as compared to RTM; 4) the heuristic algorithm we design can efficiently solve large-scale CLSC design problems under both transport mechanisms.

The main contributions of this study are as follows.

First, with particular attention to the potential synergies between forward and reverse product flows, a new circular route is added to the traditional CLSC network model such that circular routes exist at different echelons of the network. The routing problem at different echelons is effectively coordinated with the facility location and inventory control problems in the CLSC network, which effectively reduces the total empty running distance and operational costs.

Second, the proposed CLSC network model fully incorporates the operational capacity of logistics facilities and logistics equipment, backorders, delayed returns, delivery lead time and sustainability. Considering the CLSCND as an NP-hard problem, the comprehensive consideration of these practical elements greatly increases the difficulty of solving it. Therefore, a new heuristic algorithm is designed by combining local search and SA algorithms. Experimental results demonstrate that the algorithm obtains high-quality solutions in a reasonable runtime when faced with large-scale daily business operation problems.

Third, this model is further extended by considering the carbon tax policy. The experimental results indicate that no matter how the carbon emission tax changes, the average carbon emissions of the proposed CLSC network model that considers the routing problem being lower than those of the CLSC network model that does not consider the routing problem.

The remainder of this paper is organized as follows. The relevant literature is analysed in

Section 2. In Section 3, we formulate two large-scale optimization models with a three-echelon network structure that are based on a real-world CLSCND problem. In Section 4, a new algorithm based on the SA algorithm is developed to solve the models, and its optimal decisions are expected to be very complicated. In Section 5, some numerical studies are conducted using the actual case of a toy manufacturer in China to illustrate the effectiveness of the models and algorithms. Furthermore, to build a green supply chain, an effective policy tool and carbon tax are integrated into the model in Section 6. Finally, conclusions and opportunities for future research are discussed in Section 7.

2. Literature review

In line with the research focus of this paper, this section provides a brief review of recent research on CLSCND and the vehicle routing problem (VRP) and notes the differences between this paper and the literature.

2.1 Closed-loop supply chain network design

In recent years, CLSCND, a research hotspot in academic circles, has been widely studied by scholars, including its aspects such as research methodology, sustainability, uncertainty, decision problems and solution algorithms (Govindan et al., 2015; Souza, 2013). In line with the research focus of this paper, we review the literature on routing optimization and highlight the practical elements, decision problems and solution algorithms.

CLSC networks are designed with strategic, tactical and operational decisions in mind. Strategic decisions include network structure design and location, which have a long-term effect on a company's operations; tactical decisions include inventory decisions and return rules, which can affect a company's operations for months or weeks. Operational decisions include scheduling and routing, which have a short-term impact on a company's operations. Coordinating decisions on these three levels in the CLSCND process is of great importance, and it can effectively optimize a company's economic and social sustainability (Souza, 2013). As one of the core problems in CLSCND, the routing problem at the operational level directly affects the strategic and tactical decision problems (Coelho et al., 2014; Shi et al., 2020) such as threats of multi-day problem (Dror et al., 1985). However, most CLSCND studies fail to consider the routing problem, as shown in **Table 1**. In **Table 1**, Pishvaee et al. (2010) constructed a single-period bi-objective mixed-integer nonlinear programming CLSC network model incorporating both location and product flow decisions. They designed a memetic algorithm to solve it. Ramezani et al. (2014) designed a fuzzy mathematical model of a multi-period CLSC network that considers uncertainty factors, such as location and product flow decisions. They transformed and solved the model using fuzzy optimization methods and considered delivery lead time and 6σ quality in the model. The model fully considered logistics facilities with multiple capacity levels. In addition, many other studies (Keyvanshokooh et al., 2016; Soleimani et al., 2017; Sahebjamnia et al., 2018; Almaraj & Trafalis, 2019; Guo et al., 2020; Prakash et al. 2020; Liu et al., 2021; Biçe & Batun, 2021; Diabat & Jebali, 2021; Tautenhain et al., 2021; Ghomi-Avili et al., 2021; Soleimani et al., 2022; Xu et al., 2022; Kim & Do Chung, 2022) have examined CLSCND without considering the routing problem. These studies have typically considered some practical elements, such as operational capacity, backorders and sustainability and uncertainty. Furthermore, considering that the CLSCND is a complex NP-hard problem, some scholars solved it by designing efficient heuristic algorithms (Pishvaee et al., 2010; Soleimani et al., 2017; Sahebjamnia et al., 2018; Guo et al., 2020; Tautenhain et al., 2021).

The prevously mentioned CLSCND papers that do not consider the routing problem tend to reduce the product delivery process to a point-to-point delivery between two logistics nodes, which means that the truck often returns empty, seriously increasing operating costs and environmental pollution. Therefore, some studies have fully integrated the routing problem and other strategic and tactical decision problems to study CLSCND, as shown in **Table 1**. In **Table 1**, Zhalechian et al. (2016) proposed a location–routing–inventory CLSC network model under mixed uncertainty that considered economic, environmental and social impacts. The model had three echelons: suppliers, distribution/recycling centers and retailers. The recycling centers were set in partially opened distribution centers, and route optimization was used in the distribution/recycling center to retailer stage. Meanwhile, they designed a hybrid meta-heuristic algorithm to solve the constructed model. Deng et al. (2016) proposed a closed-loop location-inventory-routing problem model considering both defective returns and non-defective returns in e-commerce supply chain systems. The model set up a merchant center, which has the functions of distributing products and recycling products, and the model optimised the routing problem for terminal distribution. In addition, they designed a hybrid ant colony optimization algorithm to solve it. Guo et al. (2018) investigated a single-period location–inventory–routing problem in a CLSC network, which located the distribution center and recycling center in the same facility. Routing optimization was used in the terminal distribution stage of the CLSC network. They proposed a two-stage heuristic algorithm that introduced SA into an adaptive genetic algorithm to solve the constructed model. Other scholars designed three-echelon CLSC network model that included a routing–scheduling problem (De & Giri, 2020) and a location–routing–inventory decision problem (Yuchi et al., 2021, Sazvar et al., 2021). These models generally considered the capacity of operational facilities and operational equipment, but routing optimization was only performed for the terminal distribution stage. Moreover, most of these studies designed heuristic algorithms to solve these models.

We conduct literature review shown in **Table 1**. Based on the existing gaps, we extends our research on the CLSCND. First, most CLSCND studies are lack of consideration of the routing problem, and only a small number of studies considered routing problem in terminal delivery. These studies set up both distribution centers and recycling centers as the same facility. Therefore, our study extends the CLSCND literature that considers the routing problem. We fully consider the differences between recycling centers and distribution centers, the hierarchical nature of CLSC networks and the guidance for daily operations. Second, only a small number of CLSCND studies have partially considered realistic factors such as backorders, delayed returns and delivery lead time. These elements are the inevitable elements of CLSC operations. Our research integrates these realistic elements to improve the practicality of the network. Finally, our research integrates different decision-making problems and realistic elements, which are difficult to solve efficiently and quickly by existing algorithms.

2.2 Vehicle routing problem

The VRP, as a typical NP-hard problem, has been a hot research topic in academic circles. As one of the variants of the VRP, the vehicle routing problem with simultaneous pickup and delivery (VRPSPD) requires full consideration of product pickup and delivery in the vehicle routing process. The routing problem in a CLSC network must consider both new product delivery and old product recycling, so it is very similar to the VRPSPD. The VRPSPD has been studied by many scholars. For example, Savelsbergh and Sol discussed several features that distinguish the VRPSPD from the standard VRP and reviewed the related solution methods (Savelsbergh et al., 1995). Danloup et al. (2018) studied the VRPSPD with full consideration of transshipment and proposed a local search algorithm and a genetic algorithm to solve it. Hernández-Pérez et al. (2021) further proposed a two-stage VRPSPD, in which a portion of the customers are visited in the first stage and then in the second stage the unvisited customers are assigned to the visited customers. There have been several reviews of the VRPSPD in the literature (Berbeglia et al., 2010; Koç et al., 2020). Meanwhile, some scholars have also applied the VRPSPD to supply chain network design. For example, Azizi and Hu (2020) proposed a supply chain network model that simultaneously considers the distribution center location, pickup and delivery processes and direct distribution process; Parast et al. (2021) developed a green supply chain network model that fully considers the forward and reverse flows of perishable products, and the model includes the location, VRPSPD and inventory problems. The VRPSPD in these papers tends to exist only at the terminal distribution stage of the supply chain network, in which the corresponding node attributes are either retailers or consumers. Recently, Ranjbaran et al. (2020) proposed a milk-run routing optimization model between suppliers and assembly plants. Unlike previous milk-run models, this model considered not only the parts flow process from supplier to manufacturer but also the empty pallet flow process from manufacturer to supplier, which is very similar to the many-to-many problem in the VRPSPD (Koç et al., 2020).

Effective coordination of the routing problem with other strategic and tactical decision problems is an important issue to be considered in CLSCND. There have been many studies on the effective coordination of the routing problem with other strategic and tactical decision problems in designing logistics networks and supply chain networks. In logistics networks, Vahdani et al. (2018) designed a humanitarian logistics network model that fully considers uncertainty and includes the location, routing and inventory decisions; Chao et al. (2019) investigated a two-stage location–routing–inventory problem with time windows in food distribution networks; in addition, Wei et al. (2018) and Zhang et al.(2021) studied the routing-loading problem and production routing problem respectively. In terms of supply chain networks, Archetti et al. (2007) designed a branch-and-cut algorithm for the inventory–routing problem with vendor-managed inventory; Zhang et al. (2014) constructed a location–routing–inventory mixed-integer programming model for a supply chain network and designed a hybrid meta-heuristic algorithm consisting of initialisation, reinforcement and post-optimization to solve it. Moreover, some of the literature on the routing–location problem (Mara et al., 2021; Nagy & Salhi, 2007; Prodhon and Prins, 2014, Wei et al., 2018) and the routing–inventory problem (Coelho et al., 2014; Moin & Salhi, 2007; Daskin et al., 2002).) has also been reviewed, which is available for readers who are interested in further reading. These research papers mainly considered forward logistics and failed to consider reverse logistics.

A review of the VRP literature shows that the CLSC network model in this paper differs significantly from those in previous VRP studies. Compared with the VRPSPD under supply chain networks, this paper's CLSC network model considers different echelons for the VRPSPD while accounting for differences in node attributes. Compared with the milk-run routing optimization model proposed by Ranjbaran et al. (2020), the CLSC network model in this paper fully combines the routing problem with other strategic and tactical problems, and the VRPSPD in this model is a one-to-many-to-one problem (Koç et al., 2020). Compared with the literature on logistics and supply chain network design that considers the routing problem, the routing problem in the CLSC network model proposed in this paper fully considers the reverse flow of products and focuses on potential synergies between forward and reverse product flows.

Therefore, compared with the existing literature, the main novelties of our paper are as follows: First, we consider the routing decision at different echelons when designing CLSC networks, and introduce the CTM into the CLSC network. Second, we fully consider various practical elements of CLSC networks, including the operational capacity of logistics facilities and equipment, backorders, delivery lead times, sustainability and delayed returns. The integration of these practical elements into the CLSCND can effectively improve the practicability and operability of the network. Finally, our research problem integrates different decision problems and practical elements. To address the greatly increased complexity, a heuristic algorithm is designed to help solve the problems.

Table 1 Comparisions amongsome relevant literatures on CLSCND

Reference	Model construction							Objective		Decision content				Other Contributions
	Planning horizon		Delivery	Backorder	Delayed	Operational capacity		Economics	Sustainability	Routing	Location	Inventory	Product	
	Single	Multi	lead-time		return	facilities	equipment						flow	
Pishvaee et al. (2010)	✔					✔		✔			✔		✔	Facility Capacity Level, Memetic algorithm
Ramezani et al. (2014)		✔	✔			✔		✔			✔		✔	6σ quality, Fuzzy optimization methods
Keyvanshokooh et al. (2015)		✔				✔		✔			✔	✔	✔	Uncertainty, Benders decomposition algorithm
Soleimani et al. (2017)		✔		✔		✔		✔	✔		✔		✔	Uncertainty, Social responsibility, Genetic algorithm
Sahebjamnia et al. (2018)	✔					✔		✔	✔		✔		✔	Social impact, Meta-heuristic algorithm
Almaraj and Trafalis (2019)		✔				✔		✔			✔		✔	Robust optimization
Guo et al. (2020)	✔							✔			✔	✔		Hybrid adaptive differential evolution algorithm
Prakash et al. (2020)	✔					✔		✔	✔		✔		✔	Uncertainty, Robust optimization
Liu et al. (2021)	✔					✔		✔	✔		✔		✔	Fuzzy distribution set, Distributed robust optimization
Biçe and Batun (2021)	✔					✔		✔			✔		✔	Uncertainty, Branch and cut
Diabat and Jebali (2021)		✔				✔		✔			✔		✔	Recycling legislation
Tautenhain et al. (2021)						✔		✔	✔		✔		✔	Social objective, Lagrangian-based heuristic
Ghomi-Avili et al. (2021)		✔				✔		✔	✔		✔	✔	✔	Uncertainty and disruption risks
Soleimani (2022)		✔		✔		✔		✔	✔		✔	✔	✔	Socialsustain ability goal, Lagrangian relaxation
Xu et al. (2022)		✔				✔		✔	✔		✔		✔	Stochastic optimization
Kim and Do Chung (2022)		✔	✔			✔		✔			✔	✔	✔	Reshoring drivers

Notes: the tick (√) represents that the characteristic is involved; the solid star (★) represents that the characteristic is further refined.

