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A NOVEL BI-OBJECTIVE MODEL FOR A MULTI-PERIOD MULTI-PRODUCT CLOSED-LOOP SUPPLY CHAIN

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Keywords

Closed-Loop Supply Chain,
Multi-Objective Model,
Mixed-Integer Model,
Goal Attainment Method,
Sensitivity Analysis.

Abstract

Closed-loop supply chain (CLSC) is a kind of supply chain which contains forward and backward flows of commodities within a logistics network. In the decision-making process of CLSC, locational, inventory control and transportation issues are addressed to deal with strategic, tactical and operational decisions. This paper utilizes a novel bi-objective mixed-integer linear programming (MILP) model to formulate a multi-period multi-product CLSC design problem considering aggregate cost minimization and service level maximization at the same time. To tackle the bi-objectiveness of the model, goal attainment method (GAM) is applied which is then executed by Gurobi Python API to test the applicability of the suggested model for three different scales (small, medium and large). It is demonstrated that the proposed methodology can find the optimal solutions for different problems in a maximum of 500 seconds. Finally, a set of sensitivity analyses is carried out on the main parameters in order to test the behaviors of the objective functions and suggest managerial insights as well as decision aids. The results reveal that the model is highly dependent on the demand parameter, that is, an increase in demand is closely related to an increase in the aggregate cost and a simultaneous downward trend in the service level.

ÇOK PERİYOTLU ÇOK ÜRÜNLÜ KAPALI DÖNGÜ TEDARİK ZİNCİRİ İÇİN YENİ BİR ÇİFT-AMAÇLI MODEL

Anahtar Kelimeler

Kapalı-Döngü Tedarik Ağı,
Çok Amaçlı Model,
Karmaşık-Tamsayılı Model,
Hedefe Ulaşma Yöntemi,
Duyarlılık Analizi.

Öz

Kapalı döngü tedarik zinciri (KDTZ), bir lojistik ağ içinde ürünlerin ileri ve geri akışlarını içeren bir tür tedarik zinciridir. KDTZ'nin karar verme sürecinde, stratejik, taktik ve operasyonel kararlarla başa çıkmak için lokasyon, envanter kontrolü ve taşıma konuları ele alınmaktadır. Bu araştırma, aynı anda hem toplam maliyet minimizasyonu hem de hizmet seviyesi maksimizasyonu dikkate alınarak çok periyotlu ve çok ürünlü bir CLSC tasarım problemini formüle etmek için yeni bir çift-amaçlı karma tamsayılı doğrusal programlama (KTDP) modelini kullanmaktadır. Modelin iki yönlülüğünü sağlamak adına hedefe ulaşma yöntemi (GAM) kullanılmış ve daha sonra Gurobi Python API kullanılararak önerilen modelin üç farklı ölçekteki (küçük, orta ve büyük) problemler üzerinde uygulanabilirliği test edilmiştir. Önerilen metodolojinin farklı problemler için en uygun çözümleri maksimum 500 saniyede bulabildiği gösterilmiştir. Son olarak, amaç fonksiyonlarının davranışlarını değerlendirmek ve yönetimsel öngörüler ve karar destek çıkarımları sağlamak için anahtar parametreler üzerinde bir dizi duyarlılık analizi yapılmaktadır. onuçlar modelin talep parametresine yüksek oranda bağlı olduğunu göstermektedir. Öyle ki, talepteki bir artış toplam talepteki artışla ve aynı anda servis seviyesinde görülen aşağı yönlü trendle yakında ilişkilidir.

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1. Introduction

Supply chain is a value creating network and supply chain network design is one of the key components that determine the competitive advantage of a business. Closed-loop supply chains (CLSCs) gained significant importance in recent years due to their honoring of the sustainable development requirements through recycling and the remanufacturing of used products, which is also known as 'reverse logistics'. The idea behind reverse logistics is to reclaim used products, either under warranty or at the end of use/lease period so as to make sure that they are properly disposed, reused, recycled or remanufactured. A thorough discussion on reverse logistics can be recognized in Dekker et al. (2013).

A CLSC refers to a supply chain network where all forward and reverse logistics operations are merged to take place in a single loop to ensure economic circularity as well as environmental and social sustainability in industrial operations. As such CLSC differs from a traditional supply chain with not just its particular focus on long-term profitability and growth, but also its effort to avoid a rapid deprivation of natural resources. Environmental and social sustainability aspect is integrated through a business model which aims to contribute to low-carbon and socially responsible development process (Kumar and Kumar, 2013). The interest in CLSC is on the rise as the benefits arising from shifting to the latter can largely outweigh the costs incurred due to the transformation process. Businesses in general and manufacturers in particular can strengthen their financial positions by reselling refurbished products or substituting recycled products for their conventional raw materials. The aim here is to capture additional value by integrating all supply chain activities – most notably turning users into suppliers.

