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Sustainable closed-loop supply chain for dairy industry with robust and heuristic optimization

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ABSTRACT

This paper supplements the augmented ε-constraint approach with linearization using robust optimization and heuristics with an improved algorithm to maximize the total profit and minimize the environmental effects of a sustainable closed-loop supply chain (CLSC) in the dairy industry. The resultant mixed-integer linear programming (MILP) model is applied to a case from the dairy industry and evaluated against several test problems. The pessimistic, optimistic, and worst-case scenarios are considered along with the sensitivity analysis on the profitability of the CLSC concerning the product lifetimes. Our results inform that applying the heuristic on large-scale problems yields a 25% improvement in runtime. Furthermore, products with a longer lifetime under the worst-case scenario yield greater profit than those products with a shorter lifetime under an optimistic scenario.

1. Introduction

A sustainable supply chain (SSC) is predicated on the triple bottom line (TBL), encompassing the economy, environment, and society. Sustainable supply chain management (SSCM) has received much attention from academia and industry in recent decades (Saberi et al. 2019). SSCM helps firms to reduce their environmental risks and pollution, and improve environmental performance, yielding stronger market advantages, better brand equity and firm reputation, lower overall cost, and better consumer relations (Ansari and Kant, 2017).

While the TBL approach has been adopted in the research on sustainability performance within the domain of SSCM (Gimenez et al. 2012), the research on the environmental dimension has been more prominent (Touboulic and Walker, 2015). Research on the multiple dimensions of sustainability is crucial as the dimensions have concurrent effects on each other and sustainability performance. However, integrating all dimensions to achieve sustainable development is a key challenge for industry (Acquaye et al., 2018; Govindan and Gholizadeh, 2021). Khan et al. (2020) concede that the multi-objective optimization methods are among the best to trade-off the dimensions of sustainability to obtain optimal solutions with the highest profit for the supply chain. Homayouni et al. (2021) note that robust optimization and heuristic approaches can yield reliable solutions for uncertain practical supply chain network design problems.

Supply chain network design has been applied in areas such as waste (Ayvaz et al., 2015), energy consumption (Dayhim et al., 2014), blood (Ramezanian and Behboodi, 2017), new product development (Jahani et al., 2017), humanitarian logistics (Tofighi et al., 2016), organ allocation (Kargar et al., 2020), and cold chains (Esmizadeh et al., 2021). With greater consumer awareness of environmentally friendly products, the need to adopt practices to mitigate the adverse environmental effects of manufacturing activities has become necessary (Liu et al., 2018). The problem is also investigated in other sectors such as electricity (Golpîra et al., 2021), smelting (Gholizadeh and Fazlollahtabar, 2020), dairy (Yavari and Geraeli, 2019), white goods (Gholizadeh et al., 2020), and oil (Paydar et al., 2017). As for the risk associated with uncertainty, some of the common parameters used include uncertainty (Hassanpour et al., 2019), robustness (Hamidieh et al., 2018), and attitude of the decision makers (DMs) towards risk (Golpîra et al., 2017).

Due to shorter product life cycles and smaller profit margins, CLSC is now an operational imperative for firms. In a CLSC, the forward and reverse logistics (RL) systems are simultaneously integrated. The reverse logistics in CLSC is responsible for managing product returns for purposes such as recycle, reuse, or dispose (Govindan et al., 2017). Reverse

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Table 1
Review of recent literature on CLSC.

Source	Period	Product	Lifetime	Uncertain parameter	Objective function			Solution Approach	Context
					Single	Bi-objective	Multi-objective		
Karimi et al. (2015)	Multi	Multi		RR	Minimize total cost			Chance constraints	Dairy
Talaei et al. (2016)	Single	Multi		D-Ca		Minimize total CO_2 and total cost		ε-constraint	Copiers
Amin and Baki (2017)	Multi	Multi		D		Maximize on-time delivery and profit		Corley's and fuzzy method	–
Amin et al. (2017)	Single	Multi		D-RP	Maximize total profit			Decision tree	Tire
Jeihoonian et al. (2017)	Single	Single		RP	Maximize total profit			L-shaped algorithm-Scenario reduction algorithm	Durable products - Washing machine
Pedram et al. (2017)	Multi	Single		D-RP		Maximize job creation and total profit		CPLEX	Tire
Yousefi-Babadi et al. (2017)	Single	Multi		D-DT-CF-RP			Minimize collection, location and transport cost and average tardiness	Lagrangian relaxation	Petrochemical - Nylon plastic
Dehghan et al. (2018)	Multi	Multi		D- CF	Minimize total cost			CPLEX	Edible oil
Ebrahimi (2018)	Single	Multi		D		Maximize network efficiency and customer satisfaction		Linearization	Tire
Ghomi-Avili et al. (2018)	Multi	Single		D			Maximize total profit; Minimize CO2 emissions by production processes	Karush-Kuhn-Tucker condition Linearization	Filters
Jabbarzadeh et al. (2018)	Multi	Multi		D-CF-DC	Minimize total cost			Lagrangian relaxation	Glass
Ma and Li (2018)	Single	Single		D-RP	Maximize expected net profit over two stages			Parallel enumeration - genetic algorithm	Lead-acid battery
Yadollahinia et al. (2018)	Multi	Multi		D-CF			Maximize total profit and customer satisfaction; Minimize total distance between collection facilities	Branch-and-bound - linearization	Tire
Ghahremani-Nahr et al. (2019)	Multi	Multi		D-RP-CF-P	Minimize total cost			Whale optimization algorithm-Modified priority-based encoding	–
Yavari and Geraeli (2019)	Multi	Multi	*	D-RR		Minimize total cost and environmental pollution		Heuristic - robust optimization	Dairy
Polo et al. (2019)	Multi	Single		D	Maximize economic value-added			CPLEX	Electronics
Jouzdani and Govindan (2021)	Multi	Multi	*	Pe			Minimize SCN influence, total cost, and fuel consumption	Revised multi-choice goal programming; Chance-constrained stochastic programming	Dairy
Our paper	Multi	Multi	*	D-OC-CF-TC-RR		Maximize total profit; Minimize environmental effects		Robust optimization - heuristic method & ε-constraint approach	Diary

D: Demand; RP: Product Return; OC: Operation cost; TC: Transport cost; CF: Capacity of facilities; DR: Demand of raw material; RR: Rate of product returns; Q: Quality of returned product; P: Price (buy or sell); DT: Delivery time; Pe: Perishability.

logistics helps to mitigate the environmental effects of operations and the amount of waste produced globally. Reverse logistics also helps to create competitive advantage and is a significant contributor to a firm's profit margin through re-purposing the used products (Goudenege et al., 2013).

In 2016, the global annual waste was 2.01 billion tons; by 2046, it will be 3.4 billion tons (The World Bank, 2020). As such, Polo et al. (2019) argue that reverse logistics is indispensable for the economic and environmental issues the supply chain encounters in today's volatile market. The recovery of used products has an economic added value. With greater emphasis on sustainable production, more interaction between product development and product recovery is needed. Product recovery helps to reduce production costs and promote the environmental compatibility of the organization. Research on CLSC network design is important to SSCM (Govindan et al., 2017; Zhen et al., 2019). In addition, an integrated CLSC provides an efficient product recovery

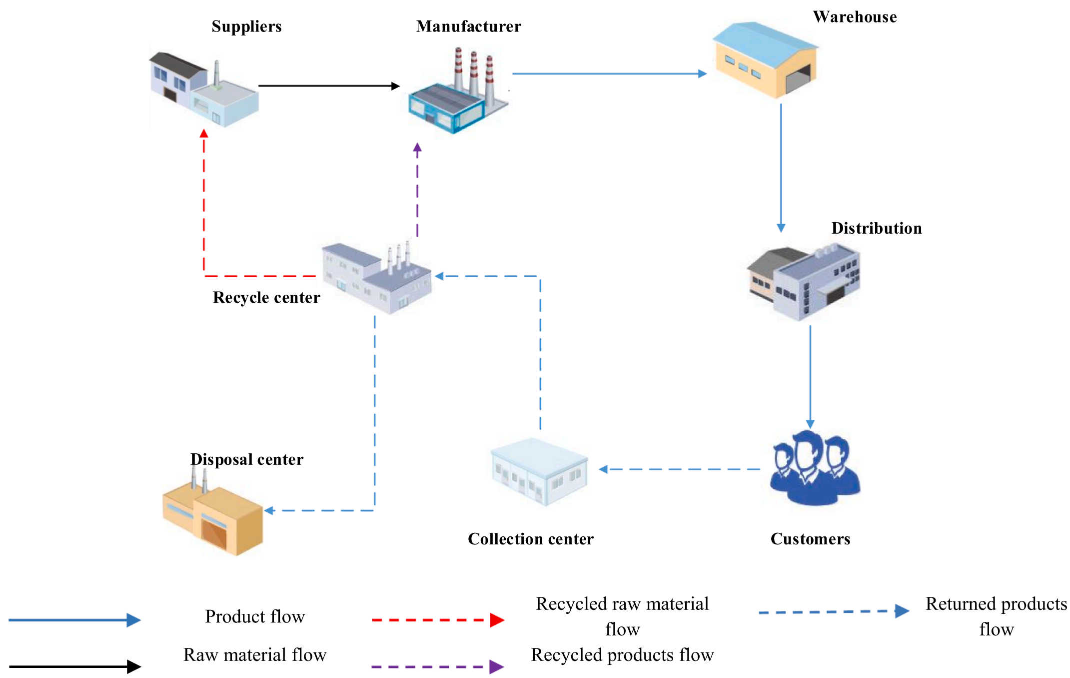

Fig. 1. Environmentally friendly CLSC network.

pathway to realise the environmental, economic, and even social goals. An efficient product recovery process and the associated CLSC configuration encourage customers to return their products at the end of their useful life and with coherent planning, reduces the environmental impact of landfills.

CLSC serves to meet demand through value-adding operations and processes, by collecting the returned products destined for reuse, recycle, or disposal (Govindan and Soleimani, 2017). CLSC design has attracted attention in recent years. With more mandated regulatory compliance, firms are now nudged towards designing suitable CLSC (Govindan et al., 2017). In designing a CLSC, managing the reverse logistics operations becomes even more difficult when the multitude of decision-making variables along with their uncertainty affects the environment. Thus, to design a CLSC, decision-makers should identify the problem areas, model them, and define appropriate performance indicators for both the forward and reverse flows of the products (Govindan et al., 2017). CLSC is especially crucial in a perishable supply chain where products such as food and drugs have especially short lifetimes (Morganti and Gonzalez-Feliu, 2015). The characteristics of such perishables such as shelf life and time-dependent prices necessitate designing a supply chain network (Sel and Bilgen, 2015).

The dairy supply chain is an important food supply chain for highly perishable products which must be collected daily under refrigeration (Glover et al., 2014). In a CLSC, after collecting from the stores, the dairy products are subject to stringent inspection and then shipped to the disposal centers or other firms for specific uses (Accorsi et al., 2016). The challenge is to respond quickly to meet demand and to reduce cost, disruptions, and risks. While eco-labelling certification has become crucial for dairy processors, it also poses new challenges in redesigning the CLSC (Yavari and Geraeli, 2019).

This paper studies the decisions of a multi-level CLSC using a dairy supply chain as a case study. Our model minimizes the environmental pollution while maximizing firm profit. The Greenhouse Gas (GHG) emissions of all the activities of the supply chain, the environmental costs for opening the facilities and transportation between the facilities are examined. Using the context of dairy products, the loss in quality and the expiry date of dairy products along with the delivery time and recycle of dairy products are also considered in the model. In this paper, Section 2 reviews the extant literature on CLSC. Section 3 provides the model development. Section 4 presents the solution approach. Section 5 validates the model using a case of a dairy processor. Section 6 concludes.

2. Literature review

In designing a CLSC, the decision on facility location considers the forward and reverse flows of the products (Prajapati et al., 2019). While some studies look at profit maximization in CLSC (Kaya and Urek, 2016; Jeihoonian et al., 2016, 2017; Masoudipour et al., 2017; Patne et al., 2018; Tosarkani and Amin, 2018a, 2018b), most studies focus on the cost aspects in the network, namely, the location/ relocation/ allocation costs of the facilities, transport costs, and operation costs. The other costs such as air pollution cost have also been studied (Yildizbaşi et al., 2018). All studies consider both the flow of products or materials and the flow of product returns (collected or not collected) (Yi et al., 2016; Jeihoonian et al., 2017; Cheraghalipour et al., 2018; Fathollahi-Fard et al., 2018; Jerbia et al., 2018). Some studies consider variables such as the amount of raw materials required (Farrokh et al., 2018) and unmet demand (Pedram et al., 2017; Wu et al., 2018). While some studies have developed green CLSC networks using multi-objective models (Talaei et al., 2016; Rad and Nahavandi, 2018; Yavari and Geraeli, 2019; Shi et al., 2017; Zhen et al., 2019), others have used a more holistic view toward sustainable CLSC networks (Govindan et al., 2016; Soleimani et al., 2017; Sahebjamnia et al., 2018).