Table 1 Comparisions amongsome relevant literatures on CLSCND (continued)

Reference	Model construction							Objective		Decision content				Other Contributions
	Planning horizon		Delivery lead-time	Backorder	Delayed return	Operational capacity		Economics	Sustainability	Routing	Location	Inventory	Product flow	
	Single	Multi				facilities	equipment							
Zhalechian et al. (2016)		✔				✔	✔	✔	✔	✔	✔	✔		
Deng et al. (2016)	✔						✔	✔		✔	✔	✔		
Guo et al. (2018)	✔						✔	✔		✔	✔	✔		
De and Giri (2020)	✔					✔	✔	✔	✔	✔			✔	
Yuchi et al. (2021)	✔					✔	✔	✔		✔	✔	✔		
Sazvar et al. (2021)		✔				✔	✔	✔	✔	✔	✔	✔	✔	
This paper		✔	★	✔	★	✔	✔	✔	✔	★	✔	✔	✔	

Notes: the tick (√) represents that the characteristic is involved; the solid star (★) represents that the characteristic is further refined.

Social impact, Uncertainty, Hybrid metaheuristic algorithms

Hybrid Ant Colony Optimization Algorithm Novel heuristic algorithm

Scheduling

Uncertainty, Novel hybrid heuristic algorithm Social goal, Demand uncertainty

Novel heuristic algorithm combining local search and SA algorithm

3. Problem description and formulation

When designing a CLSC network structure, some scholars have designed the four-echelon CLSC network with suppliers, manufacturers, distribution centers/recycling centers, and customers (Almaraj & Trafalis, 2021; Kim & Do Chung, 2022; Shahparvari, 2022). Another group of scholars has designed the three-echelon CLSC with manufacturers, distribution centers/recycling centers, and customers (Pishvaee et al., 2010; Zhalechian et al., 2016; Keyvanshokooh et al., 2016; De & Giri, 2020; Guo et al., 2020; Prakash et al., 2020; Sazvar et al., 2021; Diabat & Jebali, 2021). We refer to the latter to construct a three-echelon CLSC network. In addition, according to the existing research (Keyvanshokooh et al., 2016; Prakash et al., 2020; Diabat & Jebali, 2021), we set the distribution center and the recycling center as two kinds of facilities, i.e., the distribution center undertakes the distribution business , the recycling center undertakes the recycling business, and the specific network structure is shown in **Figure 1** and **Figure 2**.

A multi-period CLSCND problem for single product is addressed in this paper. We consider the position of a manufacturer who tries to satisfy the product demands at retailers and recover the returned products at recyclers in each period. Backorder and delayed returns are allowed, but the penalty cost will be added when the situations happen.

The network consists of forward and reverse logistics. In this location problem, the structure of a CLSC network involves the location of some potential facilities to be decided: distribution centers and recycling centers. The manufacturing center, distribution centers and retailers participate in the activities of the forward logistics. Products produced in the manufacturing center will be shipped to the distribution centers in some periods. When the products arrive, the distribution centers update the inventory and may distribute some products to retailers in some periods. The manufacturing center, recycling centers and recyclers participate in the activities of the reverse logistics. The returned products recycled by some recyclers are required to be shipped to the recycling centers in some periods. In the recycling centers, all returned products will be inspected. Some returned products available to be reused will be repaired and stored, while the rest will be scrapped. Useful returned products will be shipped back to the manufacturing center in some periods. The period intervals between any two logistics nodes can be set as different integer parameters.

To realize the forward and reverse flows of products, transportation routes must be accommodated. According to the practical experience, the following rules on the routing problem are relatively common: (i) For unified management, the trucks' starting and ending points must be in the same location. The on-route truck cannot accept a new task until it is back to the starting point. (ii) All trucks starting from the manufacturing center are homogeneous heavy-duty trucks and are responsible for the distribution task in the upstream of the supply chain; while all trucks starting from the distribution centers or recycling centers are homogeneous light-duty trucks and are responsible for the distribution task in the downstream of the supply chain. In this way, the products cannot be directly delivered from the manufacturing center to retailers or from recyclers to the manufacturing center. And the change of starting points for each truck might affect the routing decision, such as transportation order, the number of trucks in each center and total costs. However, this situation will not be discussed in our model. (iii) A truck will not execute the same type of tasks on the same route. As for the reason, one is that backorder and delayed return are allowed and scattered product demands and returned products can be collected to avoid frequent and small-batch delivery, and the other is that the manufacturer may encourage retailers and recyclers to adjust the volumes when they place orders so that the trucks are highly or fully loaded. If a truck undertakes both distribution and recycling tasks, for simplification, the distribution task has higher priority than the recycling task.

Thus, the concepts of straight routes and circular routes are proposed as follows. A straight route is that a vehicle travels back and forth between two logistics nodes to complete a distribution task for one trip. A circular route is that a vehicle travels unidirectionally along the closed circuit composed by several logistics nodes to complete at least two distribution tasks for one trip. Based on the rules, two kinds of transportation mechanisms are formulated in our models: reversible transportation mechanism (RTM) (**Figure 1**) and circular transportation mechanism (CTM) (**Figure 2**).

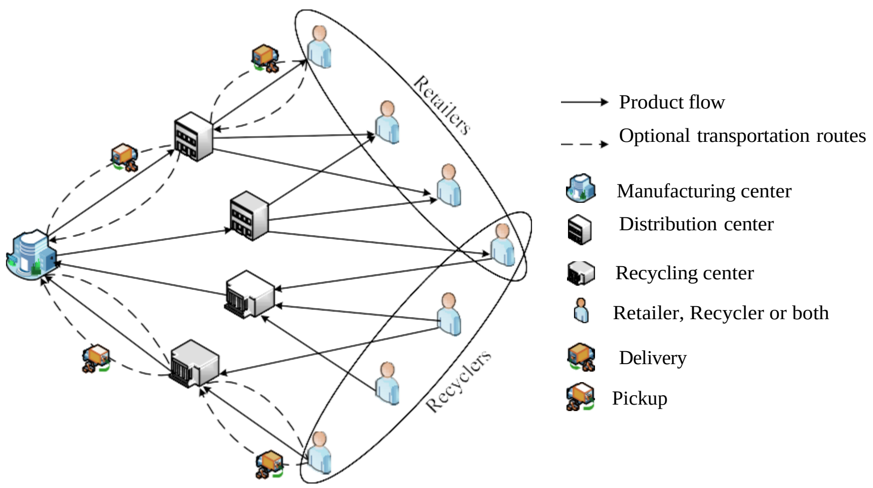

Figure 1. Product flow and route diagram in a CLSC network under RTM

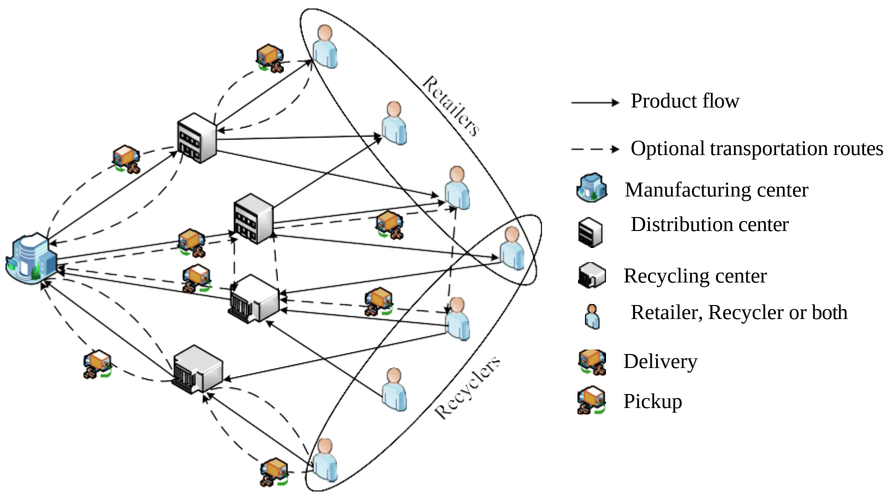

Figure 2. Product flow and route diagram in a CLSC network under CTM

The operation of a CLSC is demand-driven, so the demand of retailers and recyclers at each stage is set as $rd_{m,t}, rr_{n,t}$ respectively. Meanwhile, in order to have more realistic constructed model, this paper considers many realistic elements, including the capacity of equipment and facilities, backorders and delayed returns. The capacity of equipment and facilities mainly includes the following parameters: vehicle capacity (l_B, l_S for heavy-duty and light-duty truck), distribution center inventory capacity (cd_i), recycling center inventory capacity (cr_i), supply capacity and return capacity (sm_t, rm_t) for each period of manufacturing center. The backorder and delayed return of each period are $vm_{m,t}$ and $vn_{n,t}$ respectively, which are set as the state variables of each period in this paper. In addition, the design of CLSC networks in this paper mainly involves the location-inventory-routing decision problem. The location decision is whether to choose the corresponding distribution center or recycling center, which corresponds to two decision variables, Y_i and Z_j respectively. The inventory decision mainly controls the inventory levels of distribution centers and recycling centers in each period, corresponding to two state variables $vd_{i,t}, vr_{j,t}$ respectively. The routing problem requires the decision of available vehicles in each facility according to the transportation demand in each period, so this paper sets the available vehicles in manufacturing center, distribution center i and recycling center j as MC, MI_i, MJ_j, respectively, and they are decision variables. In addition, the distance and period interval of product transportation between nodes are closely related to each decision problem, so the distance and period interval parameters of transportation between facilities are set in this paper. The specific notations are shown in Table 2.

Table 2. Notations used in the formulation of the following models

Indices	
t	Index of operational periods $t = 1, \ldots, T$
i	Index of potential distribution center locations $i = 1, \ldots, I$
j	Index of potential recycling center locations $j = 1, \ldots, J$
m	Index of fixed locations of retailers (demands) $m = 1, \ldots, M$
n	Index of fixed locations of recyclers (returns) $n = 1, \ldots, N$
Model Parameters	
sm_t, rm_t	Supply capacity and recycle capacity limit of the manufacturing center in period t
σ_j	Disposal fraction of returned products in recycling center j
$rd_{m,t}$, $rr_{n,t}$	Product demands of retailer m and returns of recycler n in period t
cd_i, cr_j	Inventory capacity limit of potential distribution center i and potential recycling center j
l_B, l_S	Load limitation of a heavy-duty and light-duty truck
dx_i, px_i	Distance and period interval between the manufacturing center and distribution center i
du_{im}, pu_{im}	Distance and period interval between distribution center i and retailer m
dp_{mn}, pp_{mn}	Distance and period interval between retailer m and recycler n
dq_{nj}, pq_{nj}	Distance and period interval between recyclers n and recycling center j
dg_j, pg_j	Distance and period interval between recycling center j and the manufacturing center
de_{ij}, pe_{ij}	Distance and period interval between distribution center i and recycling center j
State Variables	
$vd_{i,t}$, $vr_{j,t}$	Products inventory at distribution center i and recycling center j in period t
$vm_{m,t}$	Backoreders at retailer m in period t
$vn_{n,t}$	Accumulated un-recycled returned products at recyclers n in period t
Common Decision Variables	
MC	Available trucks in the manufacturing center
MI_i, MJ_j	Available trucks in potential distribution center i and recycling center j
Y_i	$= \begin{cases} 1 & \text{If a distribution center is opened at location } i \\ 0 & \text{Otherwise} \end{cases}$
Z_j	$= \begin{cases} 1 & \text{If a recycling center is opened at location } j \\ 0 & \text{Otherwise} \end{cases}$

3.1 Economic cost measurement

A list of economic cost parameters is shown in **Table 3**. Initial investment cost on opening a new distribution center or recycling center is considered, and inventory and disposal cost are also involved in our model. In addition, backoreders and delayed returns have corresponding penalty costs. It is worth noting that shipping costs for heavy-duty and light-duty trucks can be divided into three parts: the initial investment on trucks, average empty running cost and shipping cost of marginal product. The average shipping cost of products can be estimated by experiments or previous operational data (Xiao et al., 2012).

Table 3. Economic cost parameters of the models

dfc_i, rfc_j	Fixed cost of expansion or opening new distribution center i and recycling center j
dvc_i, rvc_j	Variable cost of holding a unit of product at distribution center i and recycling center j
rdc_j	Disposal cost per unit in a recycling center j
α_m, β_n	Penalization of backoreders at retailer m and accumulated un-recycled returns at recycler n
ivi_B, ivi_S	Initial heavy-duty and light-duty trucks' investment per unit
cb_0, cb_1	Average empty running cost and shipping cost of a product for a heavy-duty truck (per kilometer)
cs_0, cs_1	Average empty running cost and shipping cost of a product for a light-duty truck (per kilometer)

3.2 Modeling under RTM

As illustrated in **Fig. 1**, a combinational model F_{RC} for the supply chain network under RTM is constructed. The decision variables for the four types of straight routes are listed in **Table 4**.

Table 4. Decision variables for the four types of straight routes

$AX_{i,t}$	Integer variable. The number of trucks that ship products from the manufacturing center to distribution center i in period t
$AU_{im,t}$	Integer variable. The number of trucks that ship products from distribution center i to retailer m in period t
$AQ_{nj,t}$	Integer variable. The number of trucks that travel from recycling center j to recycler n to load recycled products and then back to recycling center j in period t
$AG_{j,t}$	Integer variable. The number of trucks that travel from the manufacturing center to recycling center j to load recycled products and then back to the manufacturing center in period t
$X^s_{i,t}$	Quantities of products shipped from the manufacturing center to distribution center i by using straight route in period t
$U^s_{im,t}$	Quantities of products shipped from distribution center i to retailer m by using straight route in period t
$Q^s_{nj,t}$	Quantities of products shipped from recycler n to recycling center j by using straight routein period t
$G^s_{j,t}$	Quantities of products shipped from recycling center j to the manufacturing center by using straight route in period t

The CLSCND considering RTM consists of six aspects of cost. (1) Location cost, i.e. the fixed cost incurred in building distribution centers and recycling centers. (2) Vehicle cost, i.e. the fixed cost of all vehicles in manufacturing centers, distribution centers and recycling centers. (3) Inventory cost, i.e. the cost of holding inventory at opened distribution centers and recycling centers for each period. (4) Penalty cost, which are mainly due to backorders in forward logistics and delayed returns in reverse logistics. (5) Disposal cost, i.e. the cost of disposing of end-of-life recyclables at recycling centers. (6) Transport cost, which are mainly the costs incurred in the transportation of vehicles, both empty and non-empty.

