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Design and Optimization of the Dual-Channel Closed Loop Supply Chain with E-Commerce

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Abstract: The depletion of natural resources and the degradation of the ecosystem have led many countries to adopt closed-loop supply activities in both their industrial and service sectors. With the widespread use of Internet technology, these aspects motivate the incorporation of e-commerce with the classical closed-loop supply chain. This study suggests a novel mixed-integer linear programming (MILP) model that addresses the integration of e-commerce with a multi-echelon closed-loop supply chain with a multi-period planning time horizon by considering dual channels in manufacturing, and recovery facilities. To validate the model, we obtain optimal decision variables and examine the robustness and applicability of the model, and comprehensive computational experiments are performed. Moreover, sensitivity analysis is carried out to illustrate the efficacy of e-commerce integration by considering the two channels in the closed-loop supply chain. Accordingly, the total cost of the dual-channel CLSC decreases with an increase in customer demand via online retailers, the returned end of life (EOL) products, recycling ratio, and recovery ratio. Some useful managerial implications are provided based on the conducted analysis.

Keywords: mixed-integer linear programming; closed-loop supply chain; dual channel; e-commerce

1. Introduction

In recent years, governments have been applying pressure and refining legislation to encourage organizations and a broad sector of customers to adopt green and sustainable practices in their production and service activities. This is to handle the population growth, which requires more products to be manufactured, resulting in the limited availability of raw materials and an increase in the rate of pollution emissions [1,2]. These factors are motivating companies and governments to adopt and implement rational closed-loop supply chain (CLSC) activities in both the production and service sectors [3,4]. A CLSC incorporates both forward and reverse supply chain activities [5–7]. The forward supply chain is defined as a network involving raw material procurement, manufacturing of parts, assembly of parts, and delivery through distribution networks [8]. Meanwhile, the reverse supply chain is defined as a network of facilities and includes all activities from collecting end of life (EOL) products to their inspection, disassembly, and the determination of which components should be disposed of, recovered, recycled, and remanufactured to

form final products that can be reused by customers [9–11]. The European Union and European Parliament came up with several changes to the Directive 2002/96/EC on Waste Electrical and Electronic Equipment (WEEE) with the objective of improved human health [12]. Many companies adhere to this legislation, and the recycling of WEEE has led to a myriad of environmental and economic benefits due to the recovery of valuable metals and plastics in these pieces of equipment [13]. Implementing CLSC planning strategies helps in reducing companies' production costs, eliminating environmental pollution, creating social gains, and promoting the rapid development of economic benefits by applying reverse logistics to the company's activities including recycling, recovering, and remanufacturing of disused products [14]. For instance, Fuji Xerox saves around 40–65% of production costs from the manufacturing of recycled materials [15]. The rise of the Internet and related technologies has led many companies to sell their products through online retailers in addition to traditional retailers. For example, Dell sells its electronic products through online retailers such as Amazon, Flipkart, and Snapdeal [16]. Both types of retailer sell the same basic product and determine their respective optimal retail prices. In acting as the market leader, the producer has to split the market share between online and traditional retailers and decide on the wholesale price [17]. A myriad of benefits have boosted the spread of online retailers, including high accessibility, fast responses to consumer demand, low distribution costs, and fast shipping [18] as well as the positive impact from an environmental perspective [19,20]. The practice of combining online shopping with the traditional retail channel in the supply chain design has emerged recently. However, a limited number of studies have addressed the optimal design of a dual-channel supply chain network, Yadav and Singh [21] proposed multiple channel distribution for a forward supply chain network using MILP, their proposed model is a single-period single-product multi-channel forward supply chain with the aim to maximize the service level and minimize the total cost. Chen et al. [22] proposed a mixed integer nonlinear programming (MINLP) for modeling the remanufacturing network for the dual-channel CLSC. The authors investigated the proposed mathematical model while computational experiments and sensitivity analysis for model validity were not preformed. Motivated by this, we investigate the design and optimization of the CLSC with the dual-channel supply chain considering e-commerce in mathematical modeling. Specifically, we present a novel MILP model of the CLSC with the consideration of the dual channel of the traditional and online retailers in both forward and reverse logistics, which aims at minimizing the total cost of shipment, purchasing, operations, and fixed costs. The main contributions of this study are as follows:

- the integration of e-commerce activities into both forward and reverse supply chains;
- the development of an MILP model that considers the dual channel of both traditional and online retailers through manufacturing and recovery facilities;
- a sensitivity analysis study of the key parameters associated with traditional and online retailers, and exploring their effect on the total cost and number of open traditional retailers.

The remainder of the paper is organized as follows: Section 2 presents a literature review of the previous studies pertaining to the design and optimization of supply chains networks, Section 3 provides a description of the on-hand problem, handling the strategic and tactical design of the proposed dual-channel CLSC, Section 4 shows the mathematical formulation of the dual-channel CLSC, Section 5 discusses the computational experiments performed on the proposed model, and Section 6 concludes the paper.

2. Literature Review

Many researchers have traditionally investigated the design of forward and reverse supply chains as two separate issues [23]. On the one side, studies on the design of the forward supply chain include the design of a multi-echelon forward supply chain by Memari et al. [24], who developed an MILP using a metaheuristic algorithm, named a modified firefly algorithm, and verified the efficiency of their suggested algorithm, as compared with traditional ones. Designing a two-echelon, multi-commodity,

and single period supply chain considering tactical and strategic planning to minimize the total cost of the network was proposed by Sadjady and Davoudpour [25] using a Lagrangian approach. Eskandarpour et al. [26] proposed a heuristic algorithm to maximize the material flow in a four-layer, multi-product, and single-period supply chain network.