Non-linear optimization has been applied to CLSC: stochastic programming (Badri et al., 2017; Keyvanshokooh et al., 2016; Zhen et al., 2019), robust optimization (Gholizadeh et al., 2020b; Gholizadeh & Fazlollahtabar, 2020), genetic algorithm (Diabat and Al-Salem, 2015; Diabat and Deskoores, 2016; Gholizadeh et al., 2020b; Gholizadeh & Fazlollahtabar, 2020; Hiassat et al., 2017), hybrid particle swarm-genetic algorithm and other metaheuristics (Diabat, 2016; Kumar et al., 2014; Wang et al., 2016; Zohal & Soleimani, 2016). Due to the non-linearity in CLSC design, linearization (such as piecewise) or reformulation is needed (Al-Salem et al., 2016). Software packages like Lingo and GAMS and programming environments such as CPLEX and MATLAB are well used to implement the optimization approaches to obtain efficient solutions. However, such tools are mostly used on small problems (Soleimani et al., 2013) while heuristics are better suited for

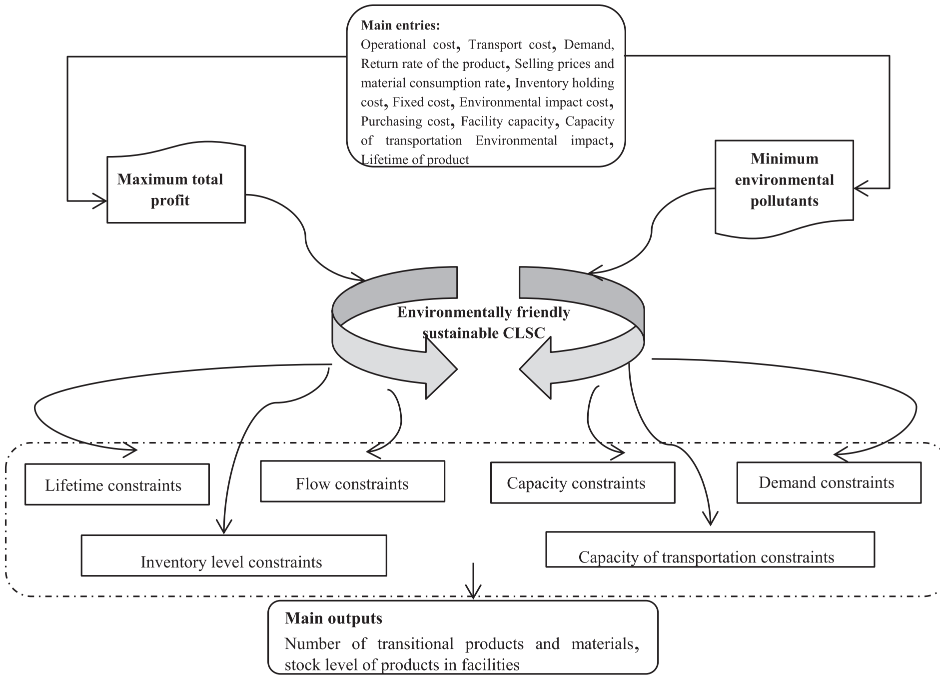

Fig. 2. Block diagram for modelling sustainable CLSC.

the large problems (Kaur & Singh, 2018).

Scenario-based planning under uncertainty has been studied using decomposition techniques or search algorithms (Aghalari et al., 2020a; 2020b). Robust modeling techniques provide optimizers in the worst-case scenario to control the model parameters (Gholizadeh & Fazlollahtabar, 2020). Table 1 shows the recent approaches on CLSC based on period, number of products, uncertain parameters, objective functions, solution approach, and the industry context. Several observations avail. First, most studies focus on one objective. Three works have studied the economic and environmental performance (Talaei et al., 2016; Ghomi-Avili et al., 2018; Yavari and Zaker, 2019). Talaei et al. (2016) examine the demand and the capacity of facilities to minimize the CO_2 and cost on a single product for multiple periods. Ghomi-Avili et al. (2018) maximize the total profit and minimize CO_2 emissions considering the demand as the only uncertain parameter using the Karush-Kuhn-Tucker condition. With three parameters of demand, quality and the rate of product returns, Yavari and Zaker (2019) minimize the total cost and environmental pollution using a heuristic. Second, the environmental impacts are normally seen as direct effects (e.g. environmental cost) and indirect effects (e.g. pollution) which can be quantified precisely. In Table 1, only one study has focused on the lifetime of products in the CLSC.

Thus, in this study, the parameters of profit and environmental pollution are considered using two solution approaches: 1) linearization using robust optimization and 2) heuristics with an improved algorithm based on the augmented ε-constraint approach.

Compared to the other models such as Yavari and Geraeli (2019), where two parameters of demand and product return rate are considered and Jouzdani and Govindan (2021) which considers only service lifetime, the proposed model suggests a new approach to treat a wider list of uncertain parameters for multi-product and multi-period CLSC design. The uncertain parameters cover all costs (i.e. production, transportation, and operation), the capacity of facilities, return rate of the product, and demand. Moreover, Jouzdani and Govindan (2021) deals with the social aspect of the dairy chain but does not consider product recovery. Other contributions of this study include:

- A framework for integrating a sustainable CLSC network which treats both environmental cost and environmental impact.
- A solution with a robust optimization approach and using an augmented ε-constraint method to convert the bi-objective model to a single-objective.
- An actual case for the proposed multi-product dairy CLSC model.

3. Model development

In Fig. 1, an environmentally friendly CLSC network has five levels in the forward flow including suppliers, processors, warehouse, distributors, and retailers, and three components in the reverse flow which include collection, recycling, and disposal of the returned products.

Following Govindan et al. (2015) and Abdolazimi et al. (2020), the environmental effect of GHG emissions and the associated environmental costs are included in the first objective function. The profit margin of the returned products and the directly supplied products are considered in the second objective function. The supply chain network begins with the supply of raw materials. It is assumed that all stages of production are completed in the processing facility. The processed products are sent to the warehouses. After the aggregation stage, the orders are shipped to the distributors. Next, the products are shipped to the retailers. In the reverse chain, the products are returned to the collection and recycling centers after the expiration of their lifetime. The returned products are collected and divided into two categories. Some returns are moved to a disposal facility of and the rest transferred to a recycling center. The recycled materials are sent to the suppliers or the processor to be used as raw materials. Fig. 2 shows the optimization block diagram.

The following assumptions are made:

- Demand, transport costs, operational costs, capacity of facilities, shipment times, raw material demand, and the return rate of products are considered uncertain.
- Deficiency is not allowed.
- Demand of each customer zone is met completely in each period.
- Suppliers and customers are in fixed positions.
- Each facility has finite capacity.

- Each retailer is allocated to only one distributor and one collection center
- The collection center purchases or replaces the returned products from the retailer

3.1. Sets, parameters, and decision variables

The list of indicators, variables, and symbols used to formulate the model are as follows.

Sets	
f	Location of collection center($f = 1, 2, ..., F$)
p	Product($p = 1, 2, ..., P$)
j	Location of producer($j = 1, 2, ..., J$)
l	Fixed location of retailers($l = 1, 2, ..., L$)
i	Fixed location of suppliers($i = 1, 2, ..., I$)
t	Period($t = 1, 2, ..., T$)
k	Location of warehouse($k = 1, 2, ..., K$)
r	Raw material($r = 1, 2, ..., R$)
d	Location of distributor($d = 1, 2, ..., D$)
q	Location of disposal center($q = 1, 2, ..., Q$)
w	Location of recycling center($w = 1, 2, ..., W$)
v	Type of vehicle($v = 1, 2, ..., V$)
Parameters	
Operating cost	
OCF_f	Operating cost of collection center f
OCJ_j	Operating cost of producer$j$
OCK_k	Operating cost of warehouse k
OCD_d	Operating cost of distributor d
OCW_w	Operating cost of recycling center w
OCQ_q	Operating cost of disposal center q
Transportation cost	
TCI_{ijrvt}	Transport cost of raw material r from supplier i to producer j with vehicle υ in period t
TCJ_{jkpvt}	Transport cost of product p from producer $j$to warehouse k with vehicle υ in period t
TCK_{kdpvt}	Transport cost of product p from warehouse k to distributor d with vehicle υ in period t
TCD_{dlpvt}	Transport cost of product p from distributor d to retailer l with vehicle υ in period t
TCL_{lfpvt}	Transport cost of product p from retailer l to collection center f with vehicle υ in period t
TCF_{fwpvt}	Transport cost of product p from collection center f to recycling center w with vehicle υ in period t
TCW_{wjpvt}	Transport cost of product p from recycling center$w$to producer j with vehicle υ in period t
TCW_{wirvt}	Transport cost of raw material $r$from recycling center $w$to supplier i with vehicle υ in period t
TCQ_{wqpvt}	Transport cost of product p from recycling center w to disposal center q with vehicle υ in period t
Inventory holding cost	
HCF_{pf}	Unit inventory holding cost of product p at collection center f in each period
HCJ_{pj}	Unit inventory holding cost of product p at producer j in each period
HCL_{pl}	Unit inventory holding cost of product p at retailer l in each period
HCK_{pk}	Unit inventory holding cost of product p at warehouse k in each period
HCD_{pd}	Unit inventory holding cost of product p at distributor d in each period
HCW_{pw}	Unit inventory holding cost of product p at recycling center w in each period
HCR_{rw}	Unit inventory holding cost of raw material $r$at recycling center w in each period
Fixed cost	
$FCOF_f$	Fixed cost of opening collection center f
$FCOJ_j$	Fixed cost of opening producer$j$
$FCOK_k$	Fixed cost of opening warehouse k
$FCOD_d$	Fixed cost of opening distributor d
$FCOW_w$	Fixed cost of opening recycling center w
$FCOQ_q$	Fixed cost of opening disposal center q
Environmental impact cost	
ECV_v	Unit cost of environmental impact on transport between facilities with vehicle υ in each period
ECJ_j	Unit cost of environmental impact for opening producer j in each period
ECW_w	Unit cost of environmental impact for opening recycling center w in each period
ECQ_q	Unit cost of environmental impact for opening disposal center q in each period
ECF_f	Unit cost of environmental impact for opening collection center f in each period
ECK_k	Unit cost of environmental impact for opening warehouse k in each period
ECD_d	Unit cost of environmental impact for opening distributor d in each period
Purchasing cost	
PCL_{plft}	Unit purchase cost of returned product p from retailer l for collection center f in period t
PCI_{rijt}	Unit purchasing cost of raw material $r$from supplier i for producer j in period t
Capacity of facilities	
$CapF_f$	Capacity of collection center f
$CapJ_j$	Capacity of producer j
$CapI_i$	Capacity of supplier i
$CapK_k$	Capacity of warehouse k
$CapD_d$	Capacity of distributor d
$CapW_w$	Capacity of recycling center w
$CapQ_q$	Capacity of disposal center q
Capacity of transportation	
$Tcap_{ijvt}$	Load capacity of transportation mode υ from supplier i to producer j in period t
$Tcap_{jkvt}$	Load capacity of transportation mode υ from producer j to warehouse k in period t
$Tcap_{kdvt}$	Load capacity of transportation mode υ from warehouse k to distributor d in period t
$Tcap_{dlvt}$	Load capacity of transportation mode υ from distributor d to retailer l in period t
$Tcap_{lfvt}$	Load capacity of transportation mode υ from retailer l to collection center f in period t
$Tcap_{fwvt}$	Load capacity of transportation mode υ from collection center f to recycling center w in period t
$Tcap_{wjvt}$	Load capacity of transportation mode υ from recycling center w to producer j in period t
$Tcap_{wivt}$	Load capacity of transportation mode υ from recycling center w to supplier i in period t
$Tcap_{wqvt}$	Load capacity of transportation mode υ from recycling center w to disposal center q in period t
Demand	
D_{plt}	Demand of retailer l for product p in period t
Environmental impact	
$EIOF_f$	Environmental impact of opening collection center f
$EIOJ_j$	Environmental impact of opening producer$j$
$EIOK_k$	Environmental impact of opening warehouse k
$EIOD_d$	Environmental impact of opening distributor d
$EIOW_w$	Environmental impact of opening recycling center w
$EIOQ_q$	Environmental impact of opening disposal center q
$EIHF_{pf}$	Environmental impact of inventory holding of product p at collection center f
$EIHJ_{pj}$	Environmental impact of inventory holding of product p at producer j
$EIHL_{pl}$	Environmental impact of inventory holding of product p at retailer l
$EIHK_{pk}$	Environmental impact of inventory holding of product p at warehouse k
$EIHD_{pd}$	Environmental impact of inventory holding of product p at distributor d
$EIHW_{pw}$	Environmental impact of inventory holding of product p at recycling center w
$EIHR_{rw}$	Environmental impact of inventory holding of raw material r at recycling center w
$EISI_{ijrv}$	Environmental impact of shipping raw material $r$from supplier i to producer j with vehicle υ
$EISJ_{jkpv}$	Environmental impact of shipping product p from producer j to warehouse k with vehicle υ
$EISK_{kdpv}$	Environmental impact of shipping product p from warehouse k to distributor d with vehicle υ

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(*continued*)