Based on the above costs, a cost function (1) is constructed in this paper. In the objective function (1), the first two items are the costs of opening distribution and recycling centers, the third and fourth are the initial trucks' investment, the fifth and sixth are the inventory cost, the seventh and eighth are the penalizations of total backorders and accumulated un-recycled returns, the ninth is the disposal cost of scrapped returned products. The last four items measure the total en-route costs under RTM.

$$\boldsymbol{Minimize} \sum_{i\in I} dfc_i Y_i + \sum_{j\in J} rfc_j Z_j + ivi_B \times MC + ivi_S \times \left(\sum_{i\in I} MI_i + \sum_{j\in J} MJ_j\right) + \sum_{i\in I}\sum_{t\in T} dvc_i vd_{i,t} + \sum_{j\in J}\sum_{t\in T} rvc_j vr_{j,t}$$

$$+ \sum_{m\in M}\sum_{t\in T} \alpha_m vm_{m,t} + \sum_{n\in N}\sum_{t\in T} \beta_n vn_{n,t} + \sum_{n\in N}\sum_{j\in J}\sum_{t\in T} rdc_j \sigma_j Q^S_{nj,t} + \sum_{i\in I}\sum_{t\in T}[(2cb_0 AX_{i,t} + cb_1 X^S_{i,t}) dx_i]$$

$$+ \sum_{j\in J}\sum_{t\in T}[(2cb_0 AG_{j,t} + cb_1 G^S_{j,t}) dg_j] + \sum_{i\in I}\sum_{m\in M}\sum_{t\in T}[(2cs_0 AU_{im,t} + cs_1 U^S_{im,t}) du_{im}]$$

$$+ \sum_{j\in J}\sum_{n\in N}\sum_{t\in T}[(2cs_0 AQ_{nj,t} + cs_1 Q^S_{nj,t}) dq_{nj}] \tag{1}$$

subject to

$$vd_{i,t} = vd_{i,t-1} + X^S_{i,t-px_i} - \sum_{m\in M} U^S_{im,t} \qquad \forall i \in I, t \in T \tag{2}$$

$$vr_{j,t} = vr_{j,t-1} + (1-\sigma_j)\sum_{n\in N} Q^S_{nj,t-pq_{nj}} - G^S_{j,t} \qquad \forall j \in J, t \in T \tag{3}$$

$$\sum_{i\in I} U^S_{im,t-pu_{im}} + vm_{m,t} = rd_{m,t} \qquad \forall m \in M, t \in T \tag{4}$$

$$\sum_{j\in J} Q^S_{nj,t} + vn_{n,t} = rr_{n,t} \qquad \forall n \in N, t \in T \tag{5}$$

$$vd_{i,t} \le Y_i cd_i \qquad \forall i \in I, t \in T \tag{6}$$

$$vr_{j,t} \le Z_j cr_j \qquad \forall j \in J, t \in T \tag{7}$$

$$\sum_{i\in I} X^S_{i,t} \le sm_t \qquad \forall t \in T \tag{8}$$

$$\sum_{j\in J} G^S_{j,t-pq_{nj}} \le rm_t \qquad \forall t \in T \tag{9}$$

$$\sum_{m\in M} U^S_{im,t} \le vd_{i,t-1} \qquad \forall i \in I, t \in T \tag{10}$$

$$G^{S}_{j,t} \leq vr_{j,t-1} \qquad \forall j \in J, t \in T \tag{11}$$

$$AX_{i,t} \geq \frac{X^{S}_{i,t}}{l_B} \qquad \forall i \in I, t \in T \tag{12}$$

$$AG_{j,t} \geq \frac{G^{S}_{j,t}}{l_B} \qquad \forall j \in J, t \in T \tag{13}$$

$$AU_{im,t} \geq \frac{U^{S}_{im,t-pu_{im}}}{l_S} \qquad \forall i \in I, m \in M, t \in T \tag{14}$$

$$AQ_{nj,t} \geq \frac{Q^{S}_{nj,t-pq_{nj}}}{l_S} \qquad \forall j \in J, n \in N, t \in T \tag{15}$$

$$\sum_{i\in I} \sum_{t=\bar{t}-2px_i}^{\bar{t}} AX_{i,t} + \sum_{j\in J} \sum_{t=\bar{t}-2pg_j}^{t} AG_{j,t} \leq MC \qquad \forall \bar{t} \in T \tag{16}$$

$$\sum_{m\in M}\sum_{t=\bar{t}-2pu_{im}}^{\bar{t}} AU_{im,t} \le MI_i \qquad \forall i \in I, \bar{t} \in T \tag{17}$$

$$\sum_{n\in N}\sum_{t=\bar{t}-2pq_{nj}}^{\bar{t}} AQ_{nj,t} \le MJ_j \qquad \forall j \in J, \bar{t} \in T \tag{18}$$

$$vd_{i,0} = 0, \quad vr_{j,0} = 0, \quad vm_{m,0} = 0, \quad vn_{n,0} = 0 \qquad \forall i \in I, j \in J, m \in M, n \in N \tag{19}$$

$$vd_{i,t}, vr_{j,t}, vm_{m,t}, vn_{n,t} \ge 0 \qquad \forall i \in I, j \in J, m \in M, n \in N, t \in T \tag{20}$$

$$X^S_{i,t}, G^S_{j,t}, U^S_{im,t}, Q^S_{nj,t}, MC, MI_i, MJ_j \ge 0 \qquad \forall i \in I, j \in J, m \in M, n \in N, t \in T \tag{21}$$

$$Y_i, Z_j \in \{0,1\} \qquad \forall i \in I, j \in J \tag{22}$$

$$AX_{i,t}, AG_{j,t}, AU_{im,t}, AQ_{nj,t} \in \textbf{Integer} \qquad \forall i \in I, j \in J, m \in M, n \in N, t \in T \tag{23}$$

Constraint (2) and constraint (3) are inventory balance constraints. Constraint (2) ensures an equilibrium relationship between the inventory levels of the distribution center in period *t* and period (*t*-1), which is related to the upstream and downstream flows of forward logistics. Similarly, constraint (3) ensures an equilibrium relationship between the inventory levels of the recycling center in period *t* and period (*t*-1), which is related to the upstream and downstream flows of reverse logistics. Constraint (4) and constraint (5) are demand constraints. Constraint (4) ensures that all reatilers' demands are either satisfied or recorded backorders. Constraint (5) ensures that all returned products are either recycled or left un-recycled in the recyclers. Constraints (6) to (9) are facility capacity constraints. Constraint (6) indicates that the inventory level of the distribution center needs to be less than or equal to the inventory capacity for each period. Similarly, constraint (7) indicates that the inventory level at the recycling center needs to be less than or equal to the inventory capacity for each period. Constraint (8) indicates that the total supply quantity of the manufacturing center needs to be less than or equal to its supply capacity for each period. Constraint (9) indicates that the total recycling quantity of the manufacturing center needs to be less than or equal to its recycling capacity for each period. Constraint (10) and constraint (11) are real-time inventory constraints. Constraint (10) indicates that the distribution quantity from the distribution center in period *t* needs to be less than or equal to the inventory level in period (*t*-1). Similarly, constraint (11) indicates that the recycling quantity from the recycling center to the manufacturing center in period *t* needs to be less than or equal to the inventory level in period (*t*-1). Constraints (12) to (18) are vehicle constraints. Among them, constraints (12) to (15) are the vehicle quantity satisfaction constraints. Constraint (12) represents that the manufacturing center has sufficient distribution vehicles to complete the amount of distribution tasks in period *t*. Constraint (13) indicates that the manufacturing center has sufficient recycling vehicles to complete the recycling tasks in period *t*. Constraint (14) indicates that the distribution center has enough distribution vehicles to complete the distribution tasks in period t. Constraint (15) indicates that the recycling center has enough recycling vehicles to complete the recycling task in period t. Constraints (16) to (18) are vehicle number limit constraints, which ensure the number of trucks which execute transportation assignments in each period cannot exceed the number of available vehicles at each center. Constraint (19) involves three hard constraints that assure the inventory level of all distribution and recycling centers, backorders of all retailers and accumulated un-recycled products of all recyclers are equal to zero at period 0. Constraints (20) to (23) enforce the non-negativity, binary and integer restrictions on corresponding decision variables.

3.3 Modeling under CTM

As illustrated in **Fig. 2**, a combinational model F_{CC} for the supply chain network under CTM is constructed. The decision variables for the two types of circular routes are listed in **Table 5**.

Table 5. Decision variables for the two types of circular routes

$AE_{ij,t}$	Integer variable. The number of trucks that ship products from the manufacturing center to distribution center i, then travel to recycling center j to load recycled products and finally back to the manufacturing center in period t
$AP_{imnj,t}$	Integer variable. The number of trucks that shipproducts from distribution center i to retailer m, travel to recycler n to load recycled products and then travel to recycling center j to unload, finally back to distribution center i in period t
$X^{C}_{ij,t}$	Quantities of products shipped from the manufacturing center to distribution center i by using the circular route in period t, the truck will travel to recycling center j.
$U^{C}_{imnj,t}$	Quantities of products shipped from distribution center i to retailer m by using the circular route, the truck will travel to recycler n and then ship returned products to recycling center j in period t
$Q^{C}_{imnj,t}$	After shiping products from distribution center i to retailer m, quantities of products shipped from recycler n to recycling center j by using the circular route in period t
$G^{C}_{ij,t}$	After shiping products to distribution center i, quantities of products shipped from recycling center j to the manufacturing center by using the circular route in period t

In contrast to RTM, CTM requires further consideration of the circular route decision variables due to the existence of circular routes in CTM, mainly in the disposal cost and transportation cost. Therefore, we add circular route decision variables to these two costs, as reflected in the disposal cost of scrapped returned products (the ninth item) and the total en-route cost (the tenth item to the thirteenth item) in CTM objective (24). In addition, unlike the RTM, the CTM has transport routes between the distribution center and the recycling center, and between the retailer and the recycler, so the objective (24) also takes into account of both transport costs.

$$\boldsymbol{Minimize} \sum_{i\in I} dfc_i Y_i + \sum_{j\in J} rfc_j Z_j + ivi_B \times MC + ivi_S \times \Big(\sum_{i\in I} MI_i + \sum_{j\in J} MJ_j\Big) + \sum_{i\in I}\sum_{t\in T} dvc_i vd_{i,t} + \sum_{j\in J}\sum_{t\in T} rvc_j vr_{j,t}$$

$$+ \sum_{m\in M}\sum_{t\in T} \alpha_m vm_{m,t} + \sum_{n\in N}\sum_{t\in T} \beta_n vn_{n,t} + \sum_{n\in N}\sum_{j\in J}\sum_{t\in T} rdc_j \sigma_j \Big(Q^S_{nj,t} + \sum_{i\in I}\sum_{m\in M} Q^C_{imnj,t}\Big)$$

$$+ \sum_{i\in I}\sum_{t\in T} \Big[\Big(2cb_0 AX_{i,t} + cb_0 \sum_{j\in J} AE_{ij,t} + cb_1 \Big(X^S_{i,t} + \sum_{j\in J} X^C_{ij,t}\Big)\Big) dx_i\Big]$$

$$+ \sum_{j\in J}\sum_{t\in T} \Big[\Big(2cb_0 AG_{j,t} + cb_0 \sum_{i\in I} AE_{ij,t} + cb_1 \Big(G^S_{j,t} + \sum_{i\in I} G^C_{ij,t}\Big)\Big) dg_j\Big]$$

$$+ \sum_{i\in I}\sum_{m\in M}\sum_{t\in T} \Big[\Big(2cs_0 AU_{im,t} + cs_0 \sum_{n\in N}\sum_{j\in J} AP_{imnj,t} + cs_1 \Big(U^S_{im,t} + \sum_{n\in N}\sum_{j\in J} U^C_{imnj,t}\Big)\Big) du_{im}\Big]$$

$$+ \sum_{j\in J}\sum_{n\in N}\sum_{t\in T} \Big[\Big(2cs_0 AQ_{nj,t} + cs_0 \sum_{i\in I}\sum_{m\in M} AP_{imnj,t} + cs_1 \Big(Q^S_{nj,t} + \sum_{i\in I}\sum_{m\in M} Q^C_{imnj,t}\Big)\Big) dq_{nj}\Big]$$

$$+ \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} cb_0 AE_{ij,t} de_{ij} + \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{n\in N}\sum_{t\in T} cs_0 AP_{imnj,t}(de_{ij} + dp_{mn}) \qquad (24)$$

subject to constrains$(\mathbf{6}) - (\mathbf{7}), (\mathbf{12}) - (\mathbf{15})$and $(\mathbf{18}) - (\mathbf{23})$

$$vd_{i,t} = vd_{i,t-1} + X^S_{i,t-px_i} + \sum_{j\in J} X^C_{ij,t-px_i} - \sum_{m\in M} \Big(U^S_{im,t} + \sum_{n\in N}\sum_{j\in J} U^C_{imnj,t}\Big) \qquad \forall i \in I, t \in T \qquad (25)$$

$$vr_{j,t} = vr_{j,t-1} + (1 - \sigma_j) \sum_{n\in N} \Big(Q^S_{nj,t-pq_{nj}} + \sum_{i\in I}\sum_{m\in M} Q^C_{imnj,t-pq_{nj}}\Big) - G^S_{j,t} - \sum_{i\in I} G^C_{ij,t} \qquad \forall j \in J, t \in T \qquad (26)$$