On the flip side, studies on the design of the reverse supply chain include a three-stage mathematical programming model developed by Pochampally and Gupta [27], involving methods such as linear integer programming and multi-criteria decision-making approaches for the strategic planning of a reverse supply chain network. Alshamsi and Diabat [28] proposed a genetic algorithm and used general algebraic modeling system (GAMS) software to solve the reverse logistics problem, with the aim of determining the optimum location and capacities of inspection and remanufacturing centers. An MILP was developed by Paydar and Olfati [29] for designing and solving a reserve logistics network of polyethylene terephthalate bottles using the two metaheuristic techniques of the genetic algorithm and the imperialist competitive algorithm. Demirel et al. [30] proposed an MILP model for the reverse logistics of end of life vehicles in Turkey, with the objective of minimizing the cost of the associated activities of the supply chain network, such as transportation, recovery, and opening facilities, via income from the remanufacturable and recyclable parts of these vehicles.

The design of a closed loop supply chain is a concern that has gained a significant amount of academic attention in recent years. Özceylan and Paksoy [31] developed an MILP for a multi-period multi-part CLSC. Their study aimed at determining the optimum number of facilities as well as the location of manufacturers and retailers using a CPLEX optimizer. System dynamic simulation of the CLSC model was proposed by Golroudbary and Zahraee [32] to assess the behavior of an electrical manufacturing company. Due to the rapid e-commerce deployment, the dual channel of both traditional stores and online retailers strongly participates in supply chain network planning. Ma et al. [33] studied how government subsidies affect the dual-channel CLSC. Dutta et al. [34] provided a multi-objective optimization network model for green reverse logistic supply chains to the Indian e-commerce market to optimize supply chain costs.

A pricing strategy refers to the strategy developed by sellers when determining their market pricing, while channel coordination is defined as the setting of manufacturer's and retailer's decisions leading to channel profit maximization [35,36]. Exploring pricing and coordination decisions in dual-channel CLSCs with different power structures considering the channel competition between direct and retail channels was proposed by Zheng et al. [37].

Taleizadeh et al. [38] explored the impact of marketing efforts on optimal decisions and economic benefits in the CLSC using Stackelberg game theory. Their study suggested a substantial impact of the two-part tariff contract on channel coordination.

Xiao et al. [39] implemented a trade-in policy in both traditional retail channel models and dual-channel models. He et al. [40] studied the effect of a dual-channel CLSC on carbon emissions considering the free riding behavior that customers enjoy thanks to traditional retailer services; nevertheless, final purchases were made through online retailers. They verified that free riding increases carbon emissions, despite the increasing dual-channel CLSC profits.

Zhu et al. [41] examined the impact of customer bargaining behavior on dual-channel CLSC under centralized decision-making, decentralized decision-making, and contract coordination using the Stackelberg game theory. Saha et al. [42] investigated a reward-driven remanufacturing policy for dual channel closed loop supply chain coordination using game theory (GT) approach. Hong et al. [43] investigated three hybrid dual-channel collection structures and indicated that the strategic alliance between the manufacturer and the retailer can effectively achieve the desired channel coordination. Xie et al. [44] combined revenue sharing and support programs using a Stackelberg game to investigate the contract coordination mechanism. Their proposed contract increases the profits of supply chain network.

Yuan et al. [45] presented an optimization analysis and GT approach to analyze the necessary conditions for achieving coordination interests under equilibrium conditions for manufacturers, retailers, and third-party online recyclers. Stackelberg game models were formulated by Wan and Hong [46] to analyze the optimal pricing and recycling policies for the CLSC with a retailer and dual collection channel to develop a coordination contract that would eliminate the channel conflict, resulting in an optimal retail price, optimal wholesale price, optimal collection rates, and optimal transfer prices. Wang et al. [47] studied the dual-channel CLSC with product customization through direct retail channels. Three pricing models were presented to analyze the optimal decisions of supply chain members using game theory. He et al. [48] studied the dual-channel CLSC with government subsidies to investigate the channel structure and pricing decisions for the manufacturer and the government's subsidy policy with new, competing, remanufactured products. The above-discussed literature review shows that almost all studies are concerned with pricing strategies and channel coordination, as indicated in Table 1. To the best of our knowledge, the study presented in this paper is the first to propose an MILP for the dual channel of the CLSC with the focus of making both tactical and strategic decisions that are crucial for the development of the supply chain in the future, according to [49]. This study enriches the literature and covers some of the gaps, as shown in Table 1, by considering the traditional and online retailers that are supplied by the products from the manufacturer in the forward supply chain and the recovery products from the reverse supply chain.

Table 1. Related literature.

References	Retail Channel		Study Point of View				
	Traditional Retailer	Online Retailer	Pricing Strategy	Channel Coordination	Tactical Planning	Strategic Planning	Modeling Approach
Özceylan and Paksoy [31]	✓				✓	✓	MILP
Xiao et al. [39]	✓	✓		✓			GT
Taleizadeh et al. [38]	✓	✓	✓	✓			GT
Zheng et al. [37]	✓	✓		✓			GT
Zhu et al. [41]	✓	✓	✓				GT
Saha et al. [42]	✓	✓		✓			GT
Hong et al. [43]	✓	✓		✓			GT
Xie et al. [44]	✓	✓		✓			GT
Yuan et al. [45]	✓	✓		✓			GT
Wan and Hong [46]	✓	✓	✓				GT
Wang et al. [47]	✓	✓	✓				GT
He et al. [48]	✓	✓	✓				GT
Chen et al. [22]	✓	✓			✓		MINLP
This study	✓	✓			✓	✓	MILP

3. Problem Description

The dual-channel CLSC is a multi-echelon multi-period supply chain that consists of two parts, as shown in Figure 1, the forward supply chain, which is connected by black solid arrows, and the reverse supply chain, which is connected by red dashed arrows. The suppliers and recycling centers provide the manufacturers with the raw materials, and the manufacturer then produces the final products that are transported to either traditional retailers or online retailers. Both online and traditional retailers provide the final products to the end customers of new products to satisfy their demands. Dismantlers collect the EOL products for reverse logistics in the dual channel and then decide whether to dispose of, recycle, or recover those collected EOL products. The potential locations of the facilities and distances between these locations are predefined and known. The capacities of facilities and demands of customers are predetermined and deterministic. The shipment cost, purchasing cost, operating costs, such as

manufacturing, collecting, disposing, recycling, and recovering, and fixed costs are predetermined and fixed. The rates of online demands in the forward and reverse chain are predefined and deterministic. The ratio of EOL products to be collected and inspected is predefined and deterministic. The ratios of the disposed, recycled, and recovered products are predetermined and deterministic.