Sets	
$EISD_{dlpv}$	Environmental impact of shipping product p from distributor d to retailer l with vehicle υ
$EISL_{lfpv}$	Environmental impact of shipping product p from retailer l to collection center f with vehicle υ
$EISF_{fwpv}$	Environmental impact of shipping product p from collection center f to recycling center w with vehicle υ
$EISW_{wjpv}$	Environmental impact for shipping product p from recycling center w to producer j with vehicle υ
$EISW_{wirv}$	Environmental impact of shipping raw material $r$from recycling center w to supplier i with vehicle υ
$EISQ_{wqpv}$	Environmental impact of shipping product p from recycling center w to disposal center q with vehicle υ
Other parameters	
SR_{plt}	Revenue generated by product p from sale to retailer l in period t
RS_{rwt}	Revenue generated by raw material r recycled recycling center w in period t
β_{rpt}	Coefficient of consumption of raw material $r$in product p in period t
θ_p	Lifetime of product p
AR_{plt}	Return rate of product p from retailer l during in period t
BR_{pwt}	Recycling rate of product p from recycling center w in period t
CR_{rwt}	Recycling rate of raw material $r$from recycling center w in period t
$BigM$	Large number, $\gg 0$
Decision variables	
XP_{pjt}	Amount of product p produced by producer j in period t
XI_{rijvt}	Amount of raw material r sent from supplier i to producer j with vehicle υ in period t
XJ_{pjkvt}	Amount of product p shipped from producer j to warehouse k with vehicle υ in period t
XK_{pkdvt}	Amount of product p shipped from warehouse k to distributor d with vehicle υ in period t
XD_{pdlvt}	Amount of product p shipped from distributor d to retailer l with vehicle υ in period t
XL_{plfvt}	Amount of product p shipped from retailer l to collection center f with vehicle υ in period t
XF_{pfwvt}	Amount of product p shipped from collection center f to recycling center w with vehicle υ in period t
XW_{pwjvt}	Amount of product p shipped from recycling center w to producer j with vehicle υ in period t
XR_{rwivt}	Amount of raw material r shipped from recycling center w to supplier i with vehicle υ in period t
XQ_{pwqvt}	Amount of product p shipped from recycling center w to disposal center q with vehicle υ in period t
SMF_{pft}	Inventory level of product p in collection center f in period t
SMJ_{pjt}	Inventory level of product p in producer j in period t
SML_{plt}	Inventory level of product p in retailer l in period t
SMK_{pkt}	Inventory level of product p in warehouse k in period t
SMD_{pdt}	Inventory level of product p in distributor d in period t
SMW_{pwt}	Inventory level of product p in recycling center w in period t
SMR_{rwt}	Inventory level of raw material r in recycling center w in period t
YF_f	1, if collection center f is opened; Else, 0.
YJ_j	1, if producer j is opened; Else, 0.
YK_k	1, if warehouse k is opened; Else, 0.
YD_d	1, if distributor d is opened; Else, 0.
YW_w	1, if recycling center w is opened; Else, 0.
YQ_q	1, if disposal center q is opened; Else, 0.
AF_{lf}	1, if retailer l is allocated to collection center f; Else, 0.
AD_{ld}	1, if retailer l is allocated to distributor d; Else, 0.
Q_{ijvt}	1 if vehicle υ is selected between supplier i and producer j in period t; Else, 0
Q_{jkvt}	1 if vehicle υ is selected between producer j and warehouse k in period t; Else, 0
Q_{kdvt}	1 if vehicle υ is selected between warehouse k and distributor d in period t; Else, 0
Q_{dlvt}	1 if vehicle υ is selected between distributor d and retailer l in period t; Else, 0
Q_{lfvt}	1 if vehicle υ is selected between retailer l and collection center f in period t; Else, 0
Q_{fwvt}	1 if vehicle υ is selected between collection center f and recycling center w in period t; Else, 0

(*continued on next column*)

(*continued*)

Sets	
Q_{wjvt}	1 if vehicle υ is selected between recycling center w and producer j in period t; Else, 0
Q_{wivt}	1 if vehicle υ is selected between recycling center w and supplier i in period t; Else, 0
Q_{wqvt}	1 if vehicle υ is selected between recycling center w and disposal center q in period t; Else, 0

3.2. Model formulation

The model is formed by the objective functions in Eqs. (1) and (2), subject to constraints (3)-(53).

3.2.1. Objective functions

Objective function (1) is defined to minimize the environmental impact of the CLSC that includes the environmental impacts caused by opening facilities, storing inventory in each facility, and shipping between two facilities. The objective function (2) is to maximize the closed-loop network total profit. The revenue of the network includes revenue from sales and the recycling of the returned products. The costs associated with the network are the operating cost of each facility, purchase cost of the returned products from the retailers and raw materials from suppliers, fixed costs for opening the required facilities, inventory holding costs of products and raw materials in the facilities, costs to transport the raw materials and product between the facilities, operating costs of facilities, and the environmental costs.

$$
\begin{aligned}
MinZ_1 = {} & \sum_p\sum_j\sum_t EIHJ_{pj}*SMJ_{pjt} + \sum_p\sum_k\sum_t EIHK_{pk}*SMK_{pkt} \\
& + \sum_p\sum_f\sum_t EIHL_{pl}*SML_{plt} + \sum_p\sum_f\sum_t EIHF_{pf}*SMF_{pft} \\
& + \sum_p\sum_d\sum_t EIHD_{pd}*SMD_{pdt} + \sum_p\sum_w\sum_t EIHW_{pw}*SMW_{pwt} \\
& + \sum_r\sum_w\sum_t EIHR_{rw}*SMR_{rwt} + \sum_j EIOJ_j*YJ_j + \sum_k EIOK_k*YK_k \\
& + \sum_f EIOF_f*YF_f + \sum_d EIOD_d*YD_d + \sum_w EIOW_w*YW_w \\
& + \sum_q EIOQ_q*YQ_q + \sum_r\sum_i\sum_j\sum_v\sum_t EISI_{ijrv}*XI_{rijvt} \\
& + \sum_p\sum_j\sum_k\sum_v\sum_t EISJ_{jkpv}*XJ_{pjkvt} \\
& + \sum_p\sum_k\sum_d\sum_v\sum_t EISK_{kdpv}*XK_{pkdvt} \\
& + \sum_p\sum_d\sum_l\sum_v\sum_t EISD_{dlpv}*XD_{pdlvt}*AD_{ld} \\
& + \sum_p\sum_l\sum_f\sum_v\sum_t EISL_{lfpv}*XL_{plfvt}*AR_{plt}*AF_{lf} \\
& + \sum_p\sum_f\sum_w\sum_v\sum_t EISF_{fwpv}*XF_{pfwvt} \\
& + \sum_p\sum_w\sum_j\sum_v\sum_t EISW_{wjpv}*XW_{pwjvt}*BR_{pwt} \\
& + \sum_r\sum_w\sum_j\sum_v\sum_t EISW_{wirv}*XW_{rwivt}*CR_{rwt} \\
& + \sum_p\sum_w\sum_q\sum_v\sum_t EISQ_{wqpv}*XQ_{pwqvt}
\end{aligned} \tag{1}
$$

$$
MaxZ_2 = \left(\begin{array}{c} \sum_{p}\sum_{d}\sum_{l}\sum_{v}\sum_{t} SR_{plt}*XD_{pdlvt}*AD_{ld} \\ +\sum_{r}\sum_{w}\sum_{j}\sum_{v}\sum_{t} RS_{rwt}*XW_{rwivt}*CR_{rwt} \end{array} \right) - \left(\begin{array}{c}
\sum_{p}\sum_{j}\sum_{t} HCJ_{pj}*SMJ_{pjt} + \sum_{p}\sum_{k}\sum_{t} HCK_{pk}*SMK_{pkt} \\
+\sum_{p}\sum_{f}\sum_{t} HCL_{pl}*SML_{plt} + \sum_{p}\sum_{f}\sum_{t} HCF_{pf}*SMF_{pft} + \sum_{p}\sum_{d}\sum_{t} HCD_{pd}*SMD_{pdt} \\
+\sum_{p}\sum_{w}\sum_{t} HCW_{pw}*SMW_{pwt} + \sum_{r}\sum_{w}\sum_{t} HCR_{rw}*SMR_{rwt} \\
+\sum_{j} FCOJ_j * YJ_j + \sum_{k} FCOK_k * YK_k + \sum_{f} FCOF_f * YF_f + \sum_{d} FCOD_d * YD_d \\
+\sum_{w} FCOW_w * YW_w + \sum_{q} FCOQ_q * YQ_q + \sum_{r}\sum_{i}\sum_{j}\sum_{v}\sum_{t} ECV_v*XI_{rijvt} \\
+\sum_{p}\sum_{j}\sum_{k}\sum_{v}\sum_{t} ECV_v*XJ_{pjkvt} + \sum_{p}\sum_{k}\sum_{d}\sum_{v}\sum_{t} ECV_v*XK_{pkdvt} \\
+\sum_{p}\sum_{d}\sum_{l}\sum_{v}\sum_{t} ECV_v*XD_{pdlvt}*AD_{ld} + \sum_{p}\sum_{l}\sum_{f}\sum_{v}\sum_{t} ECV_v*XL_{plfvt}*AR_{plt}*AF_{lf} \\
+\sum_{p}\sum_{f}\sum_{w}\sum_{v}\sum_{t} ECV_v*XF_{pfwvt} + \sum_{p}\sum_{w}\sum_{j}\sum_{v}\sum_{t} ECV_v*XW_{pwjvt}*BR_{pwt} \\
+\sum_{r}\sum_{w}\sum_{j}\sum_{v}\sum_{t} ECV_v*XW_{rwivt}*CR_{rwt} + \sum_{p}\sum_{w}\sum_{q}\sum_{v}\sum_{t} ECV_v*XQ_{pwqvt} \\
+\sum_{j} ECJ_j * YJ_j + \sum_{k} ECK_k * YK_k + \sum_{f} ECF_f * YF_f + \sum_{d} ECD_d * YD_d \\
+\sum_{w} ECW_w * YW_w + \sum_{q} ECQ_q * YQ_q + \sum_{r}\sum_{i}\sum_{j}\sum_{v}\sum_{t} TCI_{ijrvt}*XI_{rijvt} \\
+\sum_{p}\sum_{j}\sum_{k}\sum_{v}\sum_{t} TCJ_{jkpvt}*XJ_{pjkvt} + \sum_{p}\sum_{k}\sum_{d}\sum_{v}\sum_{t} TCK_{kdpvt}*XK_{pkdvt} \\
+\sum_{p}\sum_{d}\sum_{l}\sum_{v}\sum_{t} TCD_{dlpvt}*XD_{pdlvt}*AD_{ld} + \sum_{p}\sum_{l}\sum_{f}\sum_{v}\sum_{t} TCL_{lfpvt}*XL_{plfvt}*AR_{plt}*AF_{lf} \\
+\sum_{p}\sum_{f}\sum_{w}\sum_{v}\sum_{t} TCF_{fwpvt}*XF_{pfwvt} + \sum_{p}\sum_{w}\sum_{j}\sum_{v}\sum_{t} TCW_{wjpvt}*XW_{pwjvt}*BR_{pwt} \\
+\sum_{r}\sum_{w}\sum_{j}\sum_{v}\sum_{t} TCW_{wirvt}*XW_{rwivt}*CR_{rwt} + \sum_{p}\sum_{w}\sum_{q}\sum_{v}\sum_{t} TCQ_{wqpvt}*XQ_{pwqvt} \\
+\sum_{p}\sum_{l}\sum_{f}\sum_{t}\sum_{v} PCL_{plft}*XL_{plfvt} + \sum_{r}\sum_{i}\sum_{j}\sum_{v}\sum_{t} PCI_{rijt}*XI_{rijvt} \\
+\sum_{p}\sum_{j}\sum_{k}\sum_{v}\sum_{t} OCJ_j*XJ_{pjkvt} + \sum_{p}\sum_{k}\sum_{d}\sum_{v}\sum_{t} OCK_k*XK_{pkdvt} \\
+\sum_{p}\sum_{d}\sum_{l}\sum_{v}\sum_{t} OCD_d*XD_{pdlvt}*AD_{ld} + \sum_{p}\sum_{j}\sum_{t} OCJ_j*XP_{pjt} \\
+\sum_{p}\sum_{f}\sum_{w}\sum_{v}\sum_{t} OCF_f*XF_{pfwvt} + \sum_{p}\sum_{w}\sum_{j}\sum_{v}\sum_{t} OCW_w*XW_{pwjvt}*BR_{pwt} \\
+\sum_{r}\sum_{w}\sum_{j}\sum_{v}\sum_{t} OCW_w*XW_{rwivt}*CR_{rwt} + \sum_{p}\sum_{w}\sum_{q}\sum_{v}\sum_{t} OCQ_q*XQ_{pwqvt}
\end{array} \right) \quad (2)
$$

3.2.2. Flow constraints

Constraints (3)–(21) enforce the required capacity for the flow of materials and products. Constraint (3) ensures that there is sufficient input to the retailers.

$$\sum_{d}\sum_{v}\sum_{t} XD_{pdlvt} \geqslant \sum_{t} D_{plt} \forall p,l \quad (3)$$

Constraint (4) guarantees that there is sufficient inlet and outlet flows in the warehouses.

$$\sum_{j}\sum_{v}\sum_{t} XJ_{pjkvt} \geqslant \sum_{d}\sum_{v}\sum_{t} XK_{pkdvt} \quad \forall p,k \quad (4)$$

Constraints (5) to (11) arrange the eligible input streams to be greater than the output streams in each facility. It sets the balance between the input and output streams for each facility.

$$\sum_{k}\sum_{v}\sum_{t} XK_{pkdvt} \geqslant \sum_{l}\sum_{v}\sum_{t} XD_{pdlvt} \quad \forall p,d \quad (5)$$

$$\sum_{j}\sum_{v}\sum_{t} BR_{pwt} * XW_{pwjvt} \leqslant \sum_{f}\sum_{v}\sum_{t} XF_{pfwvt} \quad \forall p,w \quad (6)$$

$$\sum_{i}\sum_{v}\sum_{t} XI_{rijvt} + \sum_{w}\sum_{i}\sum_{v}\sum_{t} XW_{rwivt} \geqslant \sum_{t} \beta_{rpt} * XP_{pjt} \quad \forall p,r,j \quad (7)$$

$$\sum_{i}\sum_{v}\sum_{t} XW_{rwivt} \geqslant \sum_{f}\sum_{v}\sum_{t} CR_{rwt} * XF_{pfwvt} \quad \forall p,r,w \quad (8)$$

$$\sum_{t} XP_{pjt} \geqslant \sum_{k}\sum_{v}\sum_{t} XJ_{pjkvt} \quad \forall p,j \quad (9)$$

$$\sum_{q}\sum_{v}\sum_{t} XQ_{pwqvt} = \sum_{f}\sum_{v}\sum_{t} XF_{pfwvt}*\left(1 - \left(BR_{pwt} + CR_{rwt}\right)\right) \quad \forall p,w \quad (10)$$

$$\sum_{l}\sum_{v}\sum_{t} AR_{plt} * XL_{plfvt} \geqslant \sum_{w}\sum_{v}\sum_{t} XF_{pfwvt} \quad \forall p,f \quad (11)$$