$$\sum_{i\in I} \Big(U^S_{im,t-pu_{im}} + \sum_{n\in N}\sum_{j\in J} U^C_{imnj,t-pu_{im}}\Big) + vm_{m,t} = rd_{m,t} \qquad \forall m \in M, t \in T \qquad (27)$$

$$\sum_{j\in J} Q^S_{nj,t} + \sum_{i\in I}\sum_{j\in J}\sum_{m\in M} Q^C_{imnj,t} + vn_{n,t} = rr_{n,t} \qquad \forall n \in N, t \in T \qquad (28)$$

$$\sum_{i\in I} \Big(X^S_{i,t} + \sum_{j\in J} X^C_{ij,t}\Big) \le sm_t \qquad \forall t \in T \qquad (29)$$

$$\sum_{j\in J} G^S_{j,t-pq_{nj}} + \sum_{i\in I}\sum_{j\in J} G^C_{ij,t-pq_{nj}} \le rm_t \qquad \forall t \in T \tag{30}$$

$$\sum_{m\in M} \left(U^S_{im,t} + \sum_{n\in N}\sum_{j\in J} U^C_{imnj,t}\right) \le vd_{i,t-1} \qquad \forall i \in I, t \in T \tag{31}$$

$$G^S_{j,t} + \sum_{i\in I} G^C_{ij,t} \le vr_{j,t-1} \qquad \forall j \in J, t \in T \tag{32}$$

$$AE_{ij,t} \ge \frac{\max\left(X^C_{ij,t}, G^C_{ij,t-pe_{ij}-px_i}\right)}{l_B} \qquad \forall i \in I, j \in J, t \in T \tag{33}$$

$$AP_{imnj,t} \ge \frac{\max\left(U^C_{imnj,t}, Q^C_{imnj,t-pp_{mn}-pu_{im}}\right)}{l_S} \qquad \forall i \in I, j \in J, m \in M, n \in N, t \in T \tag{34}$$

$$\sum_{i\in I}\sum_{t=\bar{t}-2px_i}^{t} AX_{i,t} + \sum_{j\in J}\sum_{t=\bar{t}-2pg_j}^{t} AG_{j,t} + \sum_{i\in I}\sum_{j\in J}\sum_{t=\bar{t}-pg_j-pe_{ij}-px_i}^{t} AE_{ij,t} \le MC \qquad \forall \bar{t} \in T \tag{35}$$

$$\sum_{m\in M}\sum_{t=\bar{t}-2pu_{im}}^{t} AU_{im,t}+\sum_{m\in M}\sum_{n\in N}\sum_{j\in J}\sum_{t=\bar{t}-pu_{im}-pp_{mn}-pq_{nj}-pe_{ij}}^{t} AP_{imnj,t}\leq MI_i \qquad \forall i\in I,\bar{t}\in T \tag{36}$$

$$X^C_{ij,t}, G^C_{ij,t}, U^C_{imnj,t}, Q^C_{imnj,t} \geq 0 \qquad \forall i\in I, j\in J, m\in M, n\in N, t\in T \tag{37}$$

$$AE_{ij,t}, AP_{imnj,t} \in \textbf{Integer} \qquad \forall i\in I, j\in J, m\in M, n\in N, t\in T \tag{38}$$

As with the FRC model, the FCC model also contains constraints (6)-(7), (12)-(15) and (18)-(23). These constraints have the same realistic meaning. In addition, the FCC model contains decision variables for the circular routes, so the remaining constraints need to take full account of the circular route decision variables. Constraints (25) and (26) are inventory balance constraints for distribution centers and recycling centers respectively, replacing constraints (2) and (3). Constraint (25) adds the distribution quantity corresponding to the circular routes. Constraint (26) adds the recycling quantity corresponding to the circular routes. Constraints (27) and (28) are demand constraints for retailers and recyclers respectively, replacing constraints (4) and (5). Constraint (27) adds the distribution quantity distributed to retailer *m* in cycle route in period *t*. Constraint (26) adds the recycling quantity recovered to recycler *n* in cycle route in period *t*. Constraint (29) and constraint (30) are the supply and recycling capacity constraints for the manufacturing center, respectively, replacing constraints (8) and (9). Constraint (29) adds the supply quantity corresponding to the circular route. Constraint (30) adds the recycling quantity corresponding to the circular route. Constraints (31) and (32) are real-time inventory constraints for distribution centers and recycling centers respectively, replacing constraints (10) and (11). Constraint (31) indicates that the sum of the distribution quantity of distribution center *i* by the direct routes and the distribution quantity by the circular routes in period *t* needs to be less than or equal to the inventory level of distribution center *i* in period (*t*-1). Constraint (32) indicates that the sum of the recycling quantity of recycling center *j* to the manufacturing center using the direct and circular routes in period *t* needs to be less than or equal to the inventory level in period (*t*-1). Constraints (33) to (36) are vehicle constraints. And constraint (33) and constraint (34) are vehicle quantity satisfaction constraints. Constraint (33) indicates that the manufacturing center has sufficient distribution vehicles to complete the tasks of the circular routes in period *t*. This task quantity takes the maximum of the distribution and recovery quantities within the circular routes. Constraint (34) indicates that each circulation route from the distribution center needs to have sufficient distribution vehicles to complete its task quantity, which is taken as the maximum of the distribution and recovery quantities within the circulation routes. Constraints (16) to (18) are vehicle number limit constraints, which ensure that the number of trucks that execute all transportation assignments cannot exceed the number of available vehicles at the manufacturing center and distribution centers under CTM. Finally, Constraints (37) and (38) enforce the non-negativity and integer restrictions on decision variables for circular routes.

4. Solution generation method

To solve the NP-hard CLSCND problem on large scales, a heuristic method is designed, which is composed of two stages: initialization stage and improvement stage. In **Figure 3**, the flowchart of the proposed heuristic method is demonstrated.

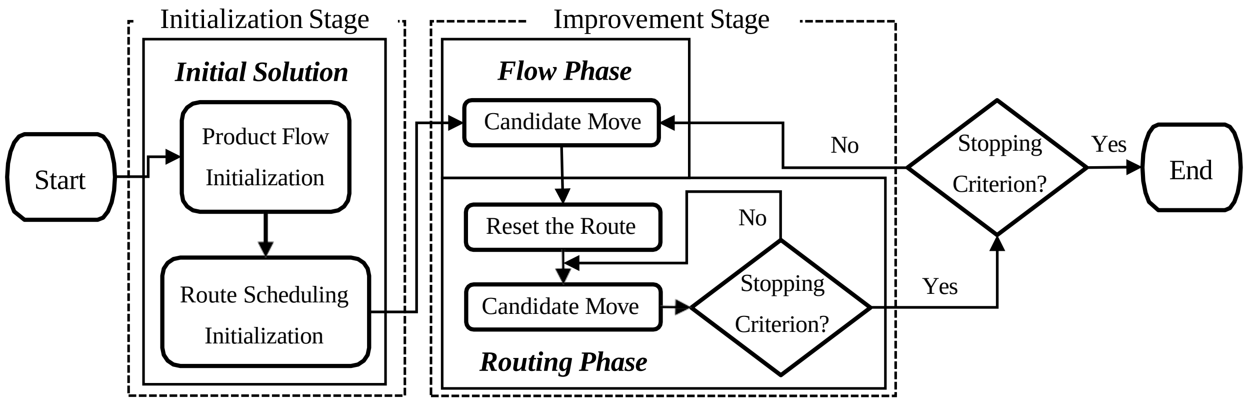

Figure 3. Flowchart of the proposed heuristic method.

Simulated Annealing (SA) is motivated by an analogy to the annealing process of solids (Metropolis et al., 1953), which can be applied to optimization problems (Kirkpatrick et al. 1983). The local search process guided in SA is shown as **Algorithm 1**. A neighborhood solution is accepted as the new current if improving the performance. Rather than always rejecting non-improvement moves at each iteration, SA accepts non-improvement moves with a probability related to TP, which is a parameter called the "temperature". The initial and final temperature values are denoted by TP_H and TP_L respectively, and the temperature decay coefficient is denoted by TDC.

Algorithm 1. SA for the models of CLSCND problem

1. Create initial solution $\aleph_0$ on initialization stage.
2. Set $\aleph = \aleph_0$, $\aleph_{\text{best}} = \aleph_0$ and $TP = TP_H$.
3. **While** $TP \geq TP_L$
4. Improve the product flow of current solution $\aleph$ on the flow phase of improvement stage.
5. Improve the route problem based on the improved product flow on the routing phase of improvement stage.
6. **If** the cost of obtained new solution $\aleph_{\text{new}}<$ the cost of $\aleph_{\text{best}}$
7. $\aleph = \aleph_{\text{new}}$, $\aleph_{\text{best}} = \aleph_{\text{new}}$.
8. **Else if** $\exp((\text{cost of } \aleph - \text{cost of } \aleph_{\text{new}})/TP) > RAND(0,1)$
9. $\aleph = \aleph_{\text{new}}$

10. $TP = TP * TDC$

4.1 Initialization Stage

Since the CLSCND problem is complicated with many constraints, we try to generate a feasible solution in the initialization step and keep the feasibility of solutions in further optimal steps. This strategy can effectively avoid the challenge that adjusts solutions to fit the constrains' requirements. An initial solution on modeling under RTM and CTM is constructed by two steps: constructing initial product flows for forward and reverse logistics and constructing initial routes under RTM and CTM (**Algorithm 2**).

Although the initial product flows for forward and reverse logistics are constructed separately, their procedures are similar. The fundamental idea is to gradually satisfy the demands of retailers or recyclers in order of period, and we make light-duty trucks fully loaded as much as possible. In each period, an opened center is randomly selected for each retailer or recycler when its demand exceeds the load limitation of a light-duty truck. Maximal product flows in the upstream and downstream of the supply chain and the inventory change of the selected center can be calculated by evaluating the supply and recycle capacity constraints of the manufacturing center and the inventory capacity constraint of the selected center. If the constraints have no effect, the product flows in the upstream and downstream will be set as the load limitation of a light-duty truck; otherwise, the product flows will be set as much as possible. Also, the product flows in the upstream and downstream will be recorded in pairs. When the unsatisfied demand of the retailer or recycler still exceeds the load limitation of a light-duty truck, but all opened centers are selected, all unopened centers will be examined to find out whether they can satisfy demands of the retailer or recycler. If such unopened centers exist, one of them can be randomly opened. After considering all the above situations, all unsatisfied demands, no matter large or small-batch, will be recorded backorders.

Initial routes under RTM and CTM can be constructed in two different ways. Under RTM, when the initial product flow is determined in the previous step, all the travel routes are also determined. Under CTM, a travel route will achieve a forward and reverse product flow at the same time. Hence, we try to match each forward flow to the corresponding reverse flow and generate as many circular routes as possible, and the rest of mismatched forward and reverse flows will be assigned on straight routes. Moreover, each time a route is formulated, one of the currently available heavy-duty and light-duty trucks is randomly selected to finish the route. If no availiable trucks can be selected, add a new one.

Algorithm 2. Constructing an initial solution on modeling under RTM and CTM

Construction of initial product flow for forward [reverse] logistics

1. Set $Y_i = 0[Z_j = 0]$, $vd_{i,t} = 0[vr_{j,t} = 0]$, $vm_{m,t} = 0[vn_{n,t} = 0]$, $X_{i,t} = U_{im,t} = G_{j,t} = Q_{nj,t} = 0$
2. **For** $t = 1$ **to** T
3. **While** $\exists m \in \{m | rd_{m,t} > 0\}[\exists n \in \{n | rr_{n,t} > 0\}]$
4. Randomly select a retailer $m[n]$ where $rd_{m,t} > 0$ $[rr_{n,t} > 0]$.
5. Set $UY = i \in \{i|Y_i = 1\}[UZ = j \in \{j|Z_j = 1\}]$.
6. **While** $UY \neq \emptyset[UZ \neq \emptyset]$ **and** $rd_{m,t} \geq l_S[rr_{n,t} \geq l_S]$
7. Randomly select a center $i[j]$ out of $UY[UZ]$, where $UY -= i[UZ -= j]$
8. $s = \min(sm_{t-px_i-pu_{im}-1}, cd_i - vd_{i,t-pu_{im}-1}, l_S)$ $[s = \min(rm_{t+pg_j+pq_{nj}+1}, cr_j - vr_{j,t+pq_{nj}}, (1-\sigma_j)l_S)]$.
9. $sm_{t-px_i-pu_{im}-1} -= s,\ vd_{i,t-pu_{im}-1} += s,\ rd_{m,t} -= s,\ X_{i,t-px_i-pu_{im}-1} += s,\ U_{im,t-pu_{im}} += s$ $[rm_{t+pg_j+pq_{nj}+1} -= s, vr_{j,t+pq_{nj}} += s,\ rr_{n,t} -= \frac{s}{1-\sigma_j}, G_{j,t+pq_{nj}+1} += s, Q_{nj,t} += \frac{s}{1-\sigma_j}]$.
10. **If** $rd_{m,t} \geq l_S[rr_{n,t} \geq l_S]$
11. Perform step 8 to obtain $s_i[s_j]$ for all unopened centers $i[j]$
12. **If** $\exists i \in \{i|s_i > 0\}[\exists j \in \{j|s_j > 0\}]$
13. Randomly select an unopened centers $i[j]$, set $Y_i = 1[Z_j = 1]$ and add $i[j]$ into $UY[UZ]$.
14. **Else**
15. $vm_{m,t} = rd_{m,t}[vn_{n,t} = rr_{n,t}]$, $rd_{m,t+1} += vm_{m,t}$ $[rr_{n,t+1} = vn_{n,t}]$, $rd_{m,t} = 0$ $[rr_{n,t} = 0]$.
16. **Else**
17. $vm_{m,t} = rd_{m,t}[vn_{n,t} = rr_{n,t}]$, $rd_{m,t+1} += vm_{m,t}$ $[rr_{n,t+1} = vn_{n,t}]$, $rd_{m,t} = 0$ $[rr_{n,t} = 0]$.