Figure 1. The proposed dual-channel closed loop supply chain (CLSC).

The model proposed in this paper determines the optimal amounts to be manufactured from the raw materials provided by the suppliers and the recycled materials supplied by recycling centers, the optimal amounts transported to both traditional and online retailers via the manufacturers or recovery centers, the optimal amounts transported to customers to satisfy their demand, the optimal number of EOL products to be collected and inspected, the disposed amounts, the optimal amounts to be recycled, and the amounts to be recovered. Additionally, the model determines the optimal number of facilities for operating the dual-channel CLSC over the planning horizon. Various parameter uncertainties were determined by applying sensitivity analysis to examine the effects of the parameters on the performance of the dual-channel CLSC to provide managerial insights for the decision-makers.

4. Mathematical Formulation

In this section, an MILP model for the dual-channel CLSC with e-commerce is proposed. Our proposed model is an extension of the traditional models of CLSC [31,50] in that it incorporates e-commerce activities. The objective function shown in Equation (1), composed of four parts, represents the total cost that is to be minimized. The first part of the objective function, z_1 , is the transportation cost between each successive set of facilities in the CLSC during the total periods of time, represented by Equation (2).

The second part, z_2 , is the cost of the set of manufacturers purchasing raw materials from suppliers and is represented by Equation (3). The third part, z_3 , is the cost of the operations, which includes manufacturing, collecting, inspection, disposal, recycling, and recovery, and is represented by Equation (4). The last part, z_4 , represents the fixed costs of opening facilities in the CLSC and is represented by Equation (5). The nomenclature that is used in the mathematical formulation of the dual-channel CLSC is presented in Table 2, including the indices, parameters, and the continuous and integer decision variables.

Table 2. Nomenclature.

Indices & Sets	
i	Set of suppliers.
j	Set of manufacturers.
k^{tr}	Set of traditional retailers.
k^{on}	Set of online retailers.
l	Set of customers.
m	Set of collection and inspection centers.
n	Set of recycling centers.
v	Set of recovery centers.
s	Set of disposal centers.
t	set of time periods.
Parameters	
SC_{ij}	Shipment cost of the quantity transported between supplier i and manufacturer j .
SC_{jk}^{tr}	Shipment cost of the quantity transported between manufacturer j and traditional retailer k^{tr} .
SC_{jk}^{on}	Shipment cost of the quantity transported between manufacturer j and online retailer k^{on} .
$SC_{k^{tr}l}$	Shipment cost of the quantity transported between traditional retailers k^{tr} and customer l .
$DC_{k^{on}l}$	Delivery cost of the quantity transported between online retailers k^{on} and customer l .
SC_{lm}	Shipment cost of the quantity transported between customer l and collection center m .
SC_{ms}	Shipment cost of the quantity transported between collection center m and disposal center s .
SC_{mv}	Shipment cost of the quantity transported between collection center m and recovery center v .
SC_{nj}	Shipment cost of the quantity transported between recycling center n and manufacturer j .
$SC_{vk^{on}}$	Shipment cost of the quantity transported between recovery center v and online retailer k^{on} .
$Ca_{\zeta t}$	The capacity of the CLSC facilities belongs to ζ in period t where $\zeta: \{i, j, k^{tr}, k^{on}, l, m, s, n, v\}$
De_{lt}	Demand of customer l in period of time t .
PC	Purchasing cost of the unit of product transported between supplier i and manufacturer j .
jc	Manufacturing cost of a product.
mc	Collection and inspection cost of an EOL product.
sic	Disposing cost of an EOL product.
yc	Recycling cost of an EOL product.
vc	Recovery cost of an EOL product.
FC_{it}	Fixed cost associated with selected supplier i in period t .
FC_{jt}	Fixed cost of opening manufacturer j in period t .

Table 2. Cont.

$FC_{k^{tr}t}$	Fixed cost of opening traditional retailer k^{tr} in period t .
FC_{mt}	Fixed cost of opening collection center m in period t .
FC_{vt}	Fixed cost of opening covering center v in period t .
FC_{nt}	Fixed cost of opening recycling center n in period t .
FC_{st}	Fixed cost of opening disposal center s in period t .
Decision Variables	
A_{ijt}	The quantity provided by supplier i to manufacturer j in period t .
$B_{jk^{tr}t}$	The quantity provided by manufacturer j to traditional retailer k^{tr} in period t .
$B_{jk^{on}t}$	The quantity provided by manufacturer j to online retailer k^{on} in period t .
$C_{k^{tr}lt}$	The quantity provided by traditional retailer k^{tr} to customer l in period t .
$C_{k^{on}lt}$	The quantity provided by online retailer k^{on} to customer l in period t .
D_{lmt}	The quantity provided by customer l to collection centers m in period t .
H_{mst}	The quantity provided by collection center m to disposal center s in period t .
F_{mnt}	The quantity provided by collection center m to recycling center n in period t .
E_{mvt}	The quantity provided by collection center m to recovery center v in period t .
I_{njt}	The quantity provided by recycling center n to manufacturer j in period t .
$J_{vk^{tr}t}$	The quantity provided by recovery center v to traditional retailer k^{tr} in period t .
$J_{vk^{on}t}$	The quantity provided by the recovery center v to online retailer k^{on} in period t .
O_{it}	A binary variable; its value is 1 if the supplier i is selected in period t ; it takes a value of 0 otherwise.
O_{jt}	A binary variable; its value is 1 if the manufacturer j is opened in period t ; it takes a value of 0 otherwise.
$O_{k^{tr}t}$	A binary variable; its value is 1 if the traditional retailers k^{tr} is opened in period t ; it takes a value of 0 otherwise.
$O_{k^{on}t}$	A binary variable; its value is 1 if the online retailers k^{on} is selected in period t ; it takes a value of 0 otherwise.
O_{mt}	A binary variable; its value is 1 if the collection center m is opened in period t ; it takes a value of 0 otherwise.
O_{st}	A binary variable; its value is 1 if the disposal center s is opened in period t ; it takes a value of 0 otherwise.
O_{nt}	A binary variable; its value is 1 if the recycling center n is opened in period t ; it takes a value of 0 otherwise.
O_{vt}	A binary variable; its value is 1 if the recovery center v is opened in period t ; it takes a value of 0 otherwise.