Constraints (12) to (17) ensure that flows for a facility exist unless the facility is open.

$$YJ_j \leqslant \sum_{p}\sum_{t} XP_{pjt} \leqslant BigM * YJ_j \quad \forall j \quad (12)$$

$$YK_k \leqslant \sum_p \sum_j \sum_t \sum_v XJ_{pjkvt} \leqslant BigM * YK_k \quad \forall k \tag{13}$$

$$YF_f \leqslant \sum_p \sum_l \sum_t \sum_v XL_{plfvt} \leqslant BigM * YF_f \quad \forall f \tag{14}$$

$$YD_d \leqslant \sum_p \sum_k \sum_t \sum_v XK_{pkdvt} \leqslant BigM * YD_d \quad \forall d \tag{15}$$

$$YW_w \leqslant \sum_p \sum_f \sum_t \sum_v XF_{pfwvt} \leqslant BigM * YW_w \quad \forall w \tag{16}$$

$$YQ_q \leqslant \sum_p \sum_w \sum_t \sum_v XQ_{pwqvt} \leqslant BigM * YQ_q \quad \forall q \tag{17}$$

Constraints (18) and (19) indicate that there is no flow between unconnected facilities.

$$AD_{ld} \leqslant \sum_p \sum_t \sum_v XD_{pdlvt} \leqslant BigM * AD_{ld} \quad \forall l, d \tag{18}$$

$$AF_{lf} \leqslant \sum_p \sum_t \sum_v XL_{plfvt} \leqslant BigM * AF_{lf} \quad \forall l, f \tag{19}$$

Constraints (20) and (21) ensure that each retailer receives the product of only one distributor and sends the returned product to only one collection center.

$$\sum_d AD_{ld} \leqslant 1 \quad \forall l \tag{20}$$

$$\sum_f AF_{lf} \leqslant 1 \quad \forall l \tag{21}$$

3.2.3. Demand constraints

Constraint (22) indicates the proportion of the returned products from each retailer to the corresponding collection center as a fraction of the retailer's demand.

$$\sum_f \sum_v \sum_t XL_{plfvt} \leqslant \sum_t D_{plt} * AR_{plt} \quad \forall p, l \tag{22}$$

3.2.4. Capacity constraints

Constraints (23) to (28) represent the capacity for each facility.

$$\sum_p XP_{pjt} \leqslant CapJ_j * YJ_j \quad \forall j, t \tag{23}$$

$$\sum_r \sum_v XI_{rijvt} \leqslant CapI_j \quad \forall j, i, t \tag{24}$$

$$\sum_p SMK_{pk(t-1)} + \sum_p \sum_j \sum_v XJ_{pjkvt} \leqslant CapK_k * YK_k \quad \forall k, t \tag{25}$$

$$\sum_p SMF_{pf(t-1)} + \sum_p \sum_l \sum_v XL_{plfvt} \leqslant CapF_f * YF_f \quad \forall f, t \tag{26}$$

$$\sum_p SMW_{pw(t-1)} + \sum_p \sum_f \sum_v XF_{pfwvt} \leqslant CapW_w * YW_w \quad \forall w, t \tag{27}$$

$$\sum_p SMD_{pd(t-1)} + \sum_p \sum_l \sum_v XD_{pdlvt} \leqslant CapD_d * YD_d \quad \forall d, t \tag{28}$$

Constraints (29) to (34) guarantee that if a facility is not established, then the corresponding transportation load is zero.

$$Q_{ijvt} \leqslant YJ_j \quad \forall i, j, t, v \tag{29}$$

$$Q_{jkvt} \leqslant YK_k \quad \forall j, k, t, v \tag{30}$$

$$Q_{kdvt} \leqslant YD_d \quad \forall k, d, t, v \tag{31}$$

$$Q_{lfvt} \leqslant YF_f \quad \forall l, f, t, v \tag{32}$$

$$Q_{fwvt} \leqslant YW_w \quad \forall f, w, t, v \tag{33}$$

$$Q_{wqvt} \leqslant YQ_q \quad \forall w, q, t, v \tag{34}$$

Constraints (35) to (43) indicate the load capacity for each transportation mode selected between facilities.

$$XI_{rijvt} \leqslant Tcap_{ijvt} * Q_{ijvt} \quad \forall r, j, i, t, v \tag{35}$$

$$XJ_{pjkvt} \leqslant Tcap_{jkvt} * Q_{jkvt} \quad \forall p, j, k, t, v \tag{36}$$

$$XK_{pkdvt} \leqslant Tcap_{kdvt} * Q_{kdvt} \quad \forall p, k, d, t, v \tag{37}$$

$$XD_{pdlvt} \leqslant Tcap_{dlvt} * Q_{dlvt} \quad \forall p, d, l, t, v \tag{38}$$

$$XL_{plfvt} \leqslant Tcap_{lfvt} * Q_{lfvt} \quad \forall p, l, f, t, v \tag{39}$$

$$XF_{pfwvt} \leqslant Tcap_{fwvt} * Q_{fwvt} \quad \forall p, w, f, t, v \tag{40}$$

$$XW_{pwjvt} \leqslant Tcap_{wjvt} * Q_{wjvt} \quad \forall p, w, j, t, v \tag{41}$$

$$XR_{rwivt} \leqslant Tcap_{wivt} * Q_{wivt} \quad \forall r, w, i, t, v \tag{42}$$

$$XQ_{pwqvt} \leqslant Tcap_{wqvt} * Q_{wqvt} \quad \forall p, w, q, t, v \tag{43}$$

3.2.5. Inventory level constraints

Constraints (44) to (50) set the stock level of each product in each facility.

$$SMJ_{pjt} = XP_{pjt} + SMJ_{pj(t-1)} - \sum_k XJ_{pjkvt} \quad \forall p, j, t, v \tag{44}$$

$$SMK_{pkt} = \sum_j XJ_{pjkvt} + SMK_{pk(t-1)} - \sum_d XK_{pkdvt} \quad \forall p, k, t, v \tag{45}$$

$$SMF_{pft} = \sum_l XL_{plfvt} + SMF_{pf(t-1)} - \sum_w XF_{pfwvt} \quad \forall p, f, t, v \tag{46}$$

$$SML_{plt} = \sum_d XD_{pdlvt} + SML_{pl(t-1)} - D_{plt} \quad \forall p, l, t, v \tag{47}$$

$$SMD_{pdt} = \sum_k XK_{pkdvt} + SMD_{pd(t-1)} - \sum_l XD_{pdlvt} \quad \forall p, d, t, v \tag{48}$$

$$SMW_{pwt} = \sum_f XF_{pfwvt} + SMW_{pw(t-1)} - \sum_j XW_{pwjvt} * BR_{pwt} \quad \forall p, w, t, v \tag{49}$$

$$SMR_{rwt} = \sum_f XF_{pfwvt} + SMR_{rw(t-1)} - \sum_i XR_{rwivt} * CR_{rwt} \quad \forall r, w, t, v \tag{50}$$

3.3. Product lifetime constraints

Constraints (51) to (53) limit the lifetime of the products. Constraint (51) states that the stock level in each distributor should be lower than its output with respect to the product lifespan in the subsequent period.

$$\sum_t SMD_{pdt} \leqslant \sum_l \sum_{t=t}^{t+(\theta_p-1)} \sum_v XD_{pdlvt} \quad \forall p, d \tag{51}$$

Constraint (52) shows the relationship between the level of each retailer's inventory and its demand according to product lifespan.

$$\sum_t SML_{plt} \leqslant \sum_{t=t}^{t+(\theta_p-1)} D_{plt} \quad \forall p, l$$

Constraint (53) indicates that the inventory level for each processor and each product plus the amount of the product recovered from the related recycling centers should be less than the total returns of the product in the subsequent period. The return volume and recovery rate are important parameters of the model and can be estimated based on the existing data of the chain. These parameters are predicted based on the experience of the manager.

$$\sum_t SMJ_{pjt} + \sum_w \sum_v BR_{pwt} * XW_{pwjvt} \leqslant \sum_k \sum_{t=t}^{t+(\theta_p-1)} \sum_v XJ_{pjkvt} \quad \forall p, j \tag{53}$$

3.4. Robust optimization requirements

In robust optimization, Mulvey et al. (1995) proposed two policies for dealing with uncertainty, namely model consistency and solution consistency. Solution consistency deals with the case when the final solution though close to optimality, is not optimal. Nevertheless, the solution is justified in terms of consistency if it can be justified for understanding a particular scenario; it has model consistency. The model's unjustifiability is measured by a penalty function. Therefore, in being justified, the penalty function is small to be proximate to optimality. The properties of the robust optimization technique proposed by Mulvey et al. (1995) are presented as follows:

Set	
S	Set of scenarios with index$s$
Parameters	
$\mathscr{P}_s$	Probability of scenario$s$
$P_{s'}$	Probability of scenario s' with $s' \subseteq s$.
ω	Infeasibility weight being set experimentally
λ	The weight of risk
b_{1s}, b_{2s}, b_{3s}	Uncertainty coefficients parameters for Scenario$s$
a_1, a_2	Certainty coefficients parameters
Decision variables	
θ_s	Linearization variable under Scenario$s$
η_s	Surplus variables for Scenario$s$
y_s	Control variable for Scenario s
x	Design variable
ξ_s	Function of cost and utility for Scenario$s$
$Q_s^+ and Q_s^-$	Additional variables to linearize the objective function
η_s	$\begin{cases} 0 & \text{ifmodelisjustified} \\ \geq 0 & \text{ifmodelisunjustified} \end{cases}$
$OBJ1_s$	Objective function 1 under Scenario$s$
$OBJ2_s$	Objective function 2 under Scenario$s$

Objective function and constraints

$$\min f(\mathbf{X}, y_1, y_2, \cdots y_s) + \omega g(\eta_1, \eta_2, \cdots, \eta_s) \tag{54}$$

s.t.

$$a_1 \mathbf{X} = a_2 \tag{55}$$

$$b_{1s}\mathbf{X} + b_{2s}\mathbf{X} + \eta_s = b_{3s} \tag{56}$$

$$\mathbf{X} \geq 0, y_s \geq 0, \eta_s \geq 0 \forall s \in \mathbf{S} \tag{57}$$

There are two expressions in the objective function in Eq. (54): the first one represents the robustness of the solution, and the second represents the consistency of the model measured by the weight ω.

$\xi_s$is a function of $\mathbf{x}$ and y_s representing cost and utility. A high variance of ξ_s indicates high risk in the decision. In other words, a small change in the uncertain parameters can cause large changes in the measured values, Mulvey et al. (1995) used Eq. (58) to illustrate the robustness of the solution:

$$f(\mathbf{X}, y_1, y_2, \cdots, y_s) = \sum_{s \in \mathbf{S}} \mathscr{P}_s \xi_s + \lambda \sum_{s \in \mathbf{S}} \mathscr{P}_s \left(\xi_s - \sum_{s \in \mathbf{S}} \mathscr{P}_{s'} \xi_{s'} \right)^2 \tag{58}$$

whereλ denotes the weight assigned to the variance of the solution. To reduce the computational time, the absolute value is used instead of a quadratic expression as follows:

$$f(\mathbf{X}, y_1, y_2, \cdots, y_s) = \sum_{s \in \mathbf{S}} \mathscr{P}_s \xi_s + \lambda \sum_{s \in \mathbf{S}} \mathscr{P}_s \left| \xi_s - \sum_{s \in \mathbf{S}} \mathscr{P}_{s'} \xi_{s'} \right| \tag{59}$$

To transfer Eq. (59) (and consequently objective function in Eq. (54)) into a linear function, two additional variables of $Q_s^+ and Q_s^-$are defined such that if $\sum_{s \in \mathbf{S}} \mathscr{P}_{s'} \xi_{s'}$ is greater than ξ_s, it is interpreted as Q_s^-, andQ_s^+ is equal to $\sum_{s \in \mathbf{S}} \mathscr{P}_{s'} \xi_{s'}$, with $\sum_{s \in \mathbf{S}} \mathscr{P}_{s'} \xi_{s'}$ smaller than ξ_s. Therefore, considering $\left|\xi_s - \sum_{s \in \mathbf{S}} \mathscr{P}_{s'} \xi_{s'}\right| = (Q_s^+ + Q_s^-)$, Eq. (23) becomes

$$f(\mathbf{X}, y_1, y_2, \cdots y_s) = \sum_{s \in \mathbf{S}} \mathscr{P}_s \xi_s + \lambda \sum_{s \in \mathbf{S}} \mathscr{P}_s (Q_s^+ + Q_s^-) \tag{60}$$

$$Q_s^+, Q_s^- \geq 0 \forall s \in \mathbf{S} \tag{61}$$

From linear programming, one of the values of $Q_s^+ and Q_s^-$ is always zero (Yu & Li, 2000).