Construction of initial routes under RTM and CTM

18. Set $MC = MI_i = MJ_j = 0$.
19. **For** $t = 1$ **to** T
20. ***RTM*:** Based on $X^S_{i,t}$, $U^S_{im,t}$, $G^S_{j,t}$, and $Q^S_{nj,t}$, randomly assign availiable heavy-duty or light-duty trucks on straight routes. **If** inadequate, **then** add a new truck and increase MC, MI_i and MJ_j.
21. ***CTM*:** Randomly select a forward flow $X^S_{i,t}$ $[U^S_{im,t}]$, find whether $G^S_{j,t+px_i+pe_{ij}} > 0[Q^S_{nj,t+pp_{mn}+pu_{im}} > 0]$ exist. **If** exist, **then** randomly select a j and assign avaliable heavy-duty[light-duty] trucks on circular routes; **Else**, assign them on straight routes. The possibly remaining reverse flows are all achieved by assigning trucks on straight routes. **If** inadequate, **then** add a new truck and increase MC, MI_i and MJ_j.

Notes: $UY[UZ]$ represents the sets of currently-open distribution (recycling) centers that are not selected

4.2 Improvement Stage

The current solution is improved by alternatively modifying decisions in two phases: the flow phase and routing phase. First, a neighboring product flow of current solution is generated by 1) random candidate moves in the flow phase, the route is reset based on moved product flow and to improve the route by SA, and 2) random candidate moves in the routing phase. The obtained new solution is improved in the flow phase, and the procedure is continued in the same manner until the stopping criterion is satisfied. Note that when the candidate moves are failed, it will skip to the next iteration of the loop. Then, the obtained product flow will be further applied as an input to the routing phase.

In reality, when the utilization rate of a center or a truck is low, we tend to transform its relevant flows or routes to other centers or trucks with higher utilization rates and further try to close the center or truck. To guide the selection of inefficient centers and trucks, roulette wheel selection (RWS), which is based on the proportion select method and sampling with replication, is applied in the candidate moves Mov_4 to Mov_8. Besides, soft constraints are used to decide the location of each distribution centers and the use of trucks. The inventory levels of all opened centers and the routes of all opened trucks will be examined after each relevant candidate move. For an opened center, if all inventory levels in each period are equal to zero, the center will automatically be closed off. For an opened truck, if there is no route on it, the truck will automatically be closed off and the number of the same truck will decrease by one.

Flow phase. In this phase, the main objective is to generate a neighboring product flow by modifying the locations of distribution and recycling centers, inventory level of each opened center and allocation of the retailers' and recyclers' demands. Five different types of candidate moves will be applied, which are Mov_1 to Mov_5 respectively. Mov_1 mainly changes the centers at both ends of the product flow by changing the location status of centers, so as to generate the neighbors of the product flow. The determination of product flows is closely related to the number of backorders and delayed returns in the planning horizon, so we generate neighbors of product flow by increasing and decreasing the number of backorders and delayed returns, which are reflected in Mov_2 and Mov_3. In addition, we generate neighbors of product flow by changing the product flow direction in spatial and temporal dimensions, which are embodied in Mov_4 and Mov_5, respectively. We randomly select a candidate move from these moves to obtain a new product flow in the neighborhood of the current product flow.

Mov_1: Center replacement. One of the opened distribution or recycling centers is randomly closed, one of the unopened distribution or recycling centers is randomly opened, and all of the flows corresponding to the eliminated center will be reassigned to the new opened center. In this move, the inventory level of the two centers are updated. If the inventory capacity of the new opened center is inadequate, the candidate move is failed.

Mov_2: Backorder or delayed return reduction. First, we randomly select a period t and a retailer m or recycler n where the backorder or delayed return exists, and randomly select an opened distribution center i or recycling center j. Then, a maximal product flow will be determined according to step 8 in **Algorithm 2**, and the smaller of the maximal product flow and the number of backorders or delayed returns is set as s. If $s = 0$ for all opened distribution centers or recycling centers, execute steps 11 to 13 in **Algorithm 2** to open a new distribution center or recycling center. Next, gradually increase the period t_1 until there is existing a period t_2 that makes $U^S_{im,t_2-pu_{im}} > s$ or $Q^S_{nj,t_2} > s/(1-\sigma_j)$. If exist, set $U^S_{im,t_2-pu_{im}} -= s$, $U^S_{im,t_1-pu_{im}} += s$, $X^S_{i,t_2-px_i-pu_{im}-1} -= s$ and $X^S_{i,t_1-px_i-pu_{im}-1} += s$, or $Q^S_{nj,t_2} -= s/(1-\sigma_j)$, $Q^S_{nj,t_1} += s/(1-\sigma_j)$, $G^S_{j,t_2+pq_{nj}+1} -= s/(1-\sigma_j)$ and $G^S_{j,t_1+pq_{nj}+1} += s/(1-\sigma_j)$. Besides, the inventory level of the selected distribution center i or recycling center j is updated; otherwise, the candidate move failed. Moreover, if $t_1 = T$, the shortage will be made up as much as possible without considering a future period t_2. For the above local search process, we hope to reduce the backorder or delayed return according to the remaining capacity of the manufacturer, distribution centers and recycling centers, thereby generating neighbors of product flow.

Mov_3: Backorder or delayed return increase. First, we randomly select a product flow $U^S_{im,t}$ or $Q^S_{nj,t}$ in the downstream of the supply chain in period t. Then, for period $t+1$, a maximal product flow will be determined according to the step 8 in **Algorithm 2**, and the smaller of the maximal product flow and the product flow $U^S_{im,t}$or $Q^S_{nj,t}$ is set as s. Next, it sets $U^S_{im,t-pu_{im}} -= s$, $U^S_{im,t+1-pu_{im}} += s$, $X^S_{i,t-px_i-pu_{im}-1} -= s$ and $X^S_{i,t-px_i-pu_{im}} += s$, or $Q^S_{nj,t} -= s/(1-\sigma_j)$, $Q^S_{nj,t+1} += s/(1-\sigma_j)$, $G^S_{j,t+pq_{nj}+1} -= s/(1-\sigma_j)$ and $G^S_{j,t+pq_{nj}+2} += s/(1-\sigma_j)$. Besides, the inventory level of the selected center i or j is updated. Moreover, if $t \geq T - pu_{im}$ (forward flow) or $t = T$(reverse flow), the product flow $U^S_{im,t}$ or $Q^S_{nj,t}$ can be directly deleted and the shortage will be increased.

Mov_4: Product flow direction change. In our models, the average inventory levels, $\sum_t vd_{i,t}/T$ and $\sum_t vr_{j,t}/T$, are simple but useful indexes to measure the utilization rates of distribution center i and recycling center j. First, the RWS is used to select a center i_1 or j_1

based on the reciprocal of the average inventory level of each center. It suggests that the centers with lower utilization are more likely to be selected. Then, it selects a period t and a retailer m or recycler n where the product flow exists randomly, and tries to find another opened center i_2 or j_2 to achieve the flow. Finally, it deletes the original flow of the center i_1 or j_1, formulates a new flow of the center i_2 or j_2, and updates the inventory levels. In the above local search process, we transfer product flows corresponding to the centers with low utilization rate to other centers from the spatial dimension, so as to generate the neighbors of product flows and improve the utilization rate of centers.

Mov_5: Stock up in advance. First, the RWS is used to select a period t based on the reciprocal of the left supply capacity sm'_t or the left recycle capacity rm'_t. It suggests that a period with a smaller manufacturer's supply capacity or recycling capacity is more likely to be selected. Then, it randomly selects a distribution center i or recycling center j where $X^S_{i,t} > 0$ or $G^S_{j,t} > 0$, searches the product flows in the upstream and downstream which are recorded in pairs. Finally, it randomly selects a pair including the product flow in the upstream in period t. If it is a forward flow, it moves the product flow in the upstream to the previous period; on the other hand, if it is a reverse flow, it moves the flow to the next period. Moreover, the inventory level of the center is also updated. In the above local search process, we transfer the product flow corresponding to the period when the manufacturer's supply ability or recycling ability is smaller to other periods from the time dimension, so as to generate the neighbors of product flows.

Routing phase. Based on the improved product flow phase, the route problem in the current solution will be reset according to the steps 18 to 21 in **Algorithm 2**. Then, the route problem is further improved by SA. For the SA parameters in this phase, the initial and final temperature values are denoted by TP'_H and TP'_L respectively, and the temperature decay coefficient is denoted by TDC'.

When the product flows for forward and reverse logistics are determined in the flow phase, effective routing optimization is conducive to the realization of reducing total cost. Relevant costs on routing phase consists of initial heavy-duty and light-duty trucks' investment and average empty running cost for heavy-duty and light-duty trucks.

The three different types of candidate moves are proposed, which are Mov_6, Mov_7 and Mov_8. The move Mov_6 can be applied to solve the model with both RTM and CTM, but the moves Mov_7 and Mov_8 can only be applied to solve the model with CTM. We randomly select a candidate move from these three moves to obtain a new route and truck assignment plan in the neighborhood of the current route and truck assignment plan. In the following moves, a new index $\boldsymbol{Util}$ is defined as the utilization rate of each truck, and it can be calculated by dividing total en-route periods by total analysis periods. Moreover, for the candidate moves Mov_6, Mov_7 and Mov_8, the first steps all use the RWS to select a heavy-duty or light-duty truck based on $1/\boldsymbol{Util}$ of each truck. It shows that the truck with lower utilization is more likely to be selected, and the local search for it is more likely to improve the quality of the solution.

Mov_6: Route reassignment. Based on the selected truck, it selects an existing route on the truck randomly, and tries to find another heavy-duty or light-duty truck to execute the route with higher $\boldsymbol{Util}$. Finally, it moves the route in the selected truck to the newly found truck, and updates the index $\boldsymbol{Util}$. In the above local search process, we hope to transfer the route corresponding to the low-utilization vehicle to the high-utilization vehicle, so as to reduce the transportation cost.

Mov_7: Straight route to circular route. Based on the selected truck, it selects an existing straight route on the truck randomly, and tries to find another straight route on another heavy-duty or light-duty truck to formulate a new circular route. Finally, it deletes the original two straight routes from the above two trucks, and finds a new heavy-duty or light-duty truck with higher $\boldsymbol{Util}$ to execute the circular route.

Mov_8: Circular route to straight route. Based on the selected truck, it selects an existing circular route on the truck randomly, and separates the circular route into two straight routes. Finally, it deletes the original circular route from the selected truck, and finds some new heavy-duty or light-duty trucks with higher $\boldsymbol{Util}$ to execute the two straight routes.

The heuristic is applied to the solution found in the routing phase. By the above three moves, the SA proceeds until $TP < TP_L{}'$ at this phase. When we exit from this phase, the stopping criterion of the algorithm is checked. If the stopping criterion ($TP < TP_L$) is met, it will stop, otherwise it will proceed to the flow phase.

To optimize location, inventory and routing decisions in supply chain network design simultaneously, Javid and Azad (2010) proposed five candidate moves to improve the current solution by modifying location and routing decisions. However, some moves are frequently unsuccessful to generate a neighborhood solution because they forcibly close a center or vehicle and reassign all relevant flows and routes to other centers or vehicles. To overcome this problem, we gradually reduce the use of inefficient centers and trucks by the RWS and apply soft constraints to close the useless centers and trucks in our heuristic method.

5. Numerical studies

To prove the model having a good large-scale engineering application value, we select a representative Chinese plastic toy manufacturer as an example for a computational experiment and simulation. The company produces, distributes and recycles plastic toy products and is located in Shantou, Guangdong Province, China. A popular plastic toy product of the company, Toy Gyro, is selected for analysis. The reasons are as follows: First, the Toy Gyro as a single product fits the single product assumption of our CLSC network model. Second, the CLSC network structure of Toy Gyro is very consistent with the CLSC network structure in this paper. Third, there is an urgent need to design CLSC for Toy Gyro products in order to reduce operational costs and environmental pollution. In addition, decision problems in the above CLSC network are consistent with our research, including the distribution centre/recycling centre location problem, the facility inventory decision problem and the routing decision problem at each echelon.

As shown in **Figure 4**, the geographic locations of 26 cities are denoted by uppercase letters (**A**–**Z**). All of these cities domicile the manufacturer's target retailers and recyclers. Meanwhile, their sites are treated as the locations of potential distribution centers and recycling centers. These cities can be divided into 13 inland cities and 13 coastal cities, and the single manufacturing center is at Shantou City (**Z**). Two sets of projects are under consideration: inland truck delivery (ITD) and countrywide truck delivery (CTD). For the project of ITD, only 13 inland cities are involved in the model, and the other 13 coastal cities will adopt sea transportation (neglected in this experiment). For the project of CTD, all of the 26 cities will be covered.