$$Z = z_1 + z_2 + z_3 + z_4 \quad (1)$$

$$z_1 = \sum_i \sum_j \sum_t A_{ijt} SC_{ij} + \sum_j \sum_{k^{tr}} \sum_t B_{jk^{tr}t} SC_{jk^{tr}} + \sum_j \sum_{k^{on}} \sum_t B_{jk^{on}t} SC_{jk^{on}} + \sum_{k^{on}} \sum_l \sum_t C_{k^{on}lt} DC_{k^{on}l} + \sum_{k^{tr}} \sum_l \sum_t C_{k^{tr}lt} SC_{k^{tr}l} + \sum_l \sum_m \sum_t D_{lmt} SC_{lm} + \sum_m \sum_s \sum_t H_{mst} SC_{ms} + \sum_m \sum_n \sum_t F_{mnt} SC_{mn} + \sum_m \sum_v \sum_t E_{mvt} SC_{mv} + \sum_n \sum_j \sum_t I_{njt} SC_{nj} + \sum_v \sum_{k^{tr}} \sum_t J_{vk^{tr}t} SC_{vk^{tr}} + \sum_v \sum_{k^{on}} \sum_t J_{vk^{on}t} DC_{vk^{on}} \quad (2)$$

$$z_2 = \sum_i \sum_j \sum_t A_{ijt} PC \quad (3)$$

$$z_3 = jc \left(\sum_j \sum_{k^{tr}} \sum_t B_{jk^{tr}t} + \sum_j \sum_{k^{on}} \sum_t B_{jk^{on}t} \right) + mc \sum_l \sum_m \sum_t D_{lmt} + sic \sum_m \sum_s \sum_t H_{mst} + nc \sum_m \sum_n \sum_t F_{mnt} + vc \sum_m \sum_v \sum_t E_{mvt} \quad (4)$$

$$z_4 = \sum_i \sum_t FC_{it} O_{it} + \sum_j \sum_t FC_{jt} O_{jt} + \sum_{k^{tr}} \sum_t FC_{k^{tr}t} O_{k^{tr}t} + \sum_m \sum_t FC_{mt} O_{mt} + \sum_s \sum_t FC_{st} O_{st} + \sum_n \sum_t FC_{nt} O_{nt} + \sum_v \sum_t FC_{vt} O_{vt} \quad (5)$$

The model is subject to a set of constraints expressed in the following relations: the capacity constraint of the suppliers described by Equation (6): the quantity transported from each supplier to all the manufacturers during each period must not surpass the capacity of that supplier.

$$\sum_j A_{ijt} \leq Ca_{it} O_{it} \quad \forall i, t \quad (6)$$

Constraints described by Equation (7) present the capacity of the manufacturer such that the quantity transported from any manufacturer to the set of forward traditional and online retailers must not exceed the capacity of that manufacturer during any period of the planning horizon.

$$\sum_{k^{tr}} B_{jk^{tr}t} + \sum_{k^{on}} B_{jk^{on}t} \leq Ca_{jt} O_{jt} \quad \forall j, t \quad (7)$$

Constraints described by Equations (8) and (9) address the capacities of traditional and online retailers and ensure that the quantity transported to the customers should not exceed the capacity of each retailer during any period of the planning horizon.

$$\sum_l C_{k^{tr}lt} \leq Ca_{k^{tr}t} O_{k^{tr}t} \quad \forall k^{tr}, t \quad (8)$$

$$\sum_l C_{k^{on}lt} \leq Ca_{k^{on}t} O_{k^{on}t} \quad \forall k^{on}, t \quad (9)$$

Constraints described by Equation (10) guarantee the satisfaction of the customer's demand over the planning horizon.

$$\sum_{k^{tr}} C_{k^{tr}lt} + \sum_{k^{on}} C_{k^{on}lt} \geq De_{lt} \quad \forall l, t \quad (10)$$

Constraints represented by Equation (11) identify the capacity of the collection and inspection centers and make sure that the amounts transferred to the disposal, recycling, and recovery centers will not exceed those centers' capacities at any time of the planning horizon.

$$\sum_s H_{mst} + \sum_n F_{mnt} + \sum_v E_{mvt} \leq Ca_{mt} O_{mt} \quad \forall m, t \quad (11)$$

Constraints on the capacity of disposal centers described by Equation (12) ensure that the quantity transported to the disposal centers from the collection and inspection centers do not exceed their capacities at any period of the planning horizon.

$$\sum_m H_{mst} \leq Ca_{st} O_{st} \quad \forall s, t \quad (12)$$

The Constraints described by Equation (13) identify the capacity of the recycling centers and guarantee that the quantities transported to the manufacturers from the recycling centers do not exceed their capacities at any period of the planning horizon.

$$\sum_j I_{njt} \leq Ca_{nt} O_{nt} \quad \forall n, t \quad (13)$$

The constraints described by Equation (14) present the limitations on the capacity of the recovery centers and ensure that the quantities transported to both the traditional and online retailers do not exceed the capacity of those centers at any period of the planning horizon.