The second term in Eq. (54), $\omega g(\eta_1, \eta_2, \cdots, \eta_s)$ explains the unjustification and shows the stability of the model. The weight ω is allocated for unjustification and illustrates the cost-benefit analysis between model robustness and the solution. $\eta_s$shows the unjustification of the parameter with uncertainty under scenario s due to the capacity constraint. From the above arguments, Eq. (58) is re-written as: (Yu & Li, 2000)

$$\min \sum_{s \in \mathbf{S}} \mathscr{P}_s \xi_s + \lambda \sum_{s \in \mathbf{S}} \mathscr{P}_s (Q_s^+ + Q_s^-) + \omega \sum_{s \in \mathbf{S}} \mathscr{P}_s \eta_s \tag{62}$$

3.4.1. Uncertain parameters

The demand, shipping costs, operating costs per period, capacity of facilities, and product return rates are treated as uncertain parameters. We add the index of the scenario (i.e. s) to specify these parameters as:

D_{plts}	Demand of retailer l for product p in period t
$CapF_{fs}$	Capacity of collection center f
$CapJ_{js}$	Capacity of producer j
$CapI_{is}$	Capacity of supplier i
$CapK_{ks}$	Capacity of warehouse k
$CapD_{ds}$	Capacity of distributor d
$CapW_{ws}$	Capacity of recycling center w
$CapQ_{qs}$	Capacity of disposal center q
AR_{plts}	Return rate of product p from retailer l during in period t
OCF_{fs}	Operating cost of collection center f
OCJ_{js}	Operating cost of producer j
OCK_{ks}	Operating cost of warehouse k
OCD_{ds}	Operating cost of distributor d
OCW_{ws}	Operating cost of recycling center w
OCQ_{qs}	Operating cost of disposal center q
TCI_{ijrvts}	Transport cost of raw material r from supplier i to producer j with vehicle v in period t
TCJ_{jkpvts}	Transport cost of product p from producer $j$to warehouse k with vehicle v in period t
TCK_{kdpvts}	Transport cost of product p from warehouse k to distributor d with vehicle v in period t
TCD_{dlpvts}	Transport cost of product p from distributor d to retailer l with vehicle v in period t
TCL_{lfpvts}	Transport cost of product p from retailer l to collection center f with vehicle v in period t
TCF_{fwpvts}	Transport cost of product p from collection center f to recycling center w with vehicle v in period t
TCW_{wjpvts}	Transport cost of product p from recycling center$w$to producer j with vehicle v in period t
TCW_{wirvts}	Transport cost of raw material $r$from recycling center $w$to supplier i with vehicle v in period t
TCQ_{wqpvts}	Transport cost of product p from recycling center w to disposal center q with vehicle v in period t

The following control variables related to each scenario are also considered:

XP_{pjts}	Amount of product p produced by producer j in period t under scenario$s$
XI_{rijvts}	Amount of raw material r sent from supplier i to producer j with vehicle v in period t under scenario$s$

(continued on next page)

(*continued*)

XP_{pjts}	Amount of product p produced by producer j in period t under scenario s
XJ_{pjkvts}	Amount of product p shipped from producer j to warehouse k with vehicle υ in period t under scenario s
XK_{pkdvts}	Amount of product p shipped from warehouse k to distributor d with vehicle υ in period t under scenario s
XD_{pdlvts}	Amount of product p shipped from distributor d to retailer l with vehicle υ in period t under scenario s
XL_{plfvts}	Amount of product p shipped from retailer l to collection center f with vehicle υ in period t under scenario s
XF_{pfwvts}	Amount of product p shipped from collection center f to recycling center w with vehicle υ in period t under scenario s
XW_{pwjvts}	Amount of product p shipped from recycling center w to producer j with vehicle υ in period t under scenario s
XR_{rwivts}	Amount of raw material r shipped from recycling center w to supplier i with vehicle υ in period t under scenario s
XQ_{pwqvts}	Amount of product p shipped from recycling center w to disposal center q with vehicle υ in period t under scenario s

Following Razavi et al. (2020), the robust optimization model is formulated as:

$$MinZF = \sum_{s} P_s OBJ1_s + \lambda \sum_{s} P_s \left(OBJ1_s - \sum_{s'} P_{s'} OBJ1_{s'} + 2\theta 1_s \right) \quad (63)$$

$$MaxRF = \sum_{s} P_s OBJ2_s - \lambda \sum_{s} P_s \left(\left(OBJ2_s - \sum_{s'} P_{s'} OBJ2_{s'} \right) + 2\theta 2_s \right) - \omega \sum_{s} P_s \eta_s \quad (64)$$

$$OBJ1_s - \sum_{s'} P_{s'} OBJ1_{s'} + \theta 1_s \geq 0 \forall s \quad (65)$$

$$OBJ2_s - \sum_{s'} P_{s'} OBJ2_{s'} + \theta 2_s \geq 0 \forall s \quad (66)$$

$$\theta 1_s, \theta 2_s \geq 0 \quad (67)$$

subject to Constraints (3) to (53)

The first and the second terms in Eqs (63) and (64) are the mean and variance of the objective functions, respectively. The last term of the objective function measures the model robustness in terms of the infeasibility values of the control constraints under each scenario. Constraints (65) and (66) are the auxiliary constraints added to the model for linearizing the non-linear objective functions. Constraint (67) affirms the non-negativity of the newly introduced variables.

4. Solution approach

As the proposed model uses two objectives (minimization and maximization), this requires establishing interaction between the target functions.

4.1. Augmented ε-constraint method

The ε -constraint method used to solve the bi-objective model is given as follows:

1. Select one objective function as the main one
2. Optimize the selected objective function for deterministic and robust models.
3. Divide the interval between the two optimal values of the sub-objective functions by a predefined number and obtain a table for$\varepsilon_2, \cdots, \varepsilon_n$.
4. Solve the problem each time with the main objective function by omitting the values$\varepsilon_2, \cdots, \varepsilon_n$.
5. Record the Pareto solutions.
6. Normalize the Pareto solutions

Since ε ~ 0 (10^{-3} to 10^{-6}) and if the target is to be maximized, ε should be positive and s_i should be negative. s_i is a surplus variable for the objective functions. Gholizadeh et al. (2020a) show that the proposed problem produces only an efficient solution. Since the objective functions units are varied, to avoid scaling issues and to eliminate dimensionality the second part of the objective function is offered, in which, $\frac{s_i}{r_i}$ is used instead of s_i where r_i is the domain of objective function i. Eqs. (68) to (70) are applied for the solution approach (Mavrotas and Florios,

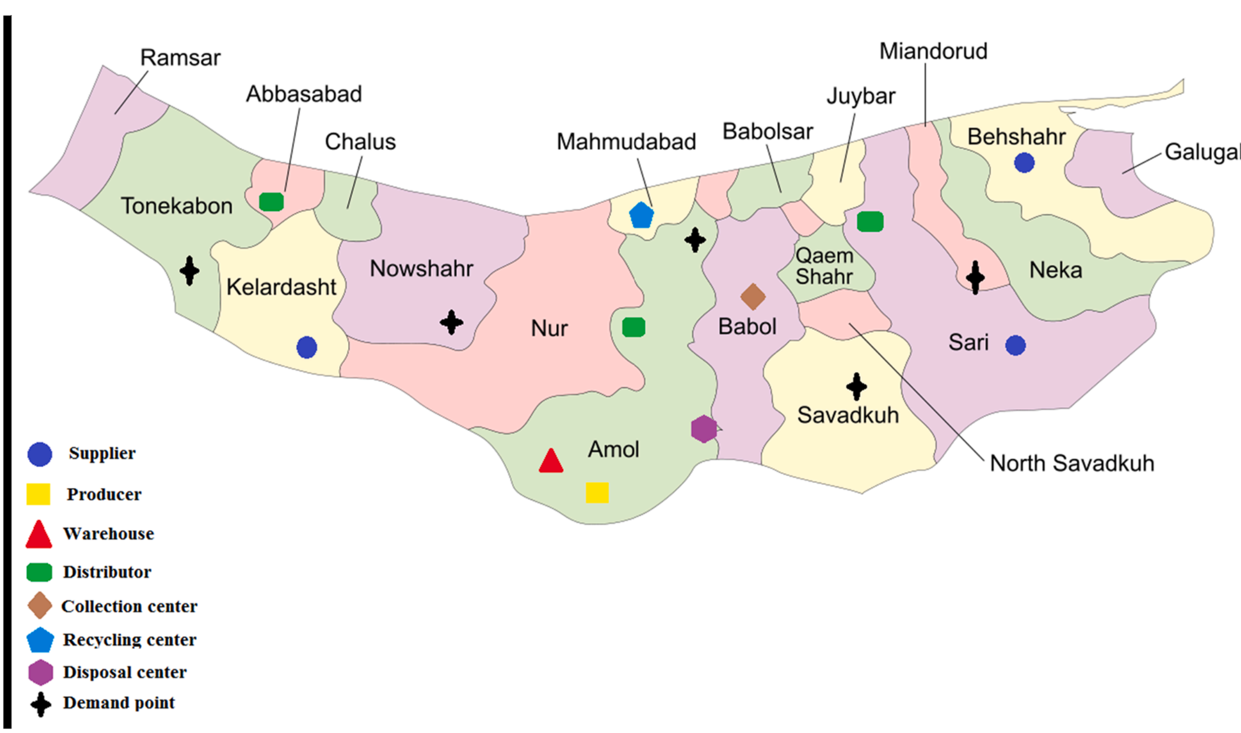

Fig. 3. Map of SIDG's CLSC in Mazandaran province.

Table 2
Payoffs obtained in step 3 of augmented ε-constraint method.

Optimal OBJ 1	Optimal OBJ 2	Type	Objective function	Problem
11700.8	98346.6	Min	OBJ1	**Deterministic model**
7900.2	117532.7	Max	OBJ2	
16600.2	106731.2	Min	OBJ1	**Robust model**
9400.2	124442.1	Max	OBJ2	

2013). Eq. (69) shows the relationship between the value of the objective function transferred to the constraint and ε. Eq. (70) computes ε, which depends on the step size of the objective function and the lower bound of the objective function.

$$Max\left(f_1(x)+\varepsilon\left(\frac{s_2}{r_2}+10^{-1}\frac{s_3}{r_3}+\cdots+10^{-(p-2)}\frac{s_p}{r_p}\right)\right) \quad (68)$$

Subject to:

$X \in F$

$$k=2,\cdots,pf_k(X)-S_k=e_k \quad (69)$$

$$k=2,\cdots,pe_k=lb_k+i_k{}^*step_k \quad (70)$$

$f_k(X)$	Main objective functions of model to be optimized
lb_k	Lower bound for objective function$k$
$step_k = r_k/g_k$	Step size of objective function$k$
r_k	Range of objective function$k$
g_k	Number of intervals needed for objective function$k$
S_k	Surplus variable for objective function$k$
F	Acceptable range

4.2. Heuristic

As heuristics are highly recommended for solving large scale optimization problems (Homayouni et al. 2021), the proposed model employs a heuristic to reduce the computational effort. To relax the binary variable and linearize the model with respect to uncertain data, a method based on the binary variable refinement is used since these variables cause non-linearity in the model. The heuristic used is as follows:

Step 1: Relax the binary constraint in the MINLP by setting $YF_f, YJ_j, YK_k, YD_d, YW_w, YQ_q$ as non-negative. Solve the relaxed MINLP to optimality.

Step 2: From the solution of the relaxed MINLP, list the non-zero values of $YF_f, YJ_j, YK_k, YD_d, YW_w, YQ_q$.

Step 3: Set $YF_f, YJ_j, YK_k, YD_d, YW_w, YQ_q \geq 0$ as 1. Set them as constraints to the original MINLP. Solve the problem to optimality.

5. Dairy industry case

Saleh Industrial Dairy Group (SIDG) is a well-known dairy product producer in Iran. In line with SIDG's development strategies and complying with government regulations, SIDG seeks to close the loop of its supply chain. As the demand, costs, and rate of returned products can vary, three scenarios are considered: optimistic, most possible, and pessimistic with the demand and costs changing in each scenario. The demand in the pessimistic scenario is less than the demand in the optimistic case. Also, the cost parameters in the pessimistic scenario is higher compared to the optimistic scenario. The environmental effects have behavior similar to the costs in the scenarios. In general, when the scenario changes from pessimistic to optimistic, the parameters change from worse to best. Scenario 1 occurs with probability P_s (25%), scenario 2 with probability (55%), and scenario 3 (20%). The currency is Iranian Toman. The input data for the problem is shown in Appendix Tables A1 to A7. Table A7 contains the values of the uncertain parameters.

Fig. 3 shows the map of SIDG's supply chain in Mazandaran province, Iran. The CLSC includes a processor($j=1$), three suppliers($i=3$), three distributors($d=3$), five retailers($l=5$), a recycling center($w=1$), a disposal center($q=1$), a collection center($f=1$) and a central warehouse($k=1$). There are three products (yogurt, cheese, and cream)($p=3$). Three raw materials (milk, protein, and permitted additives)$r=3$ are used with three periods ($t=3$)with five vehicles($v=5$) for transportation. The model was solved using MILP and heuristics on a 2.3 GHz CPU and 8 GB RAM PC.

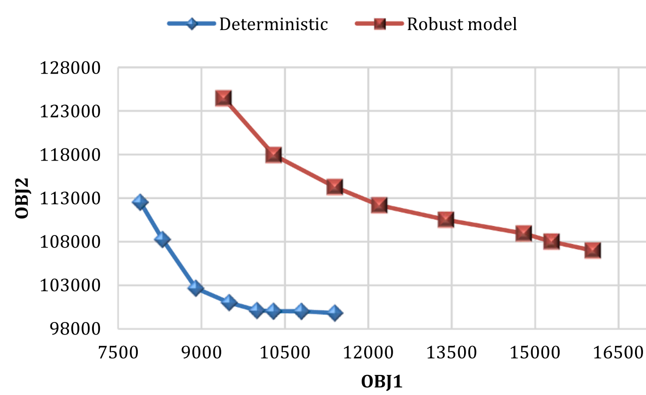

Fig. 4. Pareto curve obtained by augmented ε-constraint method.

Table 4
Normalized values of Pareto solutions in deterministic model.

Final weight (0.7*A + 0.3*B)	Normal OBJ 1 (B)	Normal OBJ 2 (A)	Pareto solution
0.126203	0.10218	0.136498	1
0.124316	0.108008	0.131305	2
0.121869	0.115676	0.124523	3
0.12283	0.12356	0.122517	4
0.123934	0.129764	0.121435	5
0.124897	0.133212	0.121334	6
0.126979	0.140193	0.121315	7
0.128974	0.147407	0.121074	8

Table 5
Normalized values of Pareto solutions in robust problem.

