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Multi-period planning of closed-loop supply chain with carbon policies under uncertainty

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ABSTRACT

Climate change and greenhouse gases emissions have caused countries to implement various carbon regulatory mechanisms in some industrial sectors around the globe to curb carbon emissions. One effective method to reduce industry environmental footprint is the use of a closed-loop supply chain (CLSC). The decision concerning the design and planning of an optimal network of the CLSC plays a vital role in determining the total carbon footprint across the supply chain and also the total cost. In this context, this research proposes an optimization model for design and planning a multi-period, multi-product CLSC with carbon footprint consideration under two different uncertainties. The demand and returns uncertainties are considered by means of multiple scenarios and uncertainty of carbon emissions due to supply chain related activities are considered by means of bounded box set and solve using robust optimization approach. The model extends further to investigate the impact of different carbon policies such as including strict carbon cap, carbon tax, carbon cap-and-trade, and carbon offset on the supply chain strategic and operational decisions. The model captures trade-offs that exist among supply chain total cost and carbon emissions. Also, the proposed model optimizes both supply chain total cost and carbon emissions across the supply chain activities. The numerical results reveal some insightful observations with respect to CLSC strategic design decisions and carbon emissions under various carbon policies and at the end we highlighted some managerial insights.

1. Introduction

The increase in atmospheric concentrations of greenhouse gases (GHG) emissions such as carbon dioxide, and methane has resulted in climate changes, global warming, and environmental issues. These have led to the introduction of restrictive environmental regulations by policy makers around the globe. According to the 2014 report by the Intergovernmental Panel on Climate Change, global emissions of GHGs have risen to unprecedented levels (increased by 10 billion metric tons during the period 2000–2010) despite a growing number of policies to reduce climate change (Du et al., 2016). Many countries introduced a range of carbon emissions reduction policies including mandatory carbon emission capacity, carbon cap, carbon emission tax, cap-and-trade, carbon offset, and joint implementation to curb the total amount of carbon emissions. In

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Malaysia, the government has pledged to cut 45% of its carbon emissions intensity by the year 2030 (COP21). Reducing and mitigating carbon emission proportion and in the meantime improving the energy usage efficiency are significant and necessary. Due to government legislations or mechanisms, customer awareness of environmental issues and the desire to have low carbon products, firms worldwide are undertaking carbon emission reduction initiatives to curb carbon footprint.

Most of the GHG emission reduction initiatives on the firm level are concerned with acquiring energy efficient equipment and facilities, using low pollution energy sources and implementing energy saving projects. However, it is necessary to investigate the impact of other sources of carbon emissions that are driven by firm operational activities and strategies in a complex supply chain (He et al., 2016). For instance, frequency of logistical activities, facility location, and transportation modes, will influence GHG emission of the firm as well as its supply chain activities, which in turn determines the carbon footprint of the final product (Choudhary et al., 2015).

Many countries strive to mitigate GHG emissions by passing legislation and developing market-based environmental strategies. These strategies not only help in emission reduction but also provide economic benefits to firms. Examples of these strategies are the "Kyoto Protocol, 1997", the "European Union Emission Trading System, 2009", "New Zealand Emissions Trading Scheme, 2009", and "Japan carbon tax scheme, 2012", etc. (Gao and Ryan, 2014). Kyoto Protocol was signed in by 181 countries as part of the "United Nations Framework Convention on Climate Change" to control GHG emissions. The Protocol introduced three mechanisms through which countries can cooperate to meet their emission reduction targets and decrease costs (Ramudhin et al., 2010). First, Emissions Trading or Carbon Market, allows countries that pollute more than their target to buy emission credit from countries that have excess credit i.e., pollute less in order to stay below their target or cap. Second, Clean Development mechanism that allows a country to gain carbon emissions credit if it invests in emission reduction projects in developing countries. Third, countries can also earn emissions credit through joint implementation, which allows a country to benefit by carrying out emission reduction projects in another industrialized country committed to its emission reductions.

Literature surveys conducted by Hua et al. (2011), Benjaafar et al. (2013), Palak et al. (2014) and Du et al., 2016 have identified a growing need for developing quantitative models and decision support systems for operations management, and supply chain management to address issues associated with curbing carbon emissions. Jin et al. (2014), Marufuzzaman et al. (2014), and Zakeri et al. (2015) developed optimization models for supply chain network design problems by incorporating various carbon policies to address the issue of carbon footprint in their operational decision making. However, their models are limited to either inventory management decisions, such as economic lot size and economic order quantity or conventional logistic design. In addition, Diabat and Simchi-Levi (2009), Chaabane et al. (2012), and Fahimnia et al. (2013) highlight that integrating environmental issues into production, supply chains, and logistics is a complex process. However, their works are limited to one carbon policy and considered deterministic parameters.