$$\sum_{k^{tr}} J_{vk^{tr}t} + \sum_{k^{on}} J_{vk^{on}t} \leq Ca_{vt} O_{vt} \quad \forall v, t \quad (14)$$

Moreover, the equilibrium constraints of the facilities of the dual-channel CLSC show that the amounts produced by the manufacturers, which are supplied by the suppliers and recycling centers, are divided between the traditional retailers and the online retailers as described by Equations (15) and (16).

$$\lambda (\sum_i A_{ijt} + \sum_n I_{njt}) - \sum_{k^{tr}} B_{jk^{tr}t} = 0 \quad \forall j, t \quad (15)$$

$$(1 - \lambda) (\sum_i A_{ijt} + \sum_n I_{njt}) - \sum_{k^{on}} B_{jk^{on}t} = 0 \quad \forall j, t \quad (16)$$

Another set of equilibrium constraints on the traditional retailers assures that the quantity transported from the manufacturers and recovery centers to a traditional retailer is equal to the quantity transported from these retailers to the customers as described by Equation (17).

$$\sum_j B_{jk^{tr}t} + \sum_v J_{vk^{tr}t} - \sum_l C_{k^{tr}lt} = 0 \quad \forall k^{tr}, t \quad (17)$$

Another set of equilibrium constraints on the online retailers is considered to make sure that the quantity transported from the manufacturers and recovery centers to this retailer is equal to the quantity transported from this retailer to the customers as described by Equation (18).

$$\sum_j B_{jk^{on}t} + \sum_v J_{vk^{on}t} - \sum_l C_{k^{on}lt} = 0 \quad \forall k^{on}, t \quad (18)$$

Equilibrium constraints on the demands of the customers show that the quantity provided by the customer is equal to a certain amount that is a proportion of End of Life products (EOL), μ , that is transported to the collection and inspection centers as described by Equation (19).

$$\mu (\sum_{k^{tr}} C_{k^{tr}lt} + \sum_{k^{on}} C_{k^{on}lt}) - \sum_m D_{lmt} = 0 \quad \forall l, t \quad (19)$$

The equilibrium constraints on the collection and inspection centers show that the quantity of the EOL product transported to these centers are distributed in proportions of the π , ρ , and τ of these products that are disposed, recycled, and recovered, respectively, as described by Equations (20)–(23).

$$\sum_s H_{mst} - \pi \sum_l D_{lmt} = 0 \quad \forall m, t \quad (20)$$

$$\sum_n F_{mnt} - \rho \sum_l D_{lmt} = 0 \quad \forall m, t \quad (21)$$

$$\sum_v E_{mvt} - \tau \sum_l D_{lmt} = 0 \quad \forall m, t \quad (22)$$

where

$$\pi + \rho + \tau = 1 \quad (23)$$

Equilibrium constraints on the amount transported to the manufacturers from the recycling centers such that it equals the amount transported from the collection and inspection centers to these centers as described by Equation (24).

$$\sum_m F_{mnt} - \sum_j I_{njt} = 0 \quad \forall n, t \quad (24)$$

Equilibrium constraints of the recovery centers, such that a proportion ϕ of the recovered products is transported to the traditional retailers, and the remainder of the recovered products is transported to the online retailers, described by Equations (25) and (26).

$$\phi \sum_m E_{mvt} - \sum_{k^{tr}} J_{vk^{tr}t} = 0 \quad \forall v, t \quad (25)$$

$$(1 - \phi) \sum_m E_{mvt} - \sum_{k^{on}} J_{vk^{on}t} = 0 \quad \forall v, t \quad (26)$$

Finally, non-negativity and integrity constraints for the decision variable as described by Equations (27) and (28).

$$A_{ijt}, B_{jk^{tr}t}, B_{jk^{on}t}, C_{k^{tr}lt}, C_{k^{on}lt}, D_{lmt}, H_{mst}, F_{mnt}, E_{mvt}, I_{njt}, J_{vk^{tr}t}, J_{vk^{on}t} \geq 0 \quad (27)$$

$$O_{\Omega t} = \begin{cases} 1 & \text{if the facility } \Omega \text{ opens in period } t \\ 0 & \text{otherwise} \end{cases} \quad \text{for all } \Omega: \{i, j, k^{tr}, k^{on}, m, s, n, v\} \quad (28)$$

5. Computational Experiments

In this section, numerical experiments were performed using the GAMS-CPLEX 12.9 solver to validate the dual-channel CLSC using a personal computer (Intel Core i7, 3 GHz CPU, RAM 16 GB, Windows 10 OS). The proposed mathematical model is composed of 389 decision variables (317 continuous and 72 binary variables) and 200 constraints. It is well known that the complexity of the dual-channel CLSC problem is NP-hard because of number of binary variables. The computational requirements are proportional with the number of binary variables [51,52] of the dual-channel CLSC, which are O_{it} , O_{jt} , $O_{k^{tr}t}$, $O_{k^{on}t}$, O_{mt} , O_{st} , O_{nt} , and O_{vt} and equal to $|i + j + k^{tr} + k^{on} + m + s + n + v| * |t|$ in the studied problem. Small size instances are used in this paper for model validation. NP-hard problems are validated by implementing the small size instances using the exact solution obtained by GAMS software [25,53].

5.1. Description of the Data

The dual-channel CLSC proposed in this study, which is depicted in Figure 1, is a single product. Multiple echelons and four time periods are composed of four suppliers, two manufacturers, two traditional retailers, two online retailers, and three customer sets. Moreover, the facilities in the reverse chain are composed of two collection and inspection centers, two disposal centers, two recycling centers and two recovery centers. Some of the data implemented in this study are taken from a study presented by Mohammed et al. [50], shown in Table 3.

Table 3. The model's parameter values.