In this context, the present study is proposing a bi-objective MILP model coupled with a multi-period, multi-product CLSC structure with a view to minimizing the aggregate cost while, at the same time, maximizing the service level. Afterwards, a number of sensitivity analyses are presented to provide decision-makers at organizations with a proper insight into optimal CLSC design policy and help them determine the optimal level of resources to be rendered throughout the CLSC network.

There are various studies in the literature that deal with different aspects of CLSC, such as design, optimization, performance metrics, and pricing. A detailed survey of studies in this domain can be found in Govindan et al. (2015) where authors review 382 articles published between January 2007 and March 2013. Stindt and Sahamie (2014) offer a database of 167 relevant publications on CLSC management in the process industry. The literature on uncertainty factors, methods, and solutions concerning CLSC is more recently presented in Stindt and Sahamie (2014).

Majority of the studies reviewed are found to deal with the design, optimization or configuration of CLSCs taking a multi-objective approach. Besides, Devika et al. (2014), Zhen et al. (2019) and Fathollahi-Fard et al. (2020) put more emphasis on 'sustainable' design of the CLSC.

Mixed-integer linear programming (MILP) models are the most famous methodologies among researchers dealing with the optimization of CLSCs. Pishvaee et al. (2011), a comparison of deterministic MILP model vs. robust MILP model based on various test problems is presented. Kannan et al. (2010), authors use a heuristics-based genetic algorithm (GA) for solving a multi-echelon multi-product multi-period MILP model. Amin and Zhang (2013) employ weighted sum and ε-constraint methods to boil their multi-objective model down into a single-objective one and use stochastic programming. In another study, Amin and Zhang (2012) introduce a fuzzy multi-objective MILP model that aims to maximize profit and weights of suppliers, while minimizing the defect rate. Ruimin et al. (2016) and Hajiaghaei-Keshteli et al. (2019) use multi-objective mixed-integer nonlinear programming (MINLP) models. The first paper employs LP-metric method, whereas the latter metaheuristics and hybridized algorithms to solve the proposed models, respectively. Economical profit/cost, environmental impact, defect rate, social responsibility, carbon emissions are among the most addressed factors that in the objective functions. A non-traditional approach is presented in Ramezani et al. (2014) where financial constraints are integrated into a MILP model which uses an objective function aiming to maximize shareholder's value (measured through change in equity) rather than profit. Paksoy et al. (2011), Olugu and Wang (2012) and Pochampally et al. (2009) rather focus on the performance metrics pertaining to the CLSCs. Kenné et al. (2012) present a numerical algorithm to solve a stochastic dynamic programming model for production planning problem associated with a CLSC. Last but not the least, applications on various industries, such as glass, tires, plastic goods, automotive, electrical and dairy goods, and battery, are presented to showcase the applicability of models (Yildizbasi et al., 2018; Pervin et al., 2019; Goli et al., 2020; Aghighi et al., 2021).

Recently, a robust optimization model is offered by Lotfi et al. (2021) in order to design a CLSC network addressing sustainability, resiliency and conditional value at risk. A heuristic relaxation algorithm is developed by Pazhani et al. (2021) to configure a multi-period multi-product CLSC network. The validation of their proposed model is also evaluated using case studies and hypothetical datasets. Mondal and Roy (2021) examine the effects of COVID-19 pandemic on the sustainable development of CLSC under mixed uncertainty. They also deal with operational decisions through a pick-up-delivery vehicle routing problem.

Based on the above survey, the following items can be listed as the main contributions of the study:

i. Development of a novel mathematical model for a multi-period multi-product CLSC network,
ii. Addressing of two important aspects of sustainable development through aggregate cost minimization and service level maximization,
iii. Application of goal attainment method (GAM) to cope with model bi-objectiveness,
iv. Presentation of sensitivity analyses to study the impact of the changes in key parameter values.

The structure of the remaining sections is organized as follows: Section 2 describes the problem and proposed mathematical model. GAM is represented in Section 3 as the solution method. The computational results are given in Section 4. Finally, the concluding remarks and outlook are explained in Section 5.

2. Problem Description

In this section, the proposed network as well as the associated mathematical model is presented. In our problem, a CLSC network includes manufacturing plants, distribution centers, customers, collection centers, recovery centers and disposal centers. The first three centers deal with forward logistics and the remaining three centers establish backward logistics. In the first phase and as a strategic decision, the aim is to determine the optimal locations for distribution centers, collection centers, recovery centers and disposal centers given the relationships between them. Then, the tactical decisions in terms of inventory control are made at distribution centers, and in the meantime, operational decisions including transportation planning and determination of product flow between different facilities are put in place.