Final weight (0.7*A + 0.3*B)	Normal OBJ 1 (B)	Normal OBJ 2 (A)	Pareto solution
0.123727	0.090962	0.137769	1
0.121469	0.10023	0.130571	2
0.121808	0.110834	0.126512	3
0.122452	0.118394	0.124191	4
0.124491	0.129494	0.122347	5
0.127337	0.143063	0.120598	6
0.128046	0.147814	0.119574	7
0.13067	0.159209	0.118438	8

Table 3
ε obtained in step 3 of augmented ε-constraint method ($\times 10^{-6}$).

Gridpoint								Obj.	Problem
7	6	5	4	3	2	1	0		
11700.8	11200.3	10600.7	10100.2	9500.7	9000.2	8400.7	7900.2	first	**Deterministic**
16600.2	15500.9	14500.6	13500.3	12500.0	11400.7	10400.4	9400.1	first	**Robust**

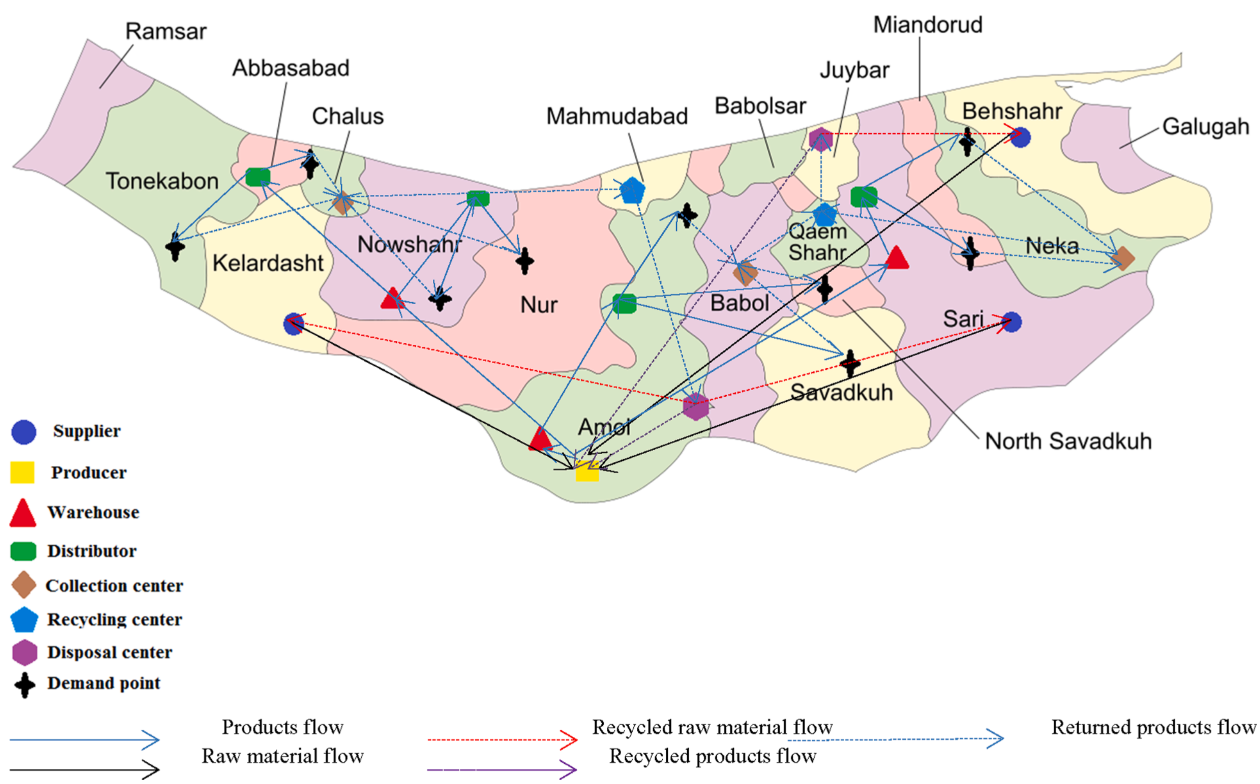

Fig. 5. Optimal dairy CLSC network.

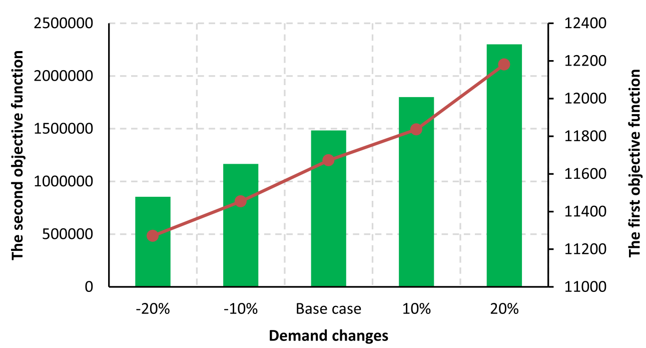

Fig. 6. Sensitivity analysis on demand.

Following Section 4.1, the augmented ε-constraint method consists of six steps. In the first step, the main objective function is selected. Due to the importance of profitability for SIDG, the second objective function (maximize revenue) was selected as the main objective of the problem. Table 2 contains the results of the second step of the algorithm on the payoffs for the deterministic and robust models.

Following step 3 of the algorithm, Table 3 shows the values of the obtained ε for the subsidiary (first) objective function that is transferred to the constraints of the deterministic and robust problems and divided into eight equal intervals.

At steps 4 and 5, a single (main) objective function is solved using the ε values for each model. Fig. 4 shows the values for the 8 Pareto solutions, which are different for the deterministic and robust models.

In the solution for the final step, based on expert opinions and the importance of the second objective function over the first, the optimal Pareto values are found so as to assign weights to the objectives and to normalize the objectives. Fig. 4 shows that the behavior of the Pareto fronts is identical for both problems. As the scales of the objective functions are different, the value of each objective was ignored.

The steps for choosing the best Pareto optimal solution are presented for the deterministic and robust models. Tables 4 and 5 show the normalized values of the Pareto solutions for the deterministic and robust models, respectively. The best Pareto solutions for the deterministic and robust problems are solutions 3 and 2, respectively. With these solutions, the values of the other decision variables are obtained i.e. the amount of stock, recycled products, disposal products, and the number of facilities to open.

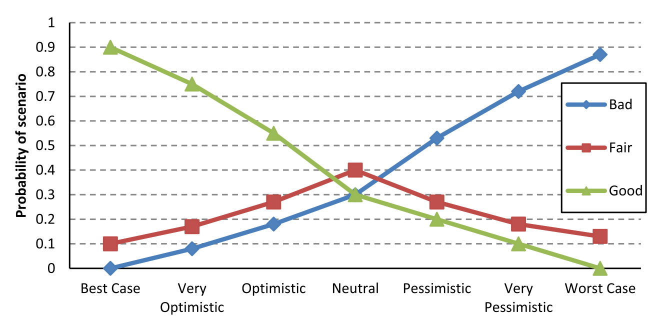

Fig. 7. Likelihood of each scenario occurring.

Fig. 5 shows the configuration of the CLSC and all transported products. For this optimized dairy CLSC, all the recycling centers (Mahmudabad and Qaem Shahr) should be open. SIDG also requires two

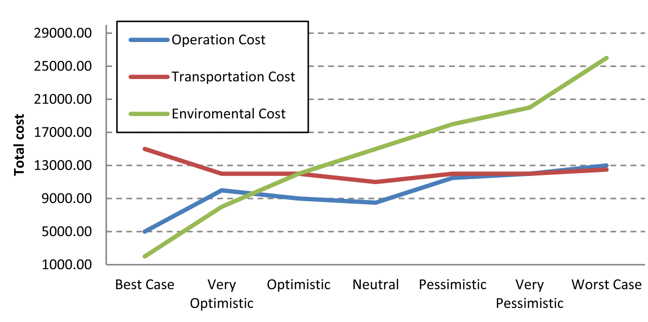

Fig. 8. Effect of scenarios on optimal supply chain cost.

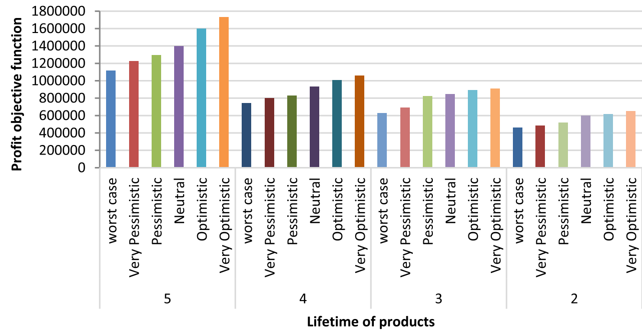

Fig. 9. Profitability of CLSC with respect to product lifetime for various scenarios.

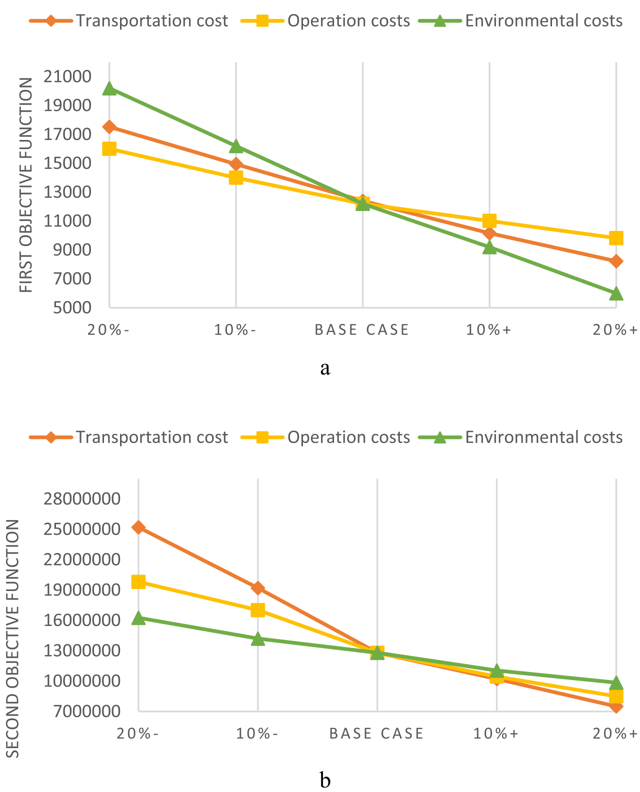

Fig. 10. Sensitivity analysis of costs on objective functions.

collection centers (Chalus and Neka), two warehouses (Sari and Nowshahr), and one disposal center (Babolsar). The returned products are reused as much as possible based on the capacity of each facility and its related costs.

5.1. Model validation

To evaluate the performance of the proposed model, 20 test problems of different sizes were developed (see Appendix Table A8). Appendix Tables B1 and B2 contain the values of the single objective function for each of the 20 experiments. The optimality gaps gained for all experiments demonstrate an acceptable range (less than 5%) and a comparison of the objective functions also shows that both the heuristic and MILP models are capable of obtaining similar results for each experiment.

The computational time for solving the heuristic and MILP methods are different in both deterministic and robust models. The heuristic method reduces the computational time by at least 25% compared to the MILP suggesting that the former outperforms when applied to large-scale problems.

5.2. Sensitivity analysis

Next, the effects of a parameter change on the objective function are examined. Fig. 6 shows the results of the sensitivity analysis on demand. The objective functions have a direct relation with the change in demand. As demand grows, and consequently an increase in production, inventory and transportation, SIDG will face a similar increase in environmental impact but profitability grows much more. As shown in Fig. 6, a 40% increase in demand leads to a 7% increase in the rate of environmental impact (first function) and a 300% increase in the profit (second function).

Fig. 7 shows the likelihood of occurrence for the three scenarios. The uncertainty in the parameters in CLSC increase through the "Best Case" to "Worst Case" situations. Using these probability values, the corresponding operation costs, transportation cost, and environmental costs of the CLSC are obtained (see Fig. 8). In Fig. 8, among all the costs, only transportation cost is fairly constant. As the environmental conditions worsen, SIDG should expect the operation costs and environmental costs to grow. Therefore, if the environmental impact is vital to the business, then SIDG needs to focus more on this area.

The different levels of uncertainty for the CLSCs are now addressed through 6 situations from the worst case (most uncertain) to very optimistic (least uncertain). The more certain the system is, regardless of the product lifetime, the more profit will be gained. However, from Fig. 9, in the trends of products with the lifetime of 4 to 5, the ones with lifetime of 5 in the worst-case scenario have more profit than those with a very optimistic scenario albeit with lifetime of 4. Thus, in uncertain CLSCs, one way to guarantee the profit is to improve the product lifetime via a better product lifecycle management plan. Also, the results suggest that the proposed model can assist complex decision-making by considering each level of uncertainty (i.e. worst case or optimistic) and increase profit by selecting products with proper lifetimes.

From Fig. 10b, the objective function decreases as cost increases but the effect of each cost variable varies. For instance, as the transportation cost varies from -20% to $+20\%$, the profit decreases in higher rates compared to the changes in the other costs. This highlights the importance of transportation cost to the profitability of the chain. Fig. 10(a) examines the change in costs with respect to the first objective function (environmental impacts). In general, spending more on the environmental, transportation, and operations costs results in less environmental impacts. However, the operations costs are the least important.

The robustness of the model is examined by changing the penalty weight ω (Eq. (62)) and generating ten realization problems. Fig. 11a,b compares the robust models (for different ω) with the deterministic model (not robust, i.e. $\omega = 0$) with respect to the mean and standard deviation of the objective functions computed for the ten realization problems. Fig. 11a,b confirm the importance of the penalty parameter (robustness) in the model whilst noting that increasing the robustness of the model does not guarantee better specified objective functions and may result in large standard deviations). Further, by specifying $\omega = 100$, we obtain the best penalty function for use to obtain results other than the deterministic model for all realizations.