Parameters	Values
FC_{it}	uniform(5,000, 10,000)
FC_{jt}	uniform(30,000, 60,000)
FC_{mt}	uniform(2500, 5000)
FC_{nt}	uniform(20,000, 30,000)
FC_{st}	uniform(4000, 5000)
$FC_{k^{tr}t}$	uniform(10,000, 12,000)
FC_{vt}	uniform(10,000, 30,000)
PC	uniform(11,13)
jc	uniform(21,24)
mc	uniform(6,9)
sic	uniform(7,9)
yc	uniform(2,4)
vc	uniform(10,15)

The distances among the different facilities in kilometers are presented in Table A3. The shipment cost of a product is estimated as 0.08 USD per km, and the delivery cost of a product requested from the online retailers is 1.0 USD per product. The capacities of the dual-channel CLSC facilities are presented in Table A1, and the customer demand is presented in Table A2.

A fraction of the customers demand ($\lambda = 0.70$) of products is supplied by traditional retailers, while the remainder of the demand is supplied by online retailers. The fraction of the EOL products ($\mu = 0.70$) is transported to the collection centers, a fraction of the collected and inspected products ($\rho = 0.30$) is recycled, and another fraction of these products ($\tau = 0.30$) is recovered, and the remainder ($\pi = 0.40$) of these products is disposed. The fraction of the recovered products ($\phi = 0.70$) is transported to the traditional retailers, while the remainder of these products is transported to the online retailers. Strategic and tactical decisions are obtained, and sensitivity analysis of dual-channel CLSC parameter changes that are beneficial from managerial perspectives is considered.

5.2. Results

Strategic and tactical decision variables for the dual-channel CLSC were obtained, and the optimal flow between facilities and the optimal opening and closure times of facilities are determined as presented in Table 4. Manufacturers are provided by the raw material through suppliers and recycling centers, and these manufacturers cooperate with recovery centers to provide the products for traditional and online retailers. The total cost of the dual-channel CLSC is 1,165,352 USD, of which 19% is transportation costs, 5% is purchasing costs, 18% is operation costs, and the remainder is the fixed costs.

Table 4. Strategic and tactical decisions for the dual-channel CLSC.

Decision Variables	From/To	t_1	t_2	t_3	t_4
A_{ijt}	supplier 2-manufacturer 4	1108	1102	0	0
	supplier 4-manufacturer 3	0	0	1026	0
B_{jkt^t}	manufacturer 1-traditional retailer 1	281	279	0	279
	manufacturer 3-traditional retailer 1	0	0	760	0
	manufacturer 3-traditional retailer 2	0	0	219	0
	manufacturer 4-traditional retailer 1	775	771	0	441
	manufacturer 4-traditional retailer 2	0	0	0	330
$B_{jk^{on}t}$	manufacturer 1-online retailer 1	120	120	0	120
	manufacturer 3-online retailer 2	0	0	420	0
	manufacturer 4-online retailer 1	332	331	0	331
$C_{k^{tr}lt}$	traditional retailer 1-customer 1	550	550	540	540
	traditional retailer 1-customer 2	620	600	391	320
	traditional retailer 1-customer 3	167	180	89	140
	traditional retailer 2-customer 2	0	0	219	330
$C_{k^{on}lt}$	online retailer 1-customer 3	538	570	111	570
	online retailer 2-customer 3	35	0	419	0
D_{lmt}	customer 1-collection center 1	0	385	378	378
	customer 1-collection center 2	385	0	0	0
	customer 2-collection center 1	434	420	427	455
	customer 3-collection center 1	518	525	434	497
H_{mst}	collection center 1-disposal center 2	381	532	496	532
	collection center 2-disposal center 1	154	0	0	0
E_{mvt}	collection center 1-recovery center 1	285	399	372	399
	collection center 2-recovery center 2	116	0	0	0
I_{njt}	recycling center 1-manufacturer 1	401	399	0	399
	recycling center 2-manufacturer 3	0	0	372	0
F_{mnt}	collection center 1-recycling center 1	286	399	0	399
	collection center 1-recycling center 2	0	0	372	0
	collection center 2-recycling center 1	116	0	0	0
$J_{vk^{tr}t}$	recovery center 1-traditional retailer 1	200	279	260	279
	recovery center 2-traditional retailer 1	81	0	0	0
$J_{vk^{on}t}$	recovery center 1-online retailer 1	86	120	111	120
	recovery center 2-online retailer 2	35	0	0	0

5.3. Sensitivity Analysis of the Dual-Channel CLSC Parameters

This section provides a comprehensive sensitivity analysis of the dual-channel CLSC parameters and their effect on the overall cost. The experimental computation manipulates four scenarios of parameter sensitivity analysis and their impact on the total supply chain cost. The baseline scenario is the current situation as presented in the previous section for all such analyses in this section using the same approach implemented in the literature [54–56]. A crucial question that the baseline can address relates to knowing that the model is valid [57]. The first scenario considers customer demand variations. The second scenario investigates the variations in the quantity produced by the manufacturer directed at both traditional and online retailers. For example, e-commerce retail grows six-fold in the US from 2000 to 2009 [58]. The third scenario handles the change in the proportions of EOL products returned for

recycling, disposal, and recovery, and their effect on the dual-channel CLSC. The last scenario considers an adjustment in the inspection ratios of items for recycling, disposal, and recovery.

5.3.1. Customer Demand Ratio Change from Traditional Retailers

Due to the advantages of e-commerce and the availability of the Internet, customer demand through online retailers has increased dramatically, and competition from traditional retailers has decreased. This study proposes changing the fraction of the products supplied to traditional retailers due to the change in the fraction of products supplied to online retailers. Therefore, the number of opening times of traditional retailers has been decreased over the planning horizon due to the increase in the online retailer demand ratio, as shown in Figure 2. Additionally, the effect of the ratios of manufactured and recovered products directed to traditional retailers on the dual-channel CLSC cost is presented in Table 5.