Increase in environmental concerns, governmental legislations, customer awareness, and social responsibilities have triggered some firms to move from conventional forward supply chains to green supply chains by recovering their end-of-life (EOL) products through re-manufacturing, repair and recycling processes. Firms realized that the issue of recycling their EOL products and reusing products residue and scrap would not only minimize environmental impact but also improve their business market status globally. For example, several major firms such as General Motors, Kodak, Walmart and Xerox are focusing on reverse logistics and recovery activities. A supply chain which integrates product recovery activities in its conventional supply chain is called closed loop supply chain (CLSC) (Abdallah et al., 2012). A large volume of the literature is available on CLSC network design (Jayaraman et al., 1999; Ko and Evan, 2007; Easwaran and Üster, 2010; Vahdani et al., 2012; Ramezani et al., 2013; Amin and Zhang, 2013; Zeballos et al., 2014; Govindan et al., 2015; Kalaitzidou et al., 2015; Gaur et al., 2016; Kumar et al., 2016; Kadambala et al., 2016; Yi et al., 2016; Tahirov et al., 2016). However, the models in the above literature are either focused on minimizing cost or maximizing profit and did not include environmental consideration under different carbon policies. The integration with environmental aspects can help policy makers to better understand how different carbon policies would reduce the negative effects of GHG. In addition, the integrated models could be used to understand the effect of policy parameters on the total cost and carbon emissions of various supply chain activities of the firm.

Consideration of uncertainties in the model parameters will represent a more realistic problem situation. Simangunsong et al. (2012) identified a comprehensive list of the sources of uncertainty and categorized them as: (1) internal organization uncertainties (e.g., manufacturing processes and product characteristics), (2) internal supply chain uncertainties (e.g., demand, supplier and supply chain configurations), and (3) external uncertainties (e.g., environmental, macroeconomic issues and disasters). Supply chain network design (SCND) has effects that last for several years, during which critical parameters such as raw material supply and demand of customers change are quite uncertain (Pishvaee et al., 2009). Reverse logistics activities are complex and tend to high degree of uncertainty. Collection rate, variety of returns, quality and quantity of returned products are highly uncertain even in a short period of time. Also, carbon emissions across the supply chain due to various activities play vital role in decisions concerning the design and planning of an optimal CLSC network. Thus, designing and planning of CLSC configuration with carbon footprint under uncertainty is highly necessary. This paper incorporates two different types of uncertainties in the model (i) uncertainty of product demand and returns, (ii) uncertainty of carbon emissions across the supply chain and investigates the impact of these uncertainties on the design and planning of a multi-period CLSC network which makes this work distinguished from existing literature. Researchers have developed methodologies to tackle uncertainty of decision-making in SCND. These include: dynamic programming, stochastic programming, robust optimization, and fuzzy programming. In particular, scenario-based stochastic programming and robust optimization could be used to study real-world problems where there is not enough historical data to estimate the probability distribution of uncertain parameters and also due to inherent uncertainty in input data. To the best of our knowledge, two different types of uncertainties (called mixed uncertainty) is hardly applied to CLSC network design problems.

This paper aims to address the above stated research gaps in the literature through investigating the following key questions:

– Which facilities should be activated with different capacity levels and which transportation mode should be selected between activated facilities to reduce carbon emissions in multi-period settings?
– What are the optimal production and transportation quantities between the facilities?
– What is the impact of different uncertainties on the design and planning problem of a multi-product multi-period CLSC?
– What is the impact of various carbon emission policies on the design and planning of CLSC as well as transportation mode selection decisions?
– What is the trade-off between supply chain total cost and carbon emission under different carbon policies?
– How do the optimal supply chain decisions under different carbon policies affect economic and environmental performance?