The two objectives are to minimize the aggregate cost and maximize the service level in order to maximize customer satisfaction. Figure 1 represents the schematic view of the suggested network.

The main assumptions of the model are listed below:

- The proposed network includes 6 different levels of facilities; i.e., manufacturing plants, distribution centers, customers, collection centers, recovery centers and disposal centers,
- Locational decisions are made at distribution centers, collections centers, recovery centers and disposal centers,
- All the required facilities should be located at the beginning of the planning period,
- Capacities of all facilities are limited,
- Parameters are deterministic,
- Multiple products are taken into account,
- There is initial inventory at each distribution center,
- No inventory is held by manufacturing plants,
- Shortage of products is allowed at distribution centers,
- A planning horizon including multiple planning periods is considered,
- Locational, inventory, allocation and transportation decisions are made at the same time.

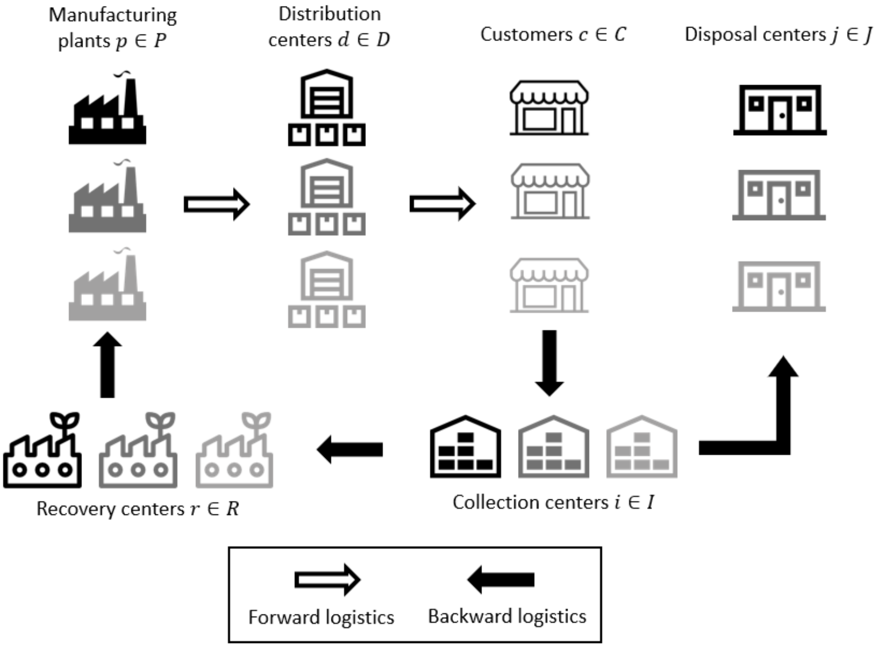

Figure 1. Schematic View of The Proposed CLSC Network of The Problem.

2.1. Mathematical Model

2.1.1. Indices and Sets

p: Index of manufacturing plants ($p \in P$),
d: Index of distribution centers ($d \in D$),
c: Index of customers ($c \in D$),
i: Index of collection centers ($i \in D$),
r: Index of recovery centers ($r \in R$),
j: Index of disposal centers ($j \in J$),
k: Index of products ($k \in K$),
t: Index of time periods ($t \in T$).

2.1.2. Parameters

DM_{ckt}: Demand of customer c for product k in period t,
CA_{pk}: Capacity of manufacturing plant p to produce product k in each period,
CB_{dk}: Capacity of distribution center d to distribute product k in each period,
CC_{ik}: Capacity of collection center i to collect product k in each period,
CD_{rk}: Capacity of recovery center r to recover product k in each period,
CE_{jk}: Capacity of disposal center j to dispose product k in each period,
TA_{kpd}: Unit shipment cost of product k from manufacturing plant p to distribution center d,
TB_{kdc}: Unit shipment cost of product k from distribution center d to customer c,
TC_{kci}: Unit shipment cost of product k from customer c to collection center i,
TD_{kir}: Unit shipment cost of product k from collection center i to recovery center r,
TE_{kij}: Unit shipment cost of product k from collection center i to disposal center j,
TF_{krp}: Unit shipment cost of product k from recovery center r to manufacturing plant p,
DA_{pd}: Distance between manufacturing plant p and distribution center d,
DB_{dc}: Distance between distribution center d and customer c,
DC_{ci}: Distance between customer c and collection center i,
DD_{ir}: Distance between collection center i and recovery center r,
DE_{ij}: Distance between collection center i and disposal center j,
DF_{rp}: Distance between recovery center r and manufacturing plant p,
α_{kct}: Return rate for product k from customer c in period t,
β_{kit}: Return rate for recoverable product k from collection center i to recovery centers in period t,
$1 - \beta_{kit}$: Return rate of disposable product k from collection center i to disposal centers in period t,