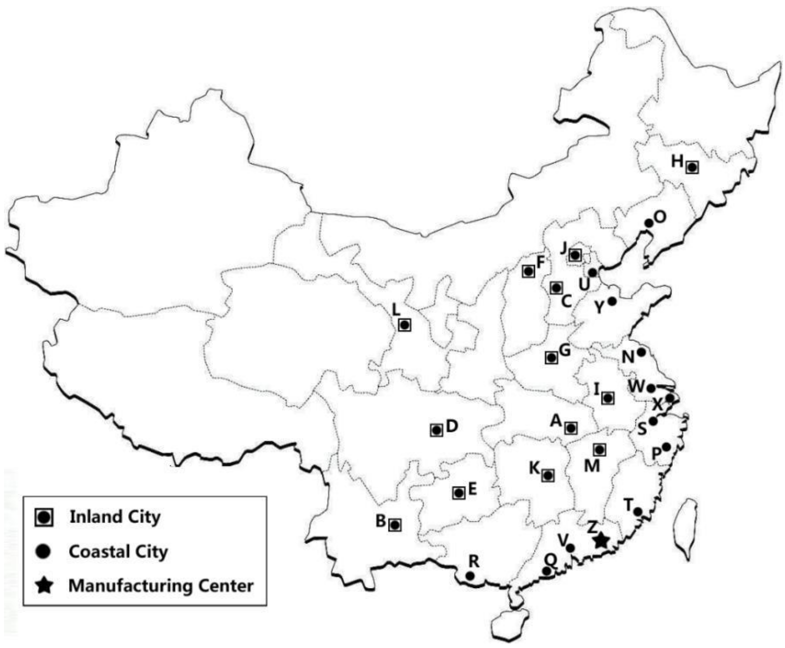

Figure 4. Geographic information of relevant cities in the CLSCND problem

Historical statistics for the models are obtained or estimated by the toy manufacturer investigation and interviews. The data on routing aspects majorly comes from the Baidu Map (*http://map.baidu.com*). The unit of each period is set as half-day and the total length of the analysis period is a month. Hence, the number of decision-making periods is equivalent to 60 periods. The problem size $|t| \times |i| \times |j| \times |m| \times |n|$ of ITD is $60 \times 13 \times 13 \times 13 \times 13 = 1{,}713{,}660$, and that of CTD is $60 \times 26 \times 26 \times 26 \times 26 = 27{,}418{,}560$. All the models and algorithms are coded and solved by C++ on an Intel(R) Core(TM) 2.60 GHz computer with 8 GB RAM.

For better analyzing the performance of the proposed models F_{RC} and F_{CC}, we conduct a sensitivity analysis which is performed with the changing parameter values of the demand of new products at retailers $rd_{m,t}$ and un-recycled returned products at recyclers $rr_{n,t}$ in each period. On the project of both ITD and CTD, the parameter values of $rd_{m,t}$ and $rr_{n,t}$ are changed from 50% to 150% with a step size of 10%. Thus, both projects generate 11 instances, and each instance is executed 10 times and the average performance is taken as the final result. The computational environments for these instances are summarized as follows. For the project of ITD, the initial temperature values $TP_H = TP'_H = 1000000$, the final temperature values $TP_L = TP'_L = 1$ and the temperature decay coefficient $TDC = TDC' = 0.95$; For the project of CTD, the initial temperature values $TP_H = 2000000$ and the other parameters remain unchanged.

We first consider instances for the ITD project. By using the proposed heuristic method, the results obtained by the model F_{RC} and F_{CC} are reported in **Table 6** and **Table 7** respectively. *No.* means the average number, *D.C.* means opened distribution centers, *R.C.* means recycling centers, and *M.C.* means the average number of heavy-duty trucks in manufacturing centers. Generally, it can be observed that the total cost, the average number of opened centers and the average number of trucks increase as the demands of new and returned products increase, but the average $\boldsymbol{Util}$ and runtime cannot match the increasing trend.

It can be observed that costs in all instances reduce when modeling under CTM. Comparing with modeling under RTM, the total cost decreases by 10.44% on average, and the maximum is 15.75%. As the demands of new and returned products increase, the improvement becomes more significant. However, the number of opened centers seems not to be affected by different transportation mechanisms, and there are no significant differences in the locations of opened centers. In total, the average number of heavy-duty trucks under CTM is 10.0 less than that under RTM, and the average number of light-duty trucks under CTM is 17.7 less than that under RTM on average. The differences increase with the demands of new and returned products in general. The results also support that the CTM can make better use of the transportation resources than RTM. For each instance, the average $\boldsymbol{Util}$ under CTM is 4.64% greater than that under RTM on average, and the maximum is 6.18%. Furthermore, the runtime of CTM is expected to be less. One of the major reasons might be that fewer trucks will be scheduled in the routing phase of the improvement stage when running the algorithm.

Table 6. Results of the instances for ITD project obtained by the model F_{RC}

Inst.	***Total Cost***			***No. Centers***		***No. Trucks***			***Average***	***Runtime***
	Average	*Worst*	*Best*	*D.C.*	*R.C*	*M.C.*	*D.C.*	*R.C*	$\boldsymbol{Util}$	***(seconds)***
1	8.88E+6	9.09E+6	8.66E+6	3	2	21.6	22.2	19.3	42.40%	21.22
2	9.38E+6	9.53E+6	9.25E+6	3	2	23.6	28	24.9	43.26%	25.41
3	9.85E+6	1.00E+7	9.65E+6	4	2	29.2	32.2	26.5	44.46%	28.48
4	9.92E+6	1.03E+7	9.72E+6	5	3	36.4	38.5	31.6	44.80%	36.51
5	1.01E+7	1.05E+7	9.80E+6	5	3	39.6	40.6	34.8	45.77%	42.75
6	1.09E+7	1.13E+7	1.07E+7	6	3	46.3	47.6	37.9	46.51%	35.91
7	1.12E+7	1.14E+7	1.10E+7	6	3	49.2	51.5	39.3	47.53%	49.16
8	1.16E+7	1.19E+7	1.12E+7	7	4	55.9	56	46.2	46.56%	66.29
9	1.17E+7	1.21E+7	1.14E+7	8	4	62.9	62.1	49.4	47.82%	62.19
10	1.23E+7	1.26E+7	1.17E+7	8	4	67.5	65.9	52.5	47.71%	64.56
11	1.27E+7	1.29E+7	1.25E+7	9	4	73.3	70.4	54.8	48.90%	68.24

Table 7. Results of the instances for ITD project obtained by the model F_{CC}

Inst.	***Total Cost***			***No. Centers***		***No. Trucks***			***Average***	***Runtime***
	Average	*Worst*	*Best*	*D.C.*	*R.C*	*M.C.*	*D.C.*	*R.C*	$\boldsymbol{Util}$	***(seconds)***
1	8.39E+6	8.69E+6	8.11E+6	3	2	17.5	29.3	5.2	46.65%	19.57
2	8.77E+6	8.89E+6	8.45E+6	3	2	17.2	34.7	5.9	48.14%	22.15
3	9.04E+6	9.27E+6	8. 75E+6	4	2	22.6	41	6	48.33%	26.07
4	9.07E+6	9.30E+6	8.81E+6	5	3	28.1	47.5	6.9	50.09%	29.00
5	9.08E+6	9.38E+6	8.89E+6	5	3	30.8	53.3	7.5	49.62%	30.19
6	9.76E+6	1.00E+7	9.45E+6	6	3	35.7	58.7	8	51.05%	28.91
7	9.97E+6	1.02E+7	9.66E+6	6	3	38.7	62.9	8.9	51.65%	41.55
8	1.02E+7	1.03E+7	1.00E+7	7	4	44	68.9	10.5	52.61%	44.74
9	1.02E+7	1.05E+7	1.01E+7	8	4	49.6	75	11.1	54.00%	52.05
10	1.06E+7	1.08E+7	1.03E+7	8	4	53.9	85.2	12.2	51.59%	56.01
11	1.07E+7	1.08E+7	1.05E+7	9	4.1	57.6	85.6	13.3	53.05%	58.33

Furthermore, there is no apparent difference in the decisions of inventory and backorders between RTM and CTM, thus the results of these decisions will not be reported in the table. According to the algorithm, CTM applies different candidate moves from RTM, and the cost on the routing phase of the improvement stage also will be affected. **Figure 5** illustrates the difference between RTM and CTM for the average transportation cost, which denotes the cost on routing phase of the improvement stage, and indicates that CTM results in more transportation cost savings with the increase of the demands of new and returned products. The average transportation cost saving accounts for a major proportion of the average total cost saving under CTM. Moreover, the gap ratio is defined as the average transportation cost gap between RTM and CTM divided by the average transportation cost under RTM. The gap ratio is 33.12% on average, and the maximum is 36.88%.

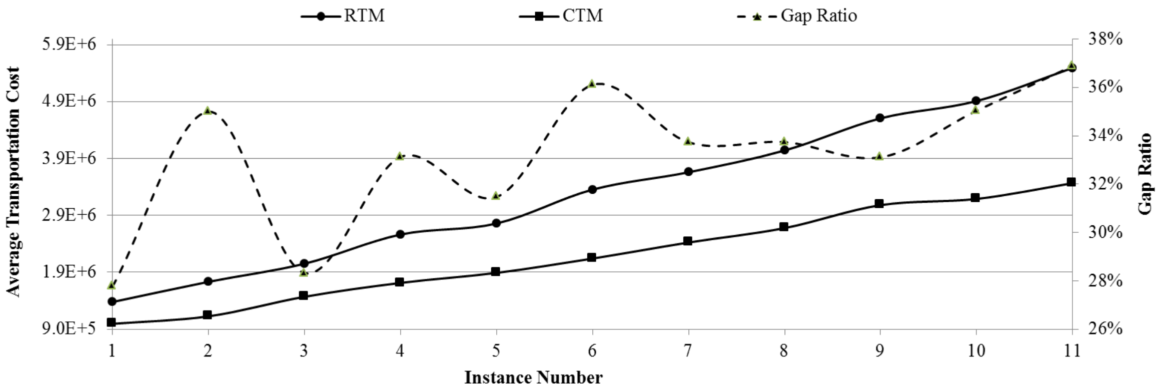

Figure 5. Transportation performance under RTM and CTM of the instances for ITD project

The instances for the CTD project are also considered, and the results obtained by model F_{RC} and F_{CC} are reported in **Table 8** and **Table 9** respectively, which further demonstrate the effectiveness of the proposed algorithms. In general, some observations in the instances for the ITD project, such as the total and transportation cost reduction under CTM, can be obtained in the instances for the CTD project. However, the performance of instance 11 for the CTD project doesn't work out as well as the others, because the significant increase of the demands of new and returned products leads to the shortage of supply capacity in the manufacturing center for many periods. Some poor results might be obtained due to a succession of failing candidate moves. On average, comparing with RTM, the total cost under CTM decreased by 10.02%, and the maximum is 15.18%; the average number of both heavy-duty trucks and light-duty trucks under CTM is less than that under RTM; the average $\boldsymbol{Util}$ under CTM is 6.04% greater than that under RTM, and the maximum is 6.55%. Meanwhile, some observations in the instances for the CTD project are different from those for the ITD project. The number of opened centers becomes unstable as the trade-off between transportation cost and backorder cost gets more complicated. Though fewer trucks are scheduled under CTM, the computation time in the moves Mov_7 and Mov_8 is expected to be longer than that in the move Mov_6 and the number base of trucks is high, thus the computation time under CTM exceeds that under RTM in many instances for the CTD project. Moreover, as the problem size is growing exponentially, the average runtime is still acceptable. As shown in **Figure 6**, the transportation cost saving under CTM becomes more significant. The gap ratio is 38.09% on average, and the maximum is

41.77%.

Table 8. Results of the instances for CTD project obtained by the model F_{RC}

Inst.	*Total Cost*			*No. Centers*		*No. Trucks*			*Average*	*Runtime*
	Average	*Worst*	*Best*	*D.C.*	*R.C*	*M.C.*	*D.C.*	*R.C*	$Util$	*(seconds)*
1	1.73E+7	1.82E+7	1.69E+7	3.4	2	20	57.8	35.7	46.56%	83.31
2	1.85E+7	1.98E+7	1.78E+7	4	2	24.7	70	41.9	47.36%	78.48
3	1.90E+7	1.96E+7	1.86E+7	4	2	23.3	77.9	47.8	49.19%	78.54
4	1.92E+7	2.01E+7	1.88E+7	5	3	31.4	92.1	56.8	48.65%	90.75
5	1.96E+7	2.00E+7	1.91E+7	6.1	3.1	44.3	102.8	62.8	48.28%	100.54
6	2.12E+7	2.18E+7	2.06E+7	6.2	3.5	41.7	118.4	70.4	48.72%	108.83
7	2.17E+7	2.29E+7	2.11E+7	7.2	3.6	52.3	123.8	74	49.46%	127.54
8	2.32E+7	2.41E+7	2.22E+7	9.3	4.7	73.1	142.9	82.3	49.45%	149.13
9	2.41E+7	2.46E+7	2.37E+7	11.5	5.9	88.9	154	94.6	49.21%	144.79
10	2.57E+7	2.70E+7	2.47E+7	15.1	6	98	171	99.2	49.20%	171.13
11	3.03E+7	3.99E+7	2.72E+7	21.7	8.1	124.2	173	115.7	47.55%	186.89

Table 9. Results of the instances for CTD project obtained by the model F_{CC}

Inst.	*Total Cost*			*No. Centers*		*No. Trucks*			*Average*	*Runtime*
	Average	*Worst*	*Best*	*D.C.*	*R.C*	*M.C.*	*D.C.*	*R.C*	$Util$	*(seconds)*
1	1.62E+7	1.65E+7	1.59E+7	3.2	2.1	15.5	72.2	3.9	52.58%	72.52
2	1.72E+7	1.77E+7	1.69E+7	4	2	18.1	84.2	4.7	55.26%	86.56
3	1.76E+7	1.79E+7	1.72E+7	4.2	2	19.5	98.3	8.5	53.86%	93.58
4	1.77E+7	1.81E+7	1.73E+7	5	3.1	28.6	110.8	10.5	54.14%	93.79
5	1.77E+7	1.81E+7	1.74E+7	6	3.1	32.9	125.5	10.1	54.47%	114.62
6	1.87E+7	1.91E+7	1.83E+7	6.6	3.1	34.8	137.3	12.1	54.86%	126.47
7	1.94E+7	2.02E+7	1.87E+7	7.5	3.8	44.8	147.2	12.2	56.01%	139.56
8	2.00E+7	2.07E+7	1.93E+7	9.5	4.7	55	166.7	15.7	54.87%	159.34
9	2.05E+7	2.09E+7	2.00E+7	11.5	5.3	65.8	182.5	18.1	54.94%	158.77
10	2.18E+7	2.27E+7	2.13E+7	13.9	6.6	83.8	194.7	19.8	55.44%	182.47
11	2.86E+7	3.40E+7	2.45E+7	23	7.2	101.7	203.8	20.9	53.63%	221.54

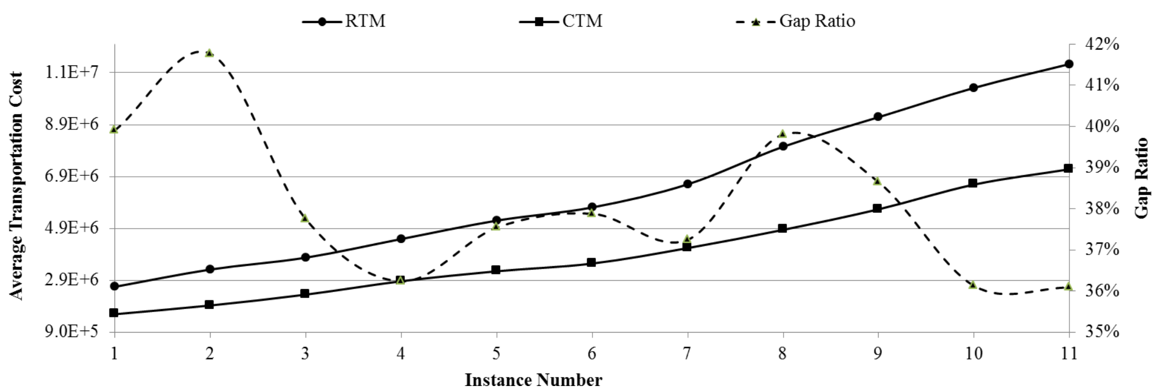

Figure 6. Transportation performance under RTM and CTM of the instances for CTD project

6. Go green

To achieve sustainability, the impact of carbon emissions is concerned. Generally, the number of carbon emissions can be generated by calculating the consumption of fuel, electricity, water and other types of energy. Waltho et al. (2019) provided a detailed review of research on carbon emission sources and related carbon taxes in CLSCs. Therefore, according to the review of Waltho et al. (2019), we set the carbon emission parameters of inventory, inspection, discarding, repairing and transportation, and set the carbon tax parameter θ. The specific parameters are shown in Table 10.