Table 5. The impact of the ratios of manufactured and recovered products for traditional retailers on the dual-channel CLSC's cost.

λ, ϕ	Transportation Cost	Purchasing Cost	Operations Cost	Fixed Cost	Total Cost (USD)	Total Cost Change
1.0	241,303.4	55,152.1	208,792.9	698,971.4	1,204,219.8	3.3%
0.9	235,389.3	55,152.1	208,792.9	698,971.4	1,198,305.6	2.9%
0.8	229,532.8	55,152.1	208,792.9	688,271.7	1,181,749.5	1.4%
0.7	223,835.5	55,152.1	208,792.9	677,572.1	1,165,352.6	0
0.6	218,269.8	55,152.1	208,792.9	683,430.8	1,165,645.6	0.02%
0.5	214,189.8	55,152.1	208,792.9	662,031.5	1,140,166.3	−2.2%
0.4	207,650.7	55,152.1	208,792.9	662,031.5	1,133,627.2	−2.8%

Figure 2. Influence of the demand via online retailers on the number of opening times of traditional retailers.

5.3.2. Influence of Customers Demand Change on Dual-Channel CLSC Costs

Sensitivity analysis of the incremental change of demand of customers β with incremental demand between 10% and 40% was performed, and the effect on the related types of costs and the total cost of the dual-channel CLSC is presented in Table 6. The total cost increased by 24% as a result of an increase in demand of 40%.

Table 6. The effect of customer demand on the dual-channel CLSC's cost.

β	Transportation Cost	Purchasing Cost	Operations Cost	Fixed Cost	Total Cost (USD)	Total Cost Change
0%	223,835.5	55,152.1	208,792.9	677,572.1	1,165,352.6	0
10%	239,992.9	60,387.1	228,611.5	749,428.5	1,278,420.0	9.7%
20%	263,073.0	66,108.8	250,272.4	760,128.1	1,339,582.3	14.9%
30%	286,139.5	71,697.7	271,430.8	760,128.1	1,389,396.2	19.2%
40%	308,340.3	77,212.9	292,310.1	771,845.6	1,449,708.9	24.4%

5.3.3. Effect of the Proportion of EOL Products on the Dual-Channel CLSC Cost

Recently, some companies and governments have begun to encourage the customer to return EOL products. To do so, they offer incentives or discounts on new products by changing the EOL products [59] as well as subsidies that play a crucial role in promoting the overall operational performance of the CLSC and social surplus [60].

Increasing the ratio of EOL products to the CLSC's reverse activities, such as recycling, recovery, and disposal, leads to a reduction in the CLSC's overall cost, as shown in Table 7, due to an increase in the amount of recycling and recovered products, and a decrease in the purchase of new (not recycled) raw materials as shown in Figure 3.

Table 7. Effect of the proportion of the EOL products directed to reverse logistics.

μ	Transportation Cost	Purchasing Cost	Operations Cost	Fixed Cost	Total Cost (USD)	Total Cost Change
0.6	208,339.1	60,857.4	201,620.5	738,728.8	1,209,545.9	3.8%
0.7	223,835.5	55,152.1	208,792.9	677,572.1	1,165,352.6	0
0.8	245,353.0	46,023.4	220,268.7	622,274.1	1,133,919.3	−2.7%
0.9	253,911.9	43,741.3	223,137.7	566,976	1,087,767.1	−6.6%

Figure 3. Impact of the ratio of EOL products on purchasing and transportation costs.

5.3.4. Impact of Reverse Ratios of Recycling, Disposal, and Recovery on the Dual-Channel CLSC's Cost

The ratios of the quantities directed after collection and inspection for recycling, recovery, and disposal affect the total performance of the dual-channel CLSC. Sensitivity analysis was performed on the change in the ratios directed to disposal, recycling, and recovery centers, as shown in Table 8.

Table 8. The change in reverse ratios of recycling, disposal, and recovery centers.

Reverse Ratios			Dual Channel CLSC Costs					
π	ρ	τ	Transportation Cost	Purchasing Cost	Operations Cost	Fixed Cost	Total Cost (USD)	Total Cost Change
0.2	0.4	0.4	228,202.4	41,839.5	206,926.6	534,600.2	1,011,568.7	−13%
0.3	0.4	0.4	219,926.6	48,495.8	207,859.8	677,572.1	1,153,854.3	−1.0%
0.4	0.3	0.3	223,835.5	55,152.1	208,792.9	677,572.1	1,165,352.6	0.0
0.4	0.4	0.3	223,546.9	51,823.9	210,321.5	677,572.1	1,163,264.4	−0.18%
0.3	0.3	0.4	228,308.8	48,495.8	203,869.4	534,600.2	1,015,274.2	−12.9%
0.3	0.3	0.5	215,228.6	45,167.7	197,417.4	534,600.2	992,413.8	−14.8%
0.4	0.3	0.3	223,835.5	55,152.1	208,792.9	677,572.1	1,165,352.6	0.0
0.3	0.4	0.3	223,258.2	48,495.8	211,850.1	677,572.1	1,161,176.2	−0.36%
0.2	0.5	0.3	222,681.0	41,839.5	214,907.3	677,572.1	1,156,999.9	−0.72%

Increasing the ratio of the amount directed to disposal centers contributes to an increase in the CLSC's overall cost due to an increase in demand for the purchase of new raw material, as seen in the first portion of Table 8. Conversely, an increment in the recovery and recycling ratios of returned EOL products reduces the total cost by reducing the amount of new material purchased and increasing the number of recovered products, and this is depicted in the second and third portions of Table 8.