FA_{kp}: Unit production cost of product k at manufacturing plant p,
FB_{kd}: Unit processing cost of product k at distribution center d,
FC_{ki}: Unit processing cost of product k at collection center i,
FD_{kr}: Unit processing cost of product k at recovery center r,
FE_{kj}: Unit processing cost of product k at disposal center j,
LA_d: Fixed establishment cost of distribution center d,
LB_i: Fixed establishment cost of collection center i,
LC_r: Fixed establishment cost of recovery center r,
LD_j: Fixed establishment cost of disposal center r,
GI_{kd}: Unit holding cost of product k at distribution center d,
GB_{kd}: Unit shortage cost of product k at distribution center d,
$I0_{kd}$: Initial inventory level of product k at distribution center d at the beginning of planning period,
δ_{pkt}: Demand of manufacturing plant p for recovered product k from recovery centers in period t,

2.1.3. Variables

X_{kpt}: Amount of product k produced by manufacturing plant p in period t,
YA_{kpdt}: Amount of product k shipped by manufacturing plant p to distribution center d in period t,
YB_{kdct}: Amount of product k shipped by distribution center d to customer c in period t,
YC_{kcit}: Amount of product k shipped by customer c to collection center i in period t,
YD_{kirt}: Amount of product k shipped by collection center i to recovery center r in period t,
YE_{kijt}: Amount of product k shipped by collection center i to disposal center j in period t,
YF_{krpt}: Amount of product k shipped by recovery center r to manufacturing plant p in period t,
ZA_d: A 0-1 variable representing whether distribution center d is established or not,
ZB_i: A 0-1 variable representing whether collection center i is established or not,
ZC_r: A 0-1 variable representing whether recovery center r is established or not,
ZD_j: A 0-1 variable representing whether disposal center j is established or not,
IV_{kdt}: Amount of inventory level of product k in distribution center d at the beginning of period t,
BO_{kdt}: Amount of shortage (back-order) for product k in distribution center d at the beginning of period t.

2.1.4. Objective Functions

Let AC and SL denote aggregate cost and service level, respectively. First objective function given by Eq. (1) defines the aggregate cost minimization including 17 terms. Terms (1)-(4) stand for establishment costs of facilities. Terms (5) and (6) express the inventory holding and shortage costs, respectively. Terms (7)-(12) indicate the transportation costs. Terms (13)-(17) show the processing costs at different facilities.

$$\begin{aligned}
\min AC = \; & \sum_{d\in D'} LA_d\, ZA_d + \sum_{i\in I'} LB_i\, ZB_i + \sum_{r\in R'} LC_r\, ZC_r \\
& + \sum_{j\in J'} LD_j\, ZD_j + \sum_{k\in K}\sum_{d\in D}\sum_{t\in T} GI_{kd}\, I_{kdt} + \sum_{k\in K}\sum_{d\in D}\sum_{t\in T} GB_{kd}\, B_{kdt} \\
& + \sum_{k\in K}\sum_{d\in D}\sum_{t\in T}\sum_{p\in P} TA_{kpd}\, DA_{pd}\, YA_{kpdt} + \sum_{k\in K}\sum_{d\in D}\sum_{t\in T}\sum_{c\in C} TB_{kdc}\, DB_{dc}\, YB_{kdct} \\
& + \sum_{k\in K}\sum_{i\in I}\sum_{t\in T}\sum_{c\in C} TC_{kci}\, DC_{ci}\, YC_{kcit} + \sum_{k\in K}\sum_{i\in I}\sum_{t\in T}\sum_{r\in R} TD_{kir}\, DD_{ir}\, YD_{kirt} \\
& + \sum_{k\in K}\sum_{i\in I}\sum_{j\in J}\sum_{r\in R} TE_{kij}\, DE_{ij}\, YE_{kijt} + \sum_{k\in K}\sum_{p\in P}\sum_{t\in T}\sum_{r\in R} TF_{krp}\, DF_{rp}\, YF_{krpt} \\
& + \sum_{k\in K}\sum_{p\in P}\sum_{t\in T} FA_{kp}\, X_{kpt} + \sum_{k\in K}\sum_{p\in P}\sum_{t\in T}\sum_{d\in D} FB_{kd}\, YA_{kpdt} \\
& + \sum_{k\in K}\sum_{c\in C}\sum_{t\in T}\sum_{i\in I} FC_{ki}\, YC_{kcit} + \sum_{k\in K}\sum_{r\in R}\sum_{t\in T}\sum_{i\in I} FD_{kr}\, YD_{kirt} \\
& + \sum_{k\in K}\sum_{j\in J}\sum_{t\in T}\sum_{i\in I} FE_{kj}\, YE_{kijt}
\end{aligned} \tag{1}$$