Table 10. Environmental cost parameters of the models

dve_i, rve_j	Carbon emission of holding a product at distribution center i and recycling center j
rie_j	Carbon emission of inspecting a returned product at recycling center j
rde_j, rre_j	Carbon emission of discarding a useless returned product and repairing a useful returned product at recycling center j
ω	Carbon emission factor, carbon emissions of per liter of fuel, *kg/L*
eb_0, eb_1	Average fuel consumption of empty running and marginal fuel consumption of a product for a heavy-duty truck (per kilometer)
es_0, es_1	Average fuel consumption of empty running and marginal fuel consumption of a product for a light-duty truck (per kilometer)
θ	Tax of carbon emission per kilogram

For simplicity, we assume that the manufacturer is required to pay a carbon tax on emission at θ. A simple way to incorporate the carbon tax into the model F_{RC} and F_{CC} can be by updating the economic cost parameters in **Table 3**. In details, economic cost parameters dvc_i, rvc_j, rdc_j, cb_0, cb_1, cs_0 and cs_1 will be turned into $dvc_i + \theta dve_i$, $rvc_j + \theta rve_j$, $rdc_j + (\theta/\sigma_j)[rde_j\sigma_j + rie_j + rre_j(1-\sigma_j)]$, $cb_0 + \theta\omega eb_0$, $cb_1 + \theta\omega eb_1$, $cs_0 + \theta\omega es_0$ and $cs_1 + \theta\omega es_1$, respectively.

The sixth instances of the project of ITD and CTD are used to study the sensitivity of carbon emissions of the CLSC network to the changes in the θ, which rangs from 0 to 0.4. Through multiple calculations, the average carbon emission is obtained and the trend lines can be drawn in **Figure 7**. For the ITD project, some solutions with high carbon emissions might be obtained under RTM when θ is small. However, the effect of θ is not significant under CTM. For the CTD project, generally, it can be observed that the average carbon emission is expected to be steadily decreased but the rate of decline is slower as the θ increase. Both projects support that the average carbon emission for all $\theta \in [0,0.4]$ will be reduced under

CTM as compared to RTM. But the gap of average carbon emission between RTM and CTM becomes smaller as the θ increase. The main reason is that transportation is the main source of carbon emissions, and when the carbon tax θ increases, the CLSC network will increase the number of distribution centers and recycling centers, or increase the number of backorders and delayed returns, so as to reduce the carbon emissions from transportation.

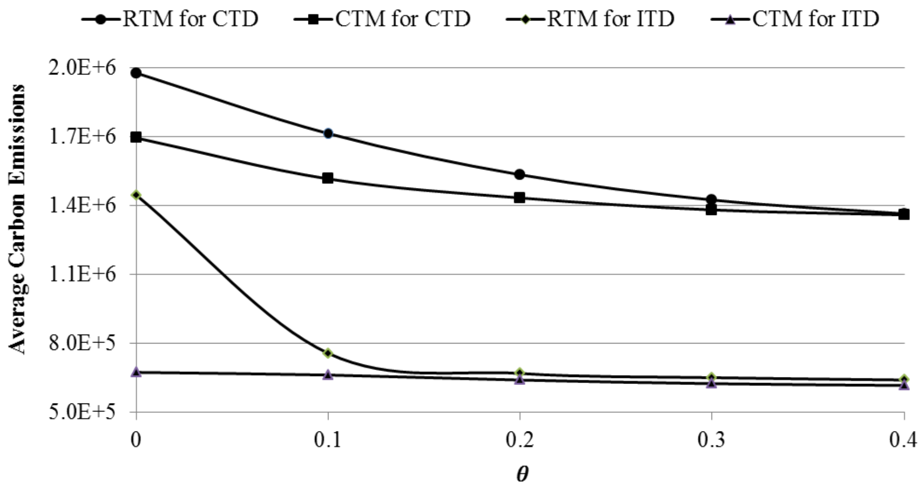

Figure 7. Trend lines of resulting carbon emissions when $\theta \in [0,0.4]$ under RTM and CTM

7. Discussion and implications

In this study, a CLSC network model with a CTM is proposed. The model takes into account realistic factors such as backorders and delayed returns. In addition, the model minimizes the operating cost of the CLSC network, while further converting carbon emissions into carbon emission cost, so as to reduce the operating cost and environmental pollution of the network. The research results show that the CLSC network model constructed in this paper can effectively improve the utilisation rate of vehicles and reduce the operating cost of the network, while significantly reducing carbon emissions. Based on the research content and findings of this paper, the implications of this research can be divided into theoretical implications and management implications.

In terms of theoretical implications: First, we for the first time propose a CLSC network model after introducing a CTM. The CTM is applied to transport operations at different echelons in a CLSC network. In addition, the CLSC network model in this paper fully considers different realisation factors, combining backorders and delayed returns for the first time, while considering the operational capacity of logistics facilities and equipment, delivery lead times and other realistic factors, so it further extends the existing theories related to the design of CLSC networks. Second, we develop a mixed-integer programming model to mathematically simulate a CLSC network model that incorporates a CTM. Third, as the constructed network model involves multiple decision problems and multiple realistic factors, its solution difficulty is greatly increased, so we develop a heuristic algorithm based on local search. This algorithm can effectively solve large-scale CLSCDN problems, and it extends the existing CLSC network model solution theory. Fourth, we further extend the theory related to sustainable supply chain network design by introducing environmental factors (carbon emissions) into the CLSC network model.

In terms of management implications: First, a sound CLSC network needs to effectively balance economic and environmental objectives. This study can effectively reduce the operating cost and carbon emissions of CLSC networks, so it provides an important decision-making tool for business managers and decision-makers to design or improve a CLSC network. Second, relevant policies such as carbon quotas and carbon taxes issued by the government are important reality factors that need to be considered in CLSC operations today. The introduction of the CTM in the CLSCND in this study can effectively reduce the carbon emissions of the network, which can encourage business managers to improve their confidence in carbon reduction, ensure the legitimacy and compliance of business operations, and enhance the social image of companies. Third, introduction of a CTM in CLSC networks can effectively improve the utilisation rate of transport vehicles in the network, i.e., reduce the investment in fixed assets, which can provide more flexible funds for managers. Fourth, the increase in the carbon tax will drive companies in the CLSC network to invest in fixed facilities, resulting in waste and idle resources. Government policy makers need to measure the social environment and social resources to formulate a reasonable carbon tax, so as to reduce companies' carbon emissions while avoiding massive waste and idleness of resources. Fifth, the CLSC network model in this paper fully integrates different realistic factors, including backorder, delayed return, the operational capacity of logistics facilities and equipment, delivery lead times, etc., which greatly enhances the practicability and operability of the CLSC network.

8. Conclusions

In this paper, comparing the point-to-point delivery between two logistics nodes or routing problem only existing at the terminal distribution stage in CLSC considered by the traditional way, we model a multi-period CLSC network that considers the circular routing planning in the different echelons of a CLSC network in order to reduce the empty running journey distance. In addition, the analysis period of the model is expected to be short, and the delivery lead time between two logistics nodes can be set as integer parameters. For designing a three-echelon supply chain network, where backorder and delayed return are allowed, RTM and CTM are introduced as two basic transportation mechanisms. Two types of circular routes are included in CTM. To solve the NP-hard CLSCND problems on large scales, a heuristic method which in composed of initialization and improvement stages is developed, and the local search process is guided in SA.

Numerical studies support the superiority of CTM, and transportation resources can be better integrated under CTM, which can be viewed in the following aspects: (i) The total cost of the CLSC network is expected to be significantly reduced under CTM compared with the total cost under RTM. The improvement mainly comes from the transportation cost-saving, and it becomes more significant as the demands of new and returned products increase. (ii) As compared to RTM, fewer heavy-duty trucks in the manufacturing center and light-duty trucks in recycling centers are used under CTM, but slightly more light-duty trucks in distribution centers are used under CTM. There are no significant differences in the location, inventory control and backorder decision between RTM and CTM. (iii) Comparing to RTM, the average utilization rate of each truck under CTM is expected to be higher, and the computation time under CTM is expected to be smaller when the problem size is small. (iv) No matter how the carbon tax on emission will be, the average carbon emission will be reduced under CTM as compared to RTM.

Several limitations and furture research of our study should be highlighted. First, in our research, the major deficiency of the proposed algorithm is focusing intently on making light-duty trucks fully loaded but neglecting to make heavy-duty trucks fully loaded. Therefore, in the future, we can improve the algorithm's solution by considering the full load of both truck types. Second, a truck might be responsible for more than one cargo-delivery and cargo-receiving task in each period and the transportation route can be disordered, thus the routing problem in CLSCND can be further enhanced in the future, especially for the terminal delivery stage. Third, the model we constructed is deterministic, but the real world is full of uncertainties, especially the demand is closely related to CLSC operations, so in the future we can consider solving the uncertainties that exist in reality based on techniques such as stochastic programming and robust optimisation. Fourth, this paper designs a CLSC model that mainly addresses the location-inventory-routing problem, which mainly considers the logistics aspects. However, there are also important problems in CLSC operations such as manufacturing and remanufacturing, which can be further investigated by integrating other CLSC operations problems in the future. Finally, problems with multi-products, multi-trucks could be interesting for future research.

Acknowledgement

This work described in this paper was partially supported by Guangdong Universities Special Key Project (Project No. 2021ZDZX3021), Guangdong Higher Education Curriculam Development and Teaching Enhancement (Project No. UICR04000052-21CTL), National Scientific Foundation of China (Project No. 71671152), and Guangdong Key Lab of Interdisciplinary Research on Data Science (Project No. 2022B1212010006)

Reference

Almaraj, I. I., & Trafalis, T. B. (2019). An integrated multi-echelon robust closed-loop supply chain under imperfect quality production. *International Journal of Production Economics*, 218, 212-227. https://doi.org/10.1016/j.ijpe.2019.04.035

Amiri, A. (2006). Designing a distribution network in a supply chain system: Formulation and efficient solution procedure. *European Journal of Operational Research*, 171(2), 567-576. https://doi.org/10.1016/j.ejor.2004.09.018

Archetti, C., Bertazzi, L., Laporte, G., & Speranza, M. G. (2007). A branch-and-cut algorithm for a vendor-managed inventory-routing problem. *Transportation science*, 41(3), 382-391. https://doi.org/10.1287/trsc.1060.0188

Azizi, V., & Hu, G. (2020). Multi-product pickup and delivery supply chain design with location-routing and direct shipment. *International Journal of Production Economics*, 226, 107648. https://doi.org/10.1016/j.ijpe.2020.107648

Asgari, N., Rajabi, M., Jamshidi, M., Khatami, M., & Farahani, R. Z. (2017). A memetic algorithm for a multi-objective obnoxious waste location-routing problem: a case study. *Annals of Operations Research*, 250(2), 279-308. https://doi.org/10.1007/s10479-016-2248-7

Berbeglia, G., Cordeau, J. F., & Laporte, G. (2010). Dynamic pickup and delivery problems. *European Journal of Operational Research*, 202(1), 8-15. https://doi.org/10.1016/ j.ejor.2009.04.024

Biçe, K., & Batun, S. (2021). Closed-loop supply chain network design under demand, return and quality uncertainty. *Computers & Industrial Engineering*, 155, 107081. https://doi.org/10.1016/ j.cie.2020.107081

Chao, C., Zhihui, T., & Baozhen, Y. (2019). Optimization of two-stage location–routing–inventory problem with time-windows in food distribution network. *Annals of Operations Research*, 273(1-2), 111-134. https://doi.org/10.1007/s10479-017-2514-3

Coelho, L. C., & Laporte, G. (2013). A branch-and-cut algorithm for the multi-product multi-vehicle inventory-routing problem. *International Journal of Production Research*, 51(23-24), 7156-7169. https://doi.org/10.1080/00207543.2012.757668