The effect of recovery process for the chain is also examined by excluding the returned products and backward flow from the chain. For this purpose, all collection and recycling centers are ignored and the unit purchase costs of the returned products from all retailers in all periods

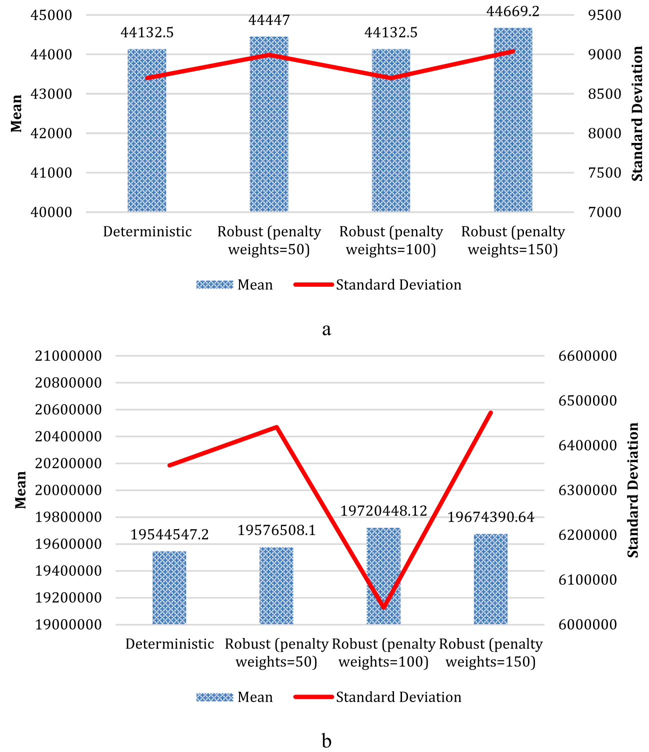

Fig. 11. Effect of robust penalty function on (a) first and (a) second objective functions.

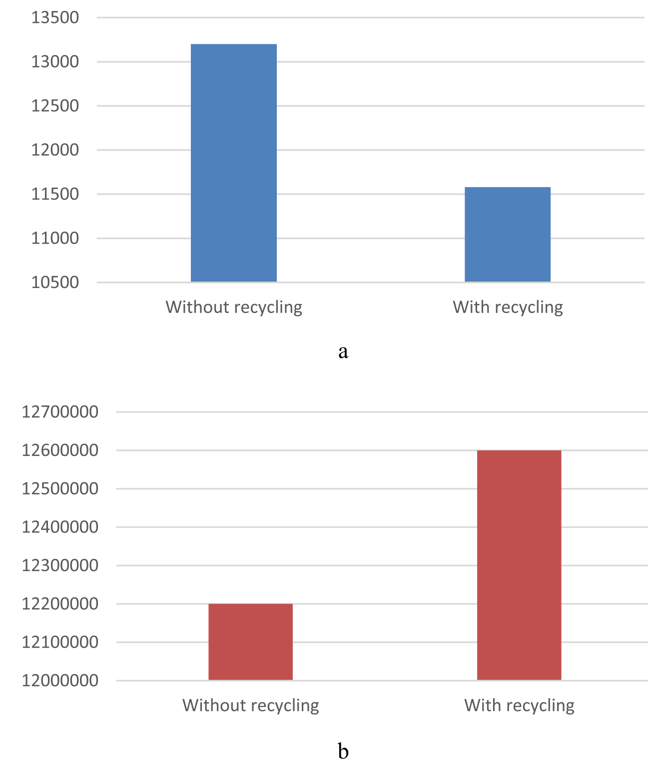

Fig. 12. Effect of recycling process on (a) first and (b) second objective functions.

are set to zero in the model. The operations costs for the return process are set to zero. Fig. 12 illustrates the objective functions with and without the recycling process. Both the environmental impacts and the profit objective functions vary by −12.2% and + 3.3%, respectively. Thus, while recycling has profit delimiting effect but the recycling process ekes out more advantages for the chain.

6. Discussion

Some managerial insights for dealing with uncertain situations can be gleaned. First, product returns in a CLSC is common, especially in the dairy industry and can be better managed for better profitability and product stewardship. In the model, several collections, recycle, and disposal centers for managing the returns were considered. The most efficient process is by converting/recycling a dairy product such as milk to another dairy product such as cheese to soften the profitability impact of the product. However, sometimes the quality of the returned product is poor. As such, the product should be disposed. In this case, selecting the profitable range that considers environmental impact is of utmost importance. For instance, milk disposal methods vary from being used as feed stock or discharging into effluent ponds. Any selection of these methods needs a careful trade-off between profitability and environmental impact of the method especially when it has an environmental impact (e.g. long time to recover or severe odour issues). Managers can forestall the weakness of their CLSC centers by using the proposed approach in this study. The findings propose an optimized capacity of the facilities used in the collection, recycle, and disposal centers to improve the facilities' economic and environmental performance to compete effectively and holistically.

Some obstacles to reducing the environmental impact in the dairy industry are the technology and the processing machinery and the quality of the transportation fleet used for distributing the products. Undoubtedly, any capital investment to improve the recycling and production processes increases the costs in the short run but in the long-run it will lift the chain profitability. The risk of financing new technologies particularly in the recycling process should be recognized. In most developed countries, the dairy sector is one in which the competition between manufacturers leads to embedding the high risks of investment. For developing countries, the government should provide more incentives to help the industry to manage this financing risk. On the transportation fleet, any investment in fleet technology will lower CO_2 emissions.

Incorporating the lifetime of products into the configuration of a CLCS under uncertainty provides a better bet of yielding long-term profitability if the decision-makers take a long-run perspective in controlling all flows. The proposed model demonstrates that although the benefits of extending the product lifetime may be negative in the short term, they are profitable over time.

7. Conclusion

In this paper, an integrated optimization model with the consideration of multi-period, multi-product, and uncertainty features was proposed for a dairy CLSC network. The chain includes the main stakeholders in the forward and return routes (i.e. collection, disposal, and recycling centers). The model was intended to determine the optimal flow of products through various facilities in the forward routes for the main products and the return routes for recycling products to meet the demand for all dairy products. The main objectives of the proposed problem are to minimize the environmental effects (such as CO_2 emissions) on the CLSC and to maximize the total profit of the CLSC. On the solution approach of the bi-objective model, an improved algorithm developed for the augmented ε-constraint approach was used. Robust optimization was employed to deal with data uncertainty and a heuristic was deliberated with the augmented ε-constraint method to linearize the model with respect to the uncertain data.

The resultant MILP model was solved systematically for a medium-size case from the dairy industry. The model was also evaluated against 20 test problems. The optimal results with a reasonable optimality gap were obtained for both the heuristic and MILP models. A comparison of the computational time for both models demonstrates at least 25% improvement in run time using the heuristic approach on large-scale problems. Sensitivity analysis of the product demands showed that the model can control the environmental impact effectively for any growth in demand and supply. Several scenarios, namely optimistic, pessimistic, and worst cases, were set up and a sensitivity analysis on the profitability of the CLSC with respect to the product lifetimes was applied. The results suggest that products with longer lifetimes in a worst-case scenario would yield more profit than those products with a shorter lifetime in a very optimistic scenario.

This study focused on the environmental impacts and the profit of the chain as two main aspects of a sustainable CLSC. Future research can focus on the social dimension, which is rarely studied. The inventory shortages and disruptions in the dairy supply chain and its logistics can also be studied. Next, pricing mechanisms which directly impact the efficiency of the product recovery strategies can be studied.

CRediT authorship contribution statement

Hadi Gholizadeh: Conceptualization, Methodology, Software. **Hamed Jahani:** Data curation, Writing - original draft. **Ahmad Abareshi:** Writing - review & editing. **Mark Goh:** Supervision, Writing - review & editing.

Appendix A

A. Input data
See Tables A1-A8.

Table A1
Average unit operating costs (1′000 Toman).

Costs	Period 1			Period 2			Period 3		
	Scenario1	Scenario2	Scenario3	Scenario1	Scenario2	Scenario3	Scenario1	Scenario2	Scenario3
Supplier 1	0.350	0.400	0.450	0.265	0.395	0.485	0.420	0.495	0.550
Supplier 2	0.450	0.500	0.550	0.298	0.387	0.465	0.450	0.500	0.560
Supplier 3	0.250	0.350	0.450	0.355	0.435	0.510	0.480	0.535	0.580
Processor	2.350	2.550	2.950	2.440	2.680	3.100	2.850	3.350	3.650
Warehouse	1.250	1.301	1.500	1.450	1.600	1.850	1.650	1.850	2.000
Distributor 1	0.330	0.350	0.400	0.310	0.380	0.410	0.300	0.400	0.450
Distributor 2	0.430	0.480	0.500	0.450	0.480	0.520	0.480	0.510	0.550
Distributor 3	0.350	0.380	0.450	0.380	0.450	0.510	0.400	0.480	0.580
Customer 1	1.235	1.450	1.800	1.345	1.480	1.820	1.405	1.495	1.850
Customer 2	1.335	1.420	1.820	1.350	1.450	1.850	1.385	1.480	1.880
Customer 3	1.425	1.480	1.840	1.325	1.420	1.800	1.415	1.450	1.850
Customer 4	1.505	1.540	1.880	1.480	1.550	1.850	1.500	1.550	1.880
Customer 5	1.245	1.430	1.850	1.285	1.480	1.880	1.345	1.450	1.850
Collection center	0.230	0.245	0.280	0.250	0.280	0.320	0.280	0.320	0.350
Recycle center	3.100	3.300	3.650	3.150	3.350	3.700	3.250	3.450	3.850
disposal center	1.550	1.650	1.850	1.600	1.750	1.950	1.500	1.600	1.800

Table A2
Average demand for products and raw materials.

Demand	Period 1			Period 2			Period 3		
	Scenario1	Scenario2	Scenario3	Scenario1	Scenario2	Scenario3	Scenario1	Scenario2	Scenario3
Processor's demand for raw material 1	500	800	1800	400	700	1500	600	900	1600
Processor's demand for raw material 2	400	600	1200	500	800	1600	600	800	1800
Processor's demand for raw material 3	600	800	1000	500	700	1200	400	600	1000
customer's demand 1 for product 1	500	800	1800	600	1000	1500	800	1200	1800
customer's demand 1 for product 2	400	600	1000	500	800	1800	600	1000	1500
customer's demand 1 for product 3	600	800	1500	400	600	1600	500	800	1800
customer's demand 2 for product 1	500	1000	1200	600	800	1600	700	1200	1800
customer's demand 2 for product 2	800	1200	1800	700	1000	1500	500	900	1500
customer's demand 2 for product 3	500	800	1800	600	1000	1500	800	1200	1800
customer's demand 3 for product 1	400	600	1000	500	800	1800	600	1000	1500
customer's demand 3 for product 2	600	1000	1500	800	1200	1800	600	1000	1500
customer's demand 3 for product 3	300	600	1200	400	900	1300	500	800	1800
customer's demand 4 for product 1	400	1000	1500	800	1200	1800	600	1000	1500
customer's demand 4 for product 2	600	800	1800	400	1000	1400	500	700	1600
customer's demand 4 for product 3	400	700	1700	500	900	1400	700	1100	1700
customer's demand 5 for product 1	300	500	900	400	700	1600	500	900	1400
customer's demand 5 for product 2	500	800	1600	500	900	1800	600	800	1800
customer's demand 5 for product 3	500	1000	1200	600	800	1600	700	1200	1800

Table A3
Average unit shipping costs (1000 Toman).

Cost	Period 1			Period 2			Period 3		
	Scenario1	Scenario2	Scenario3	Scenario1	Scenario2	Scenario3	Scenario1	Scenario2	Scenario3
From Supplier 1 to Manufacturer	120	260	450	150	250	450	180	280	480
From Supplier 2 to Manufacturer	150	280	480	180	320	520	150	250	450
From Supplier 3 to Manufacturer	100	200	350	120	220	360	150	280	380
From Manufacturer to warehouse	100	200	400	200	300	500	250	350	550
From warehouse to Distributor 1	80	180	380	100	200	400	120	225	425
From warehouse to Distributor 2	50	150	350	80	180	380	100	200	400
From warehouse to Distributor 3	100	200	300	120	250	350	150	280	380
From Distributor 1 to Customer 1	120	220	320	90	200	360	120	280	390
From Distributor 2 to Customer 1	140	250	350	110	250	340	150	320	400
From Distributor 3 to Customer 1	150	280	360	120	240	320	100	300	410
From Distributor 1 to Customer 2	80	150	270	100	220	300	140	250	420
From Distributor 2 to Customer 2	100	220	310	150	260	280	160	290	380
From Distributor 3 to Customer 2	80	180	300	120	240	350	120	280	420
From Distributor 1 to Customer 3	150	250	350	80	200	240	140	320	400
From Distributor 2 to Customer 3	160	280	360	90	180	280	100	250	390
From Distributor 3 to Customer 3	180	300	380	100	220	260	80	280	400
From Distributor 1 to Customer 4	60	120	200	110	180	290	90	290	460
From Distributor 2 to Customer 4	80	160	220	120	240	320	110	300	450
From Distributor 3 to Customer 4	100	180	250	150	260	300	120	240	420
From Distributor 1 to Customer 5	50	100	180	70	220	310	80	280	430
From Distributor 2 to Customer 5	70	120	220	80	240	320	100	260	380
From Distributor 3 to Customer 5	90	150	260	60	180	250	120	270	390
From Customer 1 to Collection center	120	220	320	90	150	280	100	220	350
From Customer 2 to Collection center	100	150	250	120	160	250	150	180	300
From Customer 3 to Collection center	120	150	280	100	140	200	120	160	280
From Customer 4 to Collection center	150	180	300	80	160	250	140	180	250
From Customer 5 to Collection center	80	120	250	150	250	300	100	200	280
From Collection center to Disposal center	20	30	50	30	50	70	50	80	100
From Collection center to Recycling center	30	50	80	20	40	60	40	60	90
From Recycling center to Supplier 1	120	220	320	80	180	220	100	150	300
From Recycling center to Supplier 2	100	180	280	120	220	280	120	180	320
From Recycling center to Supplier 3	150	250	300	100	180	250	150	220	280
From Recycling center to Manufacturer	100	180	280	110	170	250	120	160	260

Table A4
Average return rate of products.