Our second objective function given by Eq. (2) below deals with service level maximization, whereas service level is defined as the proportion of demand that is fulfilled after considering any shortages (or, backorders) in distribution centers.

$$\max SL = \frac{\sum_{k\in K}\sum_{t\in T}\sum_{c\in C} DM_{ckt} - \sum_{d\in D}\sum_{k\in K}\sum_{t\in T} BO_{kdt}}{\sum_{k\in K}\sum_{t\in T}\sum_{c\in C} DM_{ckt}} \quad (2)$$

2.1.5. Constraints

We can now define our model constraints. Namely, constraint (3) represents the capacity limitation of manufacturing plants to produce various products in each period.

$$X_{kpt} \leq CA_{pk} \qquad \forall p \in P, k \in K, t \in T. \quad (3)$$

Constraints (4)-(7) stand for the capacity limitation as well as locational decisions at distribution facilities, collection facilities, recovery facilities and disposal facilities, respectively.

$$\sum_{p\in P} YA_{kpdt} \leq CB_{dk}\, ZA_d \qquad \forall\, k \in K, t \in T, d \in D, \quad (4)$$

$$\sum_{c\in C} YC_{kcit} \leq CC_{ik}\, ZB_i \qquad \forall\, k \in K, t \in T, i \in I, \quad (5)$$

$$\sum_{i\in I} YD_{kirt} \leq CD_{rk}\, ZC_r \qquad \forall r \in R, k \in K, t \in T, \quad (6)$$

$$\sum_{i\in I} YE_{kijt} \leq CE_{jk}\, ZD_j \qquad \forall k \in K, j \in J, t \in T, \quad (7)$$

Constraints (8)-(10) show the flows of backward logistics at collection facilities, recovery facilities and disposal facilities, respectively.

$$\sum_{i\in I} YC_{kcit} = \alpha_{kct} \sum_{d\in D'} YB_{kdct} \qquad \forall c \in C, k \in K, t \in T, \quad (8)$$

$$\sum_{r\in R} YD_{kirt} = \beta_{kit} \sum_{c\in C'} YC_{kcit} \qquad \forall i \in I, k \in K, t \in T, \quad (9)$$

$$\sum_{j\in J} YE_{kijt} = (1-\beta_{kit}) \sum_{c\in C'} YC_{kcit} \qquad \forall i \in I, k \in K, t \in T, \quad (10)$$

Constraint (11) ensures that the amount of products sent by manufacturing facilities to distribution centers do not surpass the produced amount of products at a given period.

$$\sum_{d\in D} YA_{kpdt} \leq X_{kpt} \qquad \forall p \in P, k \in K, t \in T, \quad (11)$$

Constraint (12) represents the product flows at distribution centers in which the output flow is restricted to the input flow in a given period.

$$\sum_{c\in C} YB_{kdct} \leq \sum_{p\in P} YA_{kpdt} \qquad \forall d \in D, k \in K, t \in T, \quad (12)$$

Constraint (13) expresses the balance between input and output flow at collection centers.

$$\sum_{c\in C} YC_{kcit} = \sum_{r\in R} YD_{kirt} + \sum_{j\in J} YE_{kijt} \qquad \forall i \in I, k \in K, t \in T, \quad (13)$$

Constraint (14) expresses the balance between input and output flow at recovery centers.

$$\sum_{p\in P} YF_{krpt} = \sum_{i\in I} YD_{kirt} \qquad \forall r \in R, k \in K, t \in T, \quad (14)$$

Constraint (15) guarantees that the products shipped from recovery centers to manufacturing plants do not exceed their demands from recovered products.

$$\sum_{r\in R} YF_{krpt} \leq \delta_{pkt} \qquad \forall p \in P, k \in K, t \in T, \quad (15)$$

Constraint (16) ensures that the amount of products transported from distribution facilities to each customer do not exceed its demand considering the shortages.

$$\sum_{d\in D} (YB_{kdct} + BO_{kdt}) = DM_{ckt} \qquad \forall c \in C, k \in K, t \in T, \quad (16)$$

Constraints (17) and (18) indicate the inventory balance at the first period and the remaining periods, respectively.

$$I0_{kd} + \sum_{p\in P} YA_{kpdt} - \sum_{c\in C} YB_{kdct} = IV_{kdt} \qquad \forall k \in K, d \in D, t \in \{1\}, \quad (17)$$

$$IV_{kdt-1} + \sum_{p\in P} YA_{kpdt} - \sum_{c\in C} YB_{kdct} = IV_{kdt} \qquad \forall k \in K, d \in D, t \in \{2,3,\dots,T\}, \quad (18)$$