To answer these questions, this research proposes an optimization model to address a multi-period, multi-product, capacitated CLSC network design problem. An MILP formulation is used to handle the problem. Some of the parameters of the proposed model are regarded as uncertain parameters with two different uncertainties; (i) products demand and returns uncertainties are considered by means of stochastic scenarios whose probability of occurrence is known, (ii) carbon emissions due to supply chain activities are considered as uncertain parameters by means of a set-based methodology which leads to robust optimization. To make the model realistic, several supply chain requirements are taken into account, such as multiple planning periods, selection of technologies at the production facilities, transportation mode selection, as well as capacity limits on production, distribution and storage. In multiple periods, the parameters in the CLSC network are stable, whereas across different periods, there may be some changes such as investment costs and variable costs. Further, we use this model to understand the impact of various carbon regulatory policies on CLSC network design. Carbon policies that we study are carbon cap, carbon tax, carbon cap-and-trade, and carbon offset policy. The overall objective is to minimize both supply chain total cost and total carbon emissions across the supply chain. The model captures trade-offs that exist among supply chain total cost and carbon emissions. The numerical results reveal some insightful observations with respect to CLSC strategic design decisions under various carbon policies and at the end we highlight some managerial insights.

The rest of the paper is organized as follows: Section 2 reviews relevant literature. Section 3 provides problem description, assumptions, model notation and model formulation of the base model. Model formulation under various carbon emission policies is presented in Section 4. The robust optimization framework used for developing the robust counterpart model under box uncertainty set is explained in Section 5. A case study and numerical results are presented in Section 6. Finally, conclusions are made in Section 7.

2. Literature review

The literature review focuses on four main areas: (i) research related to CLSC network design, (ii) research related to carbon emission and regulations in supply chain strategic and operational decisions, (iii) research related to transportation mode selection considering carbon emission, and (iv) research overview on parameter uncertainty and solution methodology.

The literature on SCND ranges from basic incapacitated facility location models to complex capacitated multi-stage, multi-product, or multi-period models for both forward supply chain and for CLSCs. The common objective is either to minimize total cost or maximize profit by making tradeoffs among investment costs of opening facilities and variable costs. Many papers used MILP formulation for designing logistic networks and various solution methods have been developed to solve the network design problems (Jayaraman et al., 1999; Fleischmann et al., 2001; Min et al., 2006; Soleimani et al., 2013; Özceylan et al., 2014; Soleimani and Kannan, 2015; Kalaitzidou et al., 2015; Yi et al., 2016; Kadambala et al., 2016). Very useful literature reviews are presented by Melo et al., 2009; Akçalı et al., 2009; Souza, 2013; Govindan et al., 2015.

Recently, few papers proposed optimization models for supply chains to minimize the carbon footprint by changing the supply chain operations. Benjaafar et al. (2013) proposed optimization models for supply chain operational decision making under various carbon policies such as carbon cap, carbon tax rate, carbon cap-and-trade, and carbon offset policies. Palak et al. (2014) analyzed the impact of potential carbon regulatory mechanisms on supplier and transportation mode selection in a biofuel supply chain. However, these studies are limited to inventory management decisions, such as economic lot size and economic order quantity. Jin et al. (2014) proposed optimization models for major retailers and investigated the impact of three carbon policies on supply chain strategic and transportation mode selection decisions. Fareeduddin et al. (2015) extended the work of Jin et al. (2014) by incorporating reverse logistics to their traditional forward supply chain and investigated the CLSC network design and carbon emissions issues under various carbon policies. Diabat et al. (2013) studied the issues of facility location problem in CLSC with trading of carbon emission and cost of procurement. Fahimnia et al. (2013) developed a unified MILP model for a CLSC in which carbon footprint is evaluated based on the influence of forward and reverse supply chain where carbon emissions are expressed in terms of dollar carbon cost. The main two limitations of above work is that all parameters are assumed to be known and fixed and only carbon tax policy is considered. Marufuzzaman et al. (2014) proposed two-stage stochastic programming model for designing and managing biodiesel supply chains under uncertainty. Various carbon regulatory mechanisms are used to study the impact of carbon emissions on supply chain related activities. Mohajeri and Fallah (2016) developed an optimization model for a CLSC network design under uncertainty of product demand and return rate. Uncertainty was described as fuzzy numbers. Carbon emission constraints are used in the model to limit the carbon emission per unit of product supplied with different transportation modes. However, their work is limited to single-product and single period settings, and considered only carbon cap policy.