Customer	Period 1			Period 2			Period 3		
	Scenario1	Scenario2	Scenario3	Scenario1	Scenario2	Scenario3	Scenario1	Scenario2	Scenario3
1	0.2	0.3	0.5	0.3	0.2	0.5	0.15	0.35	0. 5
2	0.3	0.25	0.45	0.25	0.3	0.45	0.10	0.25	0.65
3	0.1	0.2	0.7	0.2	0.3	0.5	0.35	0.15	0. 5
4	0.15	0.25	0.6	0.1	0.35	0.55	0.15	0.20	0.65
5	0.15	0.15	0.7	0.2	0.1	0.7	0.1	0.15	0.75

Table A5
Average capacity of facilities in CLSC network.

Capacity	Period 1			Period 2			Period 3		
	Scenario1	Scenario2	Scenario3	Scenario1	Scenario2	Scenario3	Scenario1	Scenario2	Scenario3
Supplier 1	3500	3800	4000	3800	4000	4500	4000	4500	5000
Supplier 2	3800	4000	4800	4000	4500	5000	4800	5000	5500
Supplier 3	4000	4500	4800	3500	3800	4000	4500	4800	5000
Manufacturer	5000	5500	6000	5500	5800	6000	6000	6200	6500
Warehouse	4500	5000	5500	5000	5500	5800	5800	6000	6200
Distributor 1	3000	3200	3500	3200	3500	3800	3500	3800	4000
Distributor 2	3200	3500	3800	3500	3800	4000	3800	4000	4200
Distributor 3	3500	3800	4000	3800	4000	4200	4000	4200	4500
Customer 1	2500	3000	3200	2300	2500	2800	2000	2200	2500
Customer 2	2000	2200	2500	2200	2500	2800	2500	2800	3000
Customer 3	2800	3000	3500	3000	3200	3500	2500	2800	3000
Customer 4	3000	3200	3500	3200	3500	3800	2800	3000	3200
Customer 5	3200	3500	3800	3500	3800	4000	3000	3200	3500
Collection center	3500	3800	4000	3800	4000	4200	3200	3500	3800
Recycle center	2500	2800	3000	2200	2500	2800	2000	2200	2500
disposal center	1500	2000	2200	2000	2200	2500	1200	1500	1800
Veh. capacity	3500	3500	3500	3500	3500	3500	3500	3500	3500

Table A6
Average unit sale price of products and raw materials.

Sale price	Period 1	Period 2	Period 3
Product 1	2950	2880	3000
Product 2	3050	2990	3100
Product 3	3250	3160	3280
Recycled raw materials	920	870	950

Table A7
Values of uncertain parameters.

Parameter	Value	Parameter	Value	Parameter	Value
HCF_{pf}	Uniform(100,200)	$EIOF_f$	Uniform(1000,2000)	ECV_v	Uniform(10,20)
HCJ_{pj}	Uniform(110,230)	$EIOJ_j$	Uniform(2500,3700)	ECJ_j	Uniform(150,280)
HCL_{pl}	Uniform(150,270)	$EIOK_k$	Uniform(2000,3000)	ECW_w	Uniform(200,350)
HCK_{pk}	Uniform(130,250)	$EIOD_d$	Uniform(1000,2000)	ECQ_q	Uniform(180,380)
HCD_{pd}	Uniform(180,260)	$EIOW_w$	Uniform(1500,2500)	ECF_f	Uniform(20,28)
HCW_{pw}	Uniform(100,200)	$EIOQ_q$	Uniform(1000,1500)	ECK_k	Uniform(15,30)
HCR_{rw}	Uniform(100,200)	θ_p	Uniform(30,100)	ECD_d	Uniform(10,20)
$PCLpl_{ft}$	Uniform(500,8500)	$FCOF_f$	Uniform(12000,220000)	$EIHF_{pf}$	Uniform(25,55)
PCI_{tijt}	Uniform(3000,15000)	$FCOJ_j$	Uniform(15000,250000)	$EIHJ_{pj}$	Uniform(30,38)
$EIHR_{rw}$	Uniform(100,200)	$FCOK_k$	Uniform(17000,270000)	$EIHL_{pl}$	Uniform(35,45)
$EISI_{ijrv}$	Uniform(50,75)	$FCOD_d$	Uniform(19000,290000)	$EIHK_{pk}$	Uniform(20,28)
$EISJ_{jkpv}$	Uniform(60,100)	$FCOW_w$	Uniform(22000,350000)	$EIHD_{pd}$	Uniform(15,20)
$EISK_{kdpv}$	Uniform(40,80)	$FCOQ_q$	Uniform(10000,200000)	$EIHW_{pw}$	Uniform(10,20)
$EISD_{dlpv}$	Uniform(50,75)	$EISF_{fwpv}$	Uniform(40,80)	$EISW_{wirv}$	Uniform(30,60)
$EISL_{lfpv}$	Uniform(30,60)	$EISW_{wjpv}$	Uniform(100,200)	$EISQ_{wqpv}$	Uniform(100,200)

Table A8
Dimensions of problem tests.

Problem	f	p	j	l	t	i	k	s	d	q	w	v	r
1	3	2	2	3	2	2	2	3	1	1	3	2	3
2	3	2	3	2	2	2	2	3	2	1	2	2	3
3	3	3	2	3	2	3	2	3	2	1	2	2	4
4	3	2	2	3	2	3	3	3	3	2	3	3	4
5	3	2	2	3	2	3	3	3	3	2	2	3	4
6	4	4	3	4	3	3	3	3	4	2	1	3	4
7	4	4	3	2	3	4	2	3	5	3	1	4	5
8	4	2	3	2	3	4	2	3	3	3	4	4	5
9	5	4	5	6	5	8	6	3	4	3	4	4	5
10	5	4	5	6	5	8	6	3	2	2	2	2	3
11	6	5	6	7	6	8	6	3	2	2	2	2	3
12	6	5	6	7	6	9	8	3	4	2	3	2	3
13	6	5	6	7	6	9	8	3	4	3	3	3	4
14	6	6	6	7	6	9	8	3	5	3	5	3	4
15	6	6	6	7	6	10	5	3	6	3	5	3	4
16	7	6	4	8	5	10	5	3	5	1	4	4	5
17	7	6	4	8	5	10	5	3	3	1	4	4	5
18	7	5	4	8	5	5	6	3	5	1	3	4	5
19	8	5	5	8	5	5	6	3	2	4	3	5	6
20	8	4	5	8	7	5	6	3	5	4	3	5	6

B. Test results

See Tables B1-B2).

Table B1
Comparison of MILP, heuristic and robust model solutions under uncertain characteristics for second objective function.

Problem	MILP						Heuristic					
	Deterministic	Time	optimal gap%	Robust	Time	optimal gap%	Deterministic	Time	optimal gap%	Robust	Time	optimal gap%
1	11,005,413	0:02:00	2.02	11,203,245	0:02:00	1.85	10,856,423	0:01:03	2.5	11,165,047	0:02:23	1.05
2	12,363,216	0:01:00	0.036	12,310,243	0:01:15	0.5	11,032,540	0:01:10	0.00	12,300,214	0:02:46	1.2
3	15,432,507	0:02:00	1.68	16,005,846	0:02:38	0.008	15,053,697	0:01:09	1.05	15,983,540	0:03:19	0.00
4	20,337,890	0:04:56	0.39	21,347,810	0:05:06	1.36	19,725,604	0:02:11	0.005	20,457,390	0:05:17	0.00
5	15,989,631	0:10:00	3.35	18,321,479	0:10:58	2.59	15,254,793	0:02:01	0.069	18,014,068	0:07:39	1.006
6	28,012,430	00:35:24	0.32	28,975,840	00:36:51	3.61	27,899,758	0:02:11	2.03	28,102,507	0:08:42	2.13
7	21,000,364	00:54:41	3.12	22,005,874	00:54:41	0.41	20,997,259	0:03:04	0.04	21,855,075	0:11:04	0.13
8	22,301,285	00:37:41	0.795	23,147,953	00:37:41	3.66	21,736,940	0:03:01	2.14	22,951,473	0:13:49	0.065
9	25,164,705	00:10:32	0.12	26,115,408	00:11:00	0.5	24,863,144	0:04:54	1.04	25,614,709	0:16:50	0.0085
10	29,360,014	00:33:00	0.1	29,601,478	00:33:39	0.24	28,025,314	0:04:56	0.06	29,321,058	0:17:36	0.3
11	27,124,890	00:34:11	0.005	27,824,702	00:35:54	1.05	27,001,436	00:05:09	0.00	27,158,098	00:23:15	1.005
12	31,257,058	00:31:00	0.114	32,689,105	00:39:05	0.008	29,935,870	00:05:23	0.42	31,653,047	00:25:12	2.3
13	33,178,006	00:28:00	1.02	33,014,789	00:36:06	4.35	31,065,742	00:06:04	2.01	32,958,746	00:29:34	1.045
14	32,981,450	00:34:41	0.06	32,614,857	00:34:31	0.34	32,053,470	00:14:41	0.00	32,367,411	00:34:11	0.036
15	36,826,991	00:38:00	0.00	37,203,408	00:40:20	0.00	36,147,050	00:16:00	1.36	36,958,047	00:36:20	0.5
16	39,012,035	00:40:00	2.01	39,890,103	00:41:39	0.00	38,014,367	00:15:00	0.85	39,314,207	00:35:33	0.17
17	39,982,173	00:37:00	2.33	41,035,801	00:40:25	3.05	39,123,048	00:17:00	1.2	40,876,904	00:37:09	0.00
18	39,750,164	00:45:17	1.45	39,936,140	00:46:45	0.007	38,708,009	00:15:17	0.75	39,124,785	00:35:13	1.22
19	41,763,800	00:48:21	0.086	42,017,890	00:49:33	0.056	40,986,210	00:21:21	1.006	41,652,430	00:30:22	0.00
20	44,220,348	00:50:04	3.24	44,965,201	00:58:15	0.75	43,890,459	00:23:04	0.00	44,351,470	00:35:44	0.075

Table B2
Comparison of MILP, heuristic and robust model solutions under uncertain characteristics for first objective function.

Problem	MILP						Heuristic					
	Deterministic	Time	optimality gap%	Robust	Time	optimality gap%	Deterministic	Time	optimality gap%	Robust	Time	optimality gap%
1	29,420	0:04:00	2.8	28,000	0:04:56	1.56	28,810	0:02:50	2.3	25,690	0:01:85	2.80
2	38,500	0:04:19	0.51	37,000	0:05:00	1.04	36,605	0:01:70	0.08	35,140	0:01:45	0.0
3	39,600	0:04:55	0.00	39,500	0:05:34	0.94	39,100	0:02:50	1.15	38,160	0:01:87	1.09
4	45,000	0:06:56	0.82	44,000	0:07:41	0.00	41,000	0:03:8	0.025	40,500	0:03:56	2.12
5	45,600	0:3:20	1.18	45,000	0:10:00	0.76	44,000	0:11:50	0.10	43,670	0:11:00	0.0
6	53,500	00:34:44	2.71	53,000	00:38:00	0.83	51,000	00:34:5	1.95	49,850	00:30:11	2.24
7	47,000	00:44:15	0.19	47,000	00:55:47	3.22	46,850	00:52:45	0.8	46,790	00:44:5	1.01
8	46,875	00:57:02	0.00	46,500	00:43:35	5.05	46,680	00:37:0	2.10	45,500	00:35:22	0.0
9	55,630	00:17:32	0.00	55,000	00:28:02	4.03	53,800	00:11:32	1.00	53,450	00:10:50	0.06
10	55,000	00:41:05	1.15	60,000	00:33:00	2.33	53,480	00:30:00	0.06	55,720	00:29:85	0.00
11	57,000	00:44:55	0.00	58,000	00:49:18	1.25	56,650	00:33:15	0.08	57,000	00:32:15	0.35
12	71,000	00:49:00	0.71	73,000	00:52:08	0.068	69,350	00:32:00	0.32	69,200	00:30:05	0.042
13	85,500	00:45:27	0.01	85,000	00:53:12	0.00	78,500	00:25:00	1.01	78,000	00:32:06	2.11
14	85,300	00:46:33	0.04	83,000	00:54:21	0.7	76,530	00:31:41	0.10	75,666	00:36:36	0.0
15	90,000	00:45:00	0.17	90,000	00:52:30	0.05	82,620	00:39:00	1.00	82,450	00:39:28	1.46
16	97,200	00:42:37	0.80	97,000	00:59:00	1.85	89,550	00:42:00	0.55	89,000	00:42:30	0.95
17	100,000	00:47:08	0.01	100,000	01:03:36	3.65	98,640	00:35:00	1.05	98,800	00:41:5	1.8
18	98,200	00:45:19	0.04	98,000	01:11:13	2.74	93,650	00:40:5	0.15	93,000	00:44:20	0.85
19	105,321	00:42:21	1.62	105,000	01:13:22	1.21	100,000	00:45:01	1.026	99,480	00:46:37	1.016
20	110,000	00:55:17	2.33	110,000	01:23:54	0.07	108,250	00:48:14	0.00	108,000	00:55:55	0.0

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