Finally, constraints (19) and (20) define variable domains.

$$ZA_d, ZB_i, ZC_r, ZD_j \in \{0,1\} \qquad \forall i \in I, d \in D, j \in J, r \in R, \quad (19)$$

$$X_{kpt}, YA_{kpdt}, YB_{kdct}, YC_{kcit}, YD_{kirt}, YE_{kijt}, YF_{krpt}, IV_{kdt}, BO_{kdt} \in \mathbb{R}^+ \quad (20)$$
$$\forall i \in I, d \in D, j \in J, r \in R, p \in P, \forall k \in K, c \in C, t \in T.$$

3. The solution method: GAM

GAM is one of the well-known approaches to deal with multi-objectivensss which was first introduced by Gembicki and Haimes (1975). It includes a set of supreme goals, $U^* = \{u_1^*, u_2^*, \dots, u_n^*\}$, that correspond to a set of objective functions, $F(x) = \{f_1(x), f_2(x), \dots, f_n(x)\}$. The supreme value of each objective function is achieved by individually optimizing the single-objective model corresponding to that objective function. Furthermore, importance weights $W = \{w_1, w_2, \dots, w_n\}$ are assigned to each objective function, such that $\sum_{j=1}^{n} w_j = 1$. Eventually, the single-objective model that results from GAM can be represented as follows:a

$$\min Z_{GAM} = \varphi \quad (21)$$

$$f_j(x) - w_j\varphi \leq u_j^* \quad (j = 1), \quad (22)$$

$$f_j(x) + w_j\varphi \geq u_j^* \quad (j = 2), \quad (23)$$

where φ is a free scalar variable, subject to constraints (3)-(20). Here, $f_1(x) =$ AggregateCost and $f_2(x) =$ ServiceLevel. Moreover, we take into account (w_1, w_2)=(0.6, 0.4), and u_1^* and u_2^* are found by optimizing the primal single-objective model with the first and second objective function, respectively.

4. Experimental results

This section summarizes the computational results obtained for our proposed methodology using three problem instances that are randomly generated. For this purpose, Gurobi Python API is utilized to implement the model. Tables 1 and 2 illustrate the input information related to the problem scale and parameters, respectively. Here, $\mathbf{U}(a, b)$ refers to continuous uniform distribution. Figure 2 illustrates the significant impact of the problem scale on computational complexity and runtimes. The model results for the three sample problems are represented in Table 3 in terms of the objective function values and runtimes.

Table 1. Information About Different Problem Scales

Problem	P	D	C	I	R	J	K	T
#1	2	2	10	2	2	2	2	2
#2	4	4	20	4	4	4	4	4
#3	8	8	40	8	8	8	8	8

Table 2. Input Parameters of The Mathematical Model

Parameter	Value	Parameter	Value
$\boldsymbol{DM_{ckt}}$	U(20,40)	$\boldsymbol{DA_{pd}}$	U(10,50)
$\boldsymbol{CA_{pk}}$	U(1000,2000)	$\boldsymbol{DB_{dc}}$	
$\boldsymbol{CB_{dk}}$	U(200,500)	$\boldsymbol{DC_{ci}}$	
$\boldsymbol{CC_{ik}}$	U(300,800)	$\boldsymbol{DD_{ir}}$	
$\boldsymbol{CD_{rk}}$		$\boldsymbol{DE_{ij}}$	
$\boldsymbol{CE_{jk}}$		$\boldsymbol{DF_{rp}}$	
$\boldsymbol{TA_{kpd}}$	U(2,12)	$\boldsymbol{\alpha_{kct}}$	U(0.1,0.2)
$\boldsymbol{TB_{kdc}}$		$\boldsymbol{\beta_{kit}}$	U(0.2,0.4)
$\boldsymbol{TC_{kci}}$		$\boldsymbol{FA_{kp}}$	U(10, 20)
$\boldsymbol{TD_{kir}}$		$\boldsymbol{FB_{kd}}$	U(2, 5)
$\boldsymbol{TE_{kij}}$		$\boldsymbol{FC_{ki}}$	
$\boldsymbol{TF_{krp}}$		$\boldsymbol{FD_{kr}}$	
$\boldsymbol{LA_d}$	U(100000,200000)	$\boldsymbol{FE_{kj}}$	
$\boldsymbol{LB_i}$		$\boldsymbol{IO_{kd}}$	U(100, 500)
$\boldsymbol{LC_r}$		$\boldsymbol{\delta_{pkt}}$	U(200, 400)
$\boldsymbol{LD_j}$		$\boldsymbol{GB_{kd}}$	U(20, 30)
$\boldsymbol{GI_{kd}}$	U(1, 2)		