Coelho, L. C., Cordeau, J. F., & Laporte, G. (2014). Thirty years of inventory routing. *Transportation Science*, 48(1), 1-19. https://doi.org/10.1287/trsc.2013.0472

Danloup, N., Allaoui, H., & Goncalves, G. (2018). A comparison of two meta-heuristics for the pickup and delivery problem with transshipment. *Computers & Operations Research*, 100, 155-171. https://doi.org/10.1016/j.cor.2018.07.013

De, M., & Giri, B. C. (2020). Modelling a closed-loop supply chain with a heterogeneous fleet under carbon emission reduction policy. *Transportation Research Part E: Logistics and Transportation Review*, 133, 101813. https://doi.org/10.1016/j.tre.2019.11.007

Deng, S., Li, Y., Guo, H., & Liu, B. (2016). Solving a closed-loop location-inventory-routing problem with mixed quality defects returns in e-commerce by hybrid ant colony optimization algorithm. *Discrete Dynamics in Nature and Society*, 2016:1-12. https://doi.org/10.1155/2016/6467812

Diabat, A., & Jebali, A. (2021). Multi-product and multi-period closed loop supply chain network design under take-back legislation. *International Journal of Production Economics*, 231, 107879. https://doi.org/10.1016/j.ijpe.2020.107879

Dror, M., Ball, M., & Golden, B. (1985). A computational comparison of algorithms for the inventory routing problem. *Annals of Operations Research*, 4(1), 1-23. https://doi.org/10.1007/BF02022035

Daskin, M. S., Coullard, C. R., & Shen, Z. J. M. (2002). An inventory-location model: Formulation, solution algorithm and computational results. *Annals of operations research*, 110(1), 83-106. https://doi.org/10.1023/A:1020763400324

Fu, R., Qiang, Q. P., Ke, K., & Huang, Z. (2021). Closed-loop supply chain network with interaction of forward and reverse logistics. *Sustainable Production and Consumption*, 27, 737-752. https://doi.org/10.1016/j.spc.2021.01.037

Georgiadis, P., & Besiou, M. (2010). Environmental and economical sustainability of WEEE closed-loop supply chains with recycling: a system dynamics analysis. *The International Journal of Advanced Manufacturing Technology*, 47(5), 475-493. https://doi.org/10.1007/s00170-009-2362-7

Ghomi-Avili, M., Tavakkoli-Moghaddam, R., Jalali Naeini, S. G., & Jabbarzadeh, A. (2021). Competitive green supply chain network design model considering inventory decisions under uncertainty: a real case of a filter company. *International Journal of Production*

Research, 59(14), 4248-4267. https://doi.org/10.1080/00207543.2020.1760391

Govindan, K., Soleimani, H., & Kannan, D. (2015). Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. *European Journal of Operational Research*, 240(3), 603-626. https://doi.org/10.1016/j.ejor.2014.07.012

Guo, H., Li, C., Zhang, Y., Zhang, C., & Wang, Y. (2018). A nonlinear integer programming model for integrated location, inventory, and routing decisions in a closed-loop supply chain. *Complexity*, 2018:1-17. https://doi.org/10.1155/2018/2726070

Guo, H., Zhang, Y., Zhang, C., Zhang, Y., & Han, Z. (2020). A multi-commodity location-inventory problem in a closed-loop supply chain with commercial product returns. *International Journal of Production Research*, 58(22), 6899-6916. https://doi.org/10.1080/00207543.2019.1686186

Hernández-Pérez, H., Landete, M., & Rodriguez-Martin, I. (2021). The single-vehicle two-echelon one-commodity pickup and delivery problem. *Computers & Operations Research*, 127, 105152. https://doi.org/10.1016/j.cor.2020.105152

Javid, A. A., & Azad, N. (2010). Incorporating location, routing and inventory decisions in supply chain network design. *Transportation Research Part E: Logistics and Transportation Review*, 46(5), 582-597. https://doi.org/10.1016/j.tre.2009.06.005

Johari, M., & Hosseini-Motlagh, S. M. (2019). Coordination of social welfare, collecting, recycling and pricing decisions in a competitive sustainable closed-loop supply chain: a case for lead-acid battery. *Annals of Operations Research*, 1-36. https://doi.org/10.1007/s10479-019-03292-1

Keyvanshokooh, E., Ryan, S. M., & Kabir, E. (2016). Hybrid robust and stochastic optimization for closed-loop supply chain network design using accelerated Benders decomposition. *European Journal of Operational Research*, 249(1), 76-92. https://doi.org/10.1016/ j.ejor.2015.08.028

Kim, Y. G., & Do Chung, B. (2022). Closed-loop supply chain network design considering reshoring drivers. *Omega*, 102610. https://doi.org/10.1016/j.omega.2022.102610

Kirkpatrick, S., Gelatt, C. D., & Vecchi, M. P. (1983). Optimization by simulated annealing. *Science*, 220(4598), 671-680. https://doi.org/10.1126/science.220.4598.671

Koç, Ç., Laporte, G., & Tükenmez, İ. (2020). A review of vehicle routing with simultaneous pickup and delivery. *Computers & Operations Research*, 122, 104987. https://doi.org/10.1016/ j.cor.2020.104987

Liu, Y., Ma, L., & Liu, Y. (2021). A novel robust fuzzy mean-UPM model for green closed-loop supply chain network design under distribution ambiguity. *Applied Mathematical*

Modelling, 92, 99-135. https://doi.org/10.1016/j.apm.2020.10.042

Mara, S. T. W., Kuo, R. J., & Asih, A. M. S. (2021). Location‐routing problem: a classification of recent research. *International Transactions in Operational Research*, 28(6): 2941-2983. https://doi.org/10.1111/itor.12950

Metropolis, N., Rosenbluth, A. W., Rosenbluth, M. N., Teller, A. H., & Teller, E. (1953). Equation of state calculations by fast computing machines. *The Journal of Chemical Physics*, 21(6), 1087-1092. https://doi.org/10.1063/1.1699114

Moin, N. H., & Salhi, S. (2007). Inventory routing problems: a logistical overview. *Journal of the Operational Research Society*, 58(9), 1185-1194. https://doi.org/10.1057/palgrave.jors.2602264

Nagy, G., & Salhi, S. (2007). Location-routing: Issues, models and methods. *European Journal of Operational Research*, 177(2), 649-672. https://doi.org/10.1016/j.ejor.2006.04.004

Parast, Z. Z. D., Haleh, H., Darestani, S. A., & Amin-Tahmasbi, H. (2021). Green reverse supply chain network design considering location-routing-inventory decisions with simultaneous pickup and delivery. *Environmental Science and Pollution Research*, 1-22. https://doi.org/10.1007/s11356-021-13770-4

Pishvaee, M. S., Farahani, R. Z., & Dullaert, W. (2010). A memetic algorithm for bi-objective integrated forward/reverse logistics network design. *Computers & Operations Research*, 37(6), 1100-1112. https://doi.org/10.1016/j.cor.2009.09.018

Prakash, S., Kumar, S., Soni, G., Jain, V., & Rathore, A. P. S. (2020). Closed-loop supply chain network design and modelling under risks and demand uncertainty: an integrated robust optimization approach. *Annals of operations research*, 290(1), 837-864. https://doi.org/10.1007/s10479-018-2902-3

Prodhon, C., & Prins, C. (2014). A survey of recent research on location-routing problems. *European Journal of Operational Research*, 238(1), 1-17. https://doi.org/10.1016/j.ejor.2014.01.005

Rahimi, M., Baboli, A., & Rekik, Y. (2017). Multi-objective inventory routing problem: A stochastic model to consider profit, service level and green criteria. *Transportation Research Part E: Logistics and Transportation Review*, 101, 59-83. https://doi.org/10.1016/ j.tre.2017.03.001

Ramezani, M., Kimiagari, A. M., Karimi, B., & Hejazi, T. H. (2014). Closed-loop supply chain network design under a fuzzy environment. *Knowledge-Based Systems*, 59, 108-120. https://doi.org/10.1016/j.knosys.2014.01.016

Ranjbaran, F., Husseinzadeh Kashan, A., & Kazemi, A. (2020). Mathematical formulation and heuristic algorithms for optimisation of auto-part milk-run logistics network considering forward and reverse flow of pallets. *International Journal of Production Research*, 58(6), 1741-1775. https://doi.org/10.1080/00207543.2019.1617449

Sahebjamnia, N., Fathollahi-Fard, A. M., & Hajiaghaei-Keshteli, M. (2018). Sustainable tire closed-loop supply chain network design: Hybrid metaheuristic algorithms for large-scale networks. *Journal of Cleaner Production*, 196, 273-296. https://doi.org/10.1016/j.jclepro.2018.05.245

Savelsbergh, M. W., & Sol, M. (1995). The general pickup and delivery problem. *Transportation Science*, 29(1), 17-29. https://doi.org/10.1287/trsc.29.1.17

Sazvar, Z., Zokaee, M., Tavakkoli-Moghaddam, R., Salari, S. A. S., & Nayeri, S. (2021). Designing a sustainable closed-loop pharmaceutical supply chain in a competitive market considering demand uncertainty, manufacturer's brand and waste management. *Annals of Operations Research*, 1-32. https://doi.org/10.1007/s10479-021-03961-0

Soleimani, H., Chhetri, P., Fathollahi-Fard, A. M., Mirzapour Al-e-Hashem, S. M. J., & Shahparvari, S. (2022). Sustainable closed-loop supply chain with energy efficiency: Lagrangian relaxation, reformulations and heuristics. *Annals of Operations Research*, 1-26. https://doi.org/10.1007/s10479-022-04661-z

Shi, J., Chen, W., Zhou, Z., & Zhang, G. (2020). A bi-objective multi-period facility location problem for household e-waste collection. *International Journal of Production Research*, 58(2), 526-545. https://doi.org/10.1080/00207543.2019.1598591

Soleimani, H., Govindan, K., Saghafi, H., & Jafari, H. (2017). Fuzzy multi-objective sustainable and green closed-loop supply chain network design. *Computers & Industrial Engineering*, 109, 191-203. https://doi.org/10.1016/j.cie.2017.04.038

Souza, G. C. (2013). Closed‐loop supply chains: a critical review, and future research. *Decision Sciences*, 44(1), 7-38. https://doi.org/10.1111/j.1540-5915.2012.00394.x

Tautenhain, C. P., Barbosa-Povoa, A. P., Mota, B., & Nascimento, M. C. (2021). An efficient Lagrangian-based heuristic to solve a multi-objective sustainable supply chain problem. *European Journal of Operational Research*, 294(1), 70-90. https://doi.org/10.1016/j.ejor.2021.01.008

Vahdani, B., Veysmoradi, D., Noori, F., & Mansour, F. (2018). Two-stage multi-objective location-routing-inventory model for humanitarian logistics network design under uncertainty. *International Journal of Disaster Risk Reduction*, 27, 290-306.

https://doi.org/10.1016/ j.ijdrr.2017.10.015

Validi, S., Bhattacharya, A., & Byrne, P. J. (2020). Sustainable distribution system design: A two-phase DoE-guided meta-heuristic solution approach for a three-echelon bi-objective AHP-integrated location-routing model. *Annals of Operations Research*, 290(1), 191-222. https://doi.org/10.1007/s10479-018-2887-y

Wei, L., Zhang, Z., Zhang, D., & Leung, S. C. (2018). A simulated annealing algorithm for the capacitated vehicle routing problem with two-dimensional loading constraints. *European Journal of Operational Research*, 265(3), 843-859. https://doi.org/10.1016/j.ejor.2017.08.035

Xiao, Y., Zhao, Q., Kaku, I., & Xu, Y. (2012). Development of a fuel consumption optimization model for the capacitated vehicle routing problem. *Computers & Operations Research*, 39(7), 1419-1431. https://doi.org/10.1016/j.cor.2011.08.013

Xu, B. S. (2013). Progress of remanufacturing engineering and future technology expectation. *Advances in Manufacturing*, 1(1), 8-12. https://doi.org/ 10.1007/s40436-013-0003-8

Xu, Z., Pokharel, S., & Elomri, A. (2022). An eco-friendly closed-loop supply chain facing demand and carbon price uncertainty. *Annals of Operations Research*, 1-27. https://doi.org /10.1007/s10479-021-04499-x

Yao, X., & Askin, R. (2019). Review of supply chain configuration and design decision-making for new product. *International Journal of Production Research*, 57(7), 2226-2246. https://doi.org/10.1080/00207543.2019.1567954

Yolmeh, A., & Saif, U. (2021). Closed-loop supply chain network design integrated with assembly and disassembly line balancing under uncertainty: an enhanced decomposition approach. *International Journal of Production Research*, 59(9), 2690-2707. https://doi.org/10.1080/00207543.2020.1736723

Yuchi, Q., Wang, N., He, Z., & Chen, H. (2021). Hybrid heuristic for the location - inventory - routing problem in closed - loop supply chain. *International Transactions in Operational Research*, 28(3), 1265-1295. https://doi.org/10.1111/itor.12621

Zhalechian, M., Tavakkoli-Moghaddam, R., Zahiri, B., & Mohammadi, M. (2016). Sustainable design of a closed-loop location-routing-inventory supply chain network under mixed uncertainty. *Transportation Research Part E: Logistics and Transportation Review*, 89, 182-214. https://doi.org/10.1016/j.tre.2016.02.011

Zhang, Y., Qi, M., Miao, L., & Liu, E. (2014). Hybrid metaheuristic solutions to inventory location routing problem. *Transportation Research Part E: Logistics and Transportation*

Review, 70, 305-323. https://doi.org/10.1016/j.tre.2014.07.010

Zhang, Z., Luo, Z., Baldacci, R., & Lim, A. (2021). A Benders Decomposition Approach for the Multivehicle Production Routing Problem with Order-up-to-Level Policy. *Transportation Science*, 55(1), 160-178. https://doi.org/10.1287/trsc.2019.0964