5.4. Managerial Implications for the Dual-Channel CLSC

Inspired by the numerical results and sensitivity analysis from Section 5.3, this section presents some managerial implications for the dual-channel CLSC from the prospective of manufacturers, recovery centers, and governments. Manufacturers and recovery centers are recommended to increase the ratio of products directed to online retailers by considering advertisements and promotions for online shopping. This will result in a decrease in the total cost of the dual-channel CLSC, thereby increasing the total profit due to the drastic spread of the increased volume of e-commerce. The ratio of the returned products has a major impact on the total cost of dual-channel CLSC. To increase this ratio, governments are advised to support the companies and encourage the costumers to return the EOL products. This move has large economic, social, and environmental benefits.

6. Conclusions and Future Trends

This study proposes an MILP model of the dual-channel CLSC to address the increasingly widespread adoption of e-commerce, facilitated by the Internet and related technologies. The adoption of e-commerce and the customer trends of online shopping for new, remanufactured, and recovered products are driven by a variety of brands and products, the comfort afforded by e-commerce, and savings of customer time and effort. From the industry and service sector perspectives, e-commerce represents increased revenue due to cost savings and reduced air pollution, resulting in a significant environmental impact benefiting health. A computational experimental using GAMS–CPLEX 12.9 is performed to obtain optimum values of strategic and decision variables and to minimize the total cost of the dual-channel CLSC. Sensitivity analysis is conducted to investigate the impact and dependency the of strategic and tactical decisions on the major key parameters of the developed model, and the robustness, validity, and applicability of the proposed model are demonstrated.

Among the key findings of the conducted computational experiments and comprehensive sensitivity analysis compared with baseline , the number of opened traditional retailers decreases with the increase in the online retailer demand ratio, accordingly, the total dual-channel CLSC decreases.

Moreover, the total dual-channel CLSC decreases with the increase of the returned EOL products, recycling ratio, and recovery ratio.

Regarding the limitations of this study, the study does not consider the response of customers to both traditional and online retailers, the carbon emissions due to the trade-offs between traditional and online retailers are ignored, and the uncertainty in the demand in both traditional and online retailers was not taken into consideration. Future research directions may include the following:

- The uncertainty of model parameters and the environmental and social impacts can be taken into consideration in dual-channel CLSC models using stochastic optimization approaches, such as the Mulvey robust optimization approach [61], the sample average approximation method [62], and the robust optimization approach developed by Bertsimas et al. [63] and Ben-Tal et al. [64].
- To improve the efficiency of computations and the quality of solutions for large and complex dual-channel CLSC problems is mandatory, heuristics and meta-heuristics approaches can be used [65,66].
- The supply chain risks (operational and disruption risks) and ripple effect on the dual-channel CLSC can be considered, and alternative plans using digital supply chain twins can be provided [67].
- Carbon and greenhouse gas emissions can be included in mathematical models to investigate their effects on model performance.
- The linkage between dual-channel CLSC and circular economy from application and theoretical points of view can be implemented.

The findings of this study are expected to be beneficial to both academics and managerial practitioners. For academicians, this study suggests new future trends, as mentioned in this section. Furthermore, this study contributes in helping managerial practitioners to realize the importance of online retailers, besides traditional ones; in addition, it motivates them to cooperate with governments in educating customers about the recycling and recovery of EOL products. This, in turn, could consolidate environmental sustainability.

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Abbreviations

The following abbreviations are used in this manuscript:

MILP	Mixed Integer linear Programming
GT	Game theory
MINLP	Mixed Integer Non Linear Programming
CLSC	Closed Loop Supply Chain
EOL	End of Life
e-commerce	electronic commerce

Appendix A

Table A1. The capacities of CLSC facilities for different periods of time.

	t_1	t_2	t_3	t_4
Supplier 1	1400	1440	1470	1480
Supplier 2	1500	1520	1530	1540
Supplier 3	1400	1410	1420	1440
Supplier 4	1450	1520	1500	1530
Manufacturer 1	1250	1170	1120	1150
Manufacturer 2	1240	1210	1200	1250
Manufacturer 3	1400	1400	1410	1410
Manufacturer 4	1200	1280	1280	1320
Traditional retailer 1	1900	1710	1120	1100
Traditional retailer 2	1650	1300	900	1050
Online retailer 1	720	740	750	730
Online retailer 2	900	920	810	840
Collection-center1	2700	2700	2700	2750
Collection-center2	2680	2600	2660	2680
Disposal-center 1	1660	1660	1670	1680
Disposal-center 2	1670	1670	1670	1690
Recycling-center1	1620	1680	1610	1790
Recycling-center2	1600	1760	1890	1880
Recovery-center1	1620	1810	1700	1900
Recovery-center2	1700	1780	1690	1800

Table A2. The customers demand of products.

	t_1	t_2	t_3	t_4
Customer 1	550	550	540	540
Customer 2	620	600	610	650
Customer 3	740	750	620	710

Table A3. Distances between the dual-channel CLSC facilities (km).

	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
Supplier 1	80	100	150	120
Supplier 2	100	120	160	80
Supplier 3	220	130	200	160
Supplier 4	160	110	130	150
	Traditional retailer 1	Traditional retailer 2	Online retailer 1	Online retailer 2
Manufacturer 1	100	115	80	110
Manufacturer 2	110	120	90	100
Manufacturer 3	90	100	100	80
Manufacturer 4	80	80	120	130

Table A3. Cont.

	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
	Customer 1	Customer 2	Customer 3	
Traditional retailer 1	100	80	120	
Traditional retailer 2	110	90	130	
Collection center 1	110	100	90	
Collection center 2	90	115	110	
	Disposal center 1	Disposal center 2	Recycling center 1	Recycling center 2
collection center 1	150	130	100	90
collection center 2	160	170	90	120
	Recovery 1	Recovery 2		
Collection center 1	80	110		
Collection center 2	100	70		
	Manufacturer 1	Manufacturer 2	Manufacturer 3	Manufacturer 4
Recycling center 1	100	130	160	170
Recycling center 2	140	200	150	220
	Traditional retailer 1	Traditional retailer 2	Online retailer 1	Online retailer 2
Recovery center 1	50	60	90	110
Recovery center 2	60	80	110	100

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