Table 3. Computational Results Obtained For The Proposed Methodology

Problem	$\boldsymbol{Z_{GAM}}$	$\boldsymbol{u_1^*}$	$\boldsymbol{u_2^*}$	**AggregateCost**	**ServiceLevel**	Runtime (s)
#1	0.194	676022.518	1	676022.634	0.923	1.06
#2	0.089	1476802.274	1	1476802.327	0.964	2.19
#3	272131.165	6442388.235	0.988	6605666.934	0.983	457.64

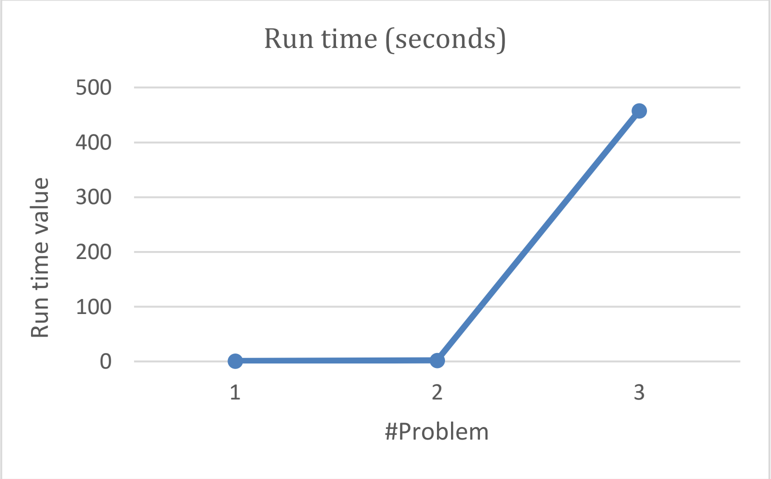

Figure. 2. Run Time Comparison of Different Problems

Furthermore, in order to evaluate the reactions of the objective functions to the changes in key parameter values (i.e., demand and return rates), a set of sensitivity analyses is conducted. The results of these analyses are presented in Table 4 and Figures 3-5.

Table 4. Results of the sensitivity analyses

DM_{ckt}	−20%	−10%	0%	+10%	+20%
AC	676022.624	676022.630	676022.634	684512.182	693001.847
SL	0.929	0.925	0.923	0.923	0.923
α_{kct}	−20%	−10%	0%	+10%	+20%
AC	676022.632	676022.633	676022.634	678039.408	680056.299
SL	0.924	0.923	0.923	0.923	0.923
β_{kit}	−20%	−10%	0%	+10%	+20%
AC	676022.634	676022.634	676022.634	676210.134	676397.750
SL	0.923	0.923	0.923	0.923	0.923