Transportation mode selection plays an important role in mitigating carbon emissions in logistics systems and this may result in significant impact on both economic and environmental performance of a firm and the supply chain as whole. Chen and Wang (2016) and Bauer et al. (2010) addressed the issue of incorporating environmental related costs into fright planning and proposed an integer programming formulation that minimizes GHG emissions of transportation activities. Hoen et al. (2014) investigated the effect of carbon emission regulations on transportation mode selection problem in terms of cost (inventory, transport, and emission costs for transport modes) and carbon emissions of the solution under uncertain demand. Konur and Schaefer (2014) incorporated two transportation modes into an economic order quantity model to examine the impact of different carbon regulatory policies on retailer decision. Wang et al. (2015) examined the effect of carbon emission taxes on transportation mode selection and social welfare. Chen and Wang (2016) examined the impact of carbon cap and carbon cap-and-trade on retailer optimal order quantity and transportation mode selection under uncertain demand. These studies are limited to either inventory or production related decisions. To the best of our knowledge only Jin et al. (2014) proposed optimization models for a major retailer where they included freight transportation and investigated the impact of different carbon regulatory policies on the supply chain operational decisions.

Several papers considered the uncertain nature of various input parameters on CLSC design (Listeş, 2007; El-Sayed et al., 2010; Ramezani et al., 2013). Salema et al. (2007) proposed an MILP formulation that incorporates stochastic scenario based programming approach for designing a generic reverse logistic network where uncertainty on product demands and returns are considered. Pishvaee et al. (2009) developed a scenario based stochastic programming model for integrated logistics network design under uncertainty. Lee and Dong (2009) proposed a two-stage stochastic program model for the design of a multi-period CLSC network. Product demand and returns are considered as uncertain parameters. Cardoso et al. (2013) developed an MILP formulation for design and planning of integrated reverse logistics network with forward SC under uncertain product demand. Uncertainty was modelled through scenario-based approach. Amin and Zhang (2013) proposed an MILP formulation for designing CLSC network. They investigated the impact of demand and return uncertainties on the network by using stochastic scenario-based approach. Very few studies employed robust optimization of CLSC network under uncertainty. Pishvaee et al. (2011) presented an initial study on robust methodology to handle inherent uncertainty in CLSC network using varying set of a box uncertainty set. Keyvanshokooh et al. (2016) proposed a multi-period CLSC network design model under different types of uncertainties simultaneously including stochastic scenarios for transportation costs and polyhedral uncertainty sets for demands and returns, which they solve via a novel hybrid robust-stochastic programming approach. Meysam et al. (2016) proposed an integrated CLSC network and a supplier selection problem under three uncertainty sets: box, polyhedral, and interval plus polyhedral. In all of the above literature, parameters uncertainty is limited to CLSC network design problems. These studies didn't consider environmental issues and carbon emission related uncertainties.

A more detailed classification of some of the recently published literature on SCND and carbon emission reduction policies is presented in Table 1. This classification is based on the following aspects; supply chain network structure, modelling features, parameter uncertainty, carbon regulatory policies, modelling methodologies and solution methods. The last row of Table 1 specifies the characteristics of this research. Table 1 shows that, most of the research in CLSC network design for carbon emissions under various carbon regulatory policies assumed deterministic conditions. Most of the network design problems were modeled as MILP. Exact methods, heuristics, meta-heuristics, Lagrangian and decomposition methods were commonly employed to solve such complex, NP-hard problems. Choudhary et al. (2015) considered carbon emission related regulatory policies in the context of integrated forward and reverse logistics. However, their work is limited to single product and single period setting. Fareeduddin et al. (2015) proposed multi-product multi-period CLSC network design model to study the network design problem when different carbon regulatory policies were taken into consideration. However, both papers, were limited to deterministic models.

This paper addresses several gaps in the literature. First, we integrate carbon footprint consideration and correspondingly various emission related regulatory policies in the context of multi-period CLSC network design and planning with parameters uncertainty. Second, this research considers two different types of parameter uncertainties to make the model closer to reality. Third, we consider different types of transportation modes with limited capacity since transportation is a major contributor of carbon emissions. By addressing the above considerations, we hope to provide answers to real life supply chain issues.

Table 1
Configuration of some recently published literature on SCND and carbon regulatory policies.

Reference articles	Network type	Multi-product	Multi-period	Parameters (demand, return rate, variable costs, etc.)				Limited capacitated		Carbon policies				Modeling	Sol. type	Sol. method
				Deterministic	Stochastic	Robust	Fuzzy	Facilities	Transport mode	Carbon cap	Carbon tax	Cap-and-trade	Carbon offset			
Salema et al. (2007)	R	x			x			x						MILP	E	B&B
Pishvaee et al. (2009)	CL				x			x						MILP	E	CP
Diabat and Simchi-Levi (2009)	F	x		x				x		x				MILP	E	CP
Easwaran and Üster (2