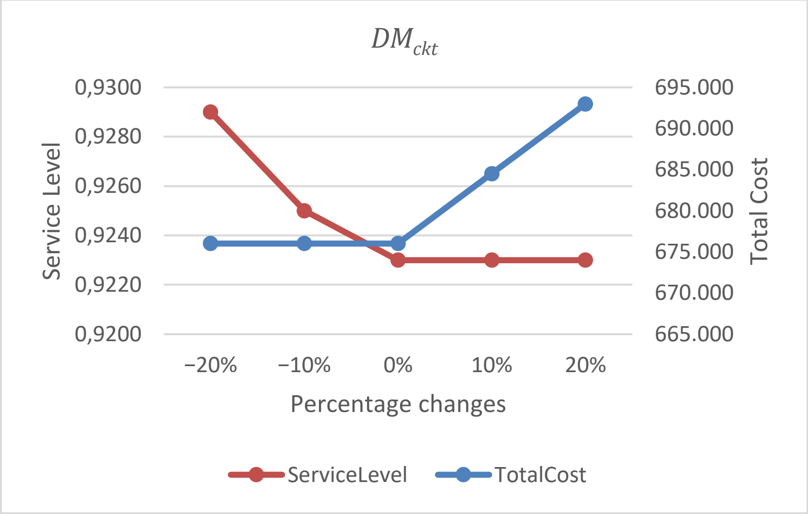

Figure 3. Sensitivity analysis for DM_{ckt}

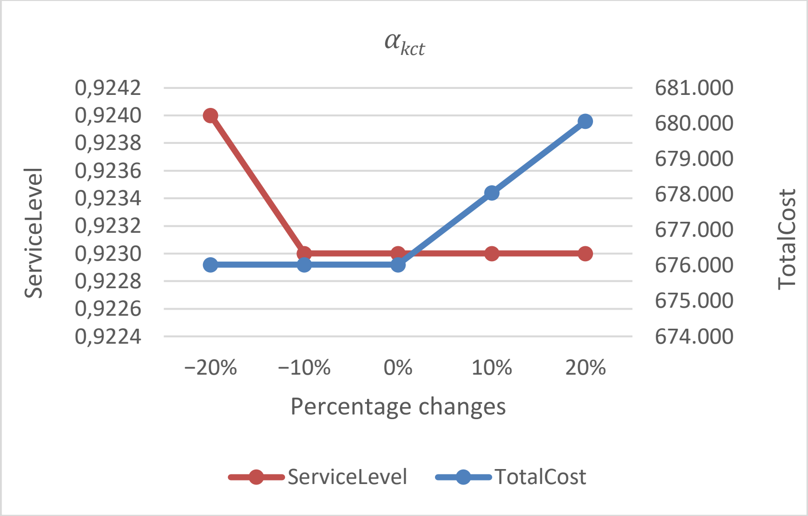

Figure 4. Sensitivity analysis for α_{kct}

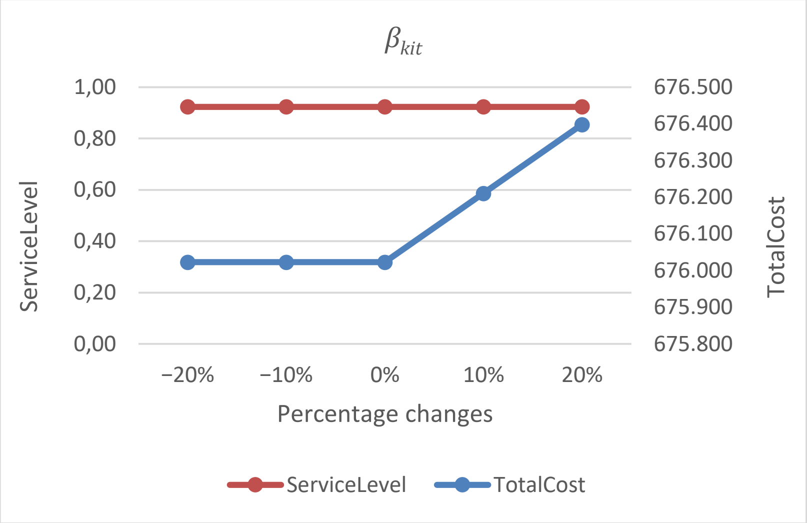

Figure 5. Sensitivity analysis for β_{kit}

We can observe from Table 4 and Figures 3-5 that change in key parameter valeus can significantly affect the solution values and, thereby, optimal policy. Demand turns out to be the most important parameter when compared to the return rates as the objective function values show a higher sensitivity to the fluctuations in demand. By increasing the demand parameter, we see that the aggregate cost also increases while service level follows a downward trend. A similar behaviour is also observed for the product return rates α_{kct}. Yet, for different change intervals considered for the recoverable product return rates β_{kit} (from collection to recovery facilities), service level remains fixed and shows almost no change. On the other hand, it is positively correlated to the aggregate cost.

With the help of these implications, managers and decision makers can decide on the optimal policy for the timing and amount resources to be utilized throughout the CLSC network.

5. Conclusion and Outlook

In this study, a multi-period multi-product CLSC network design that simultaneously minimizes the aggregate cost and maximize the service level is proposed. Six different network elements, namely, manufacturing plants, distribution centers, customers, collection facilities, recovery facilities and disposal facilities, were taken into account to make strategic, tactical and operational decisions. A novel bi-objective MILP model was then formulated to represent the problem. Moreover, GAM was employed to tackle the bi-objectiveness of the model. To test the efficiency of the model, three problems in different scales were analyzed using the Gurobi Python API. Finally, a set of sensitivity analyses were conducted to evaluate the responses of objective function values to the changes in demand as well as two return rate parameters. It was demonstrated that the objective value is most sensitive to the demand parameter and, therefore, the latter should be paid utmost attention by managers during the decision-making process.

The following outlook is presented for future research:

i. Objectives such as total pollution minimization and total job opportunity maximization can be incorporated into the problem with a view to addressing more issues from sustainable development domain,
ii. Assumptions can be relaxed to make the model more realistic by handling parameter uncertainty and using approaches such as fuzzy programming, robust optimization and stochastic optimal control,
iii. Application of heuristic and meta-heuristic algorithms can be considered to tackle the model complexity at larger scales,
iv. Different transportation modes and routing decisions can be accommodated in the model to make the latter closer to the real-world.

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Conflict of Interest

No conflict of interest was declared by the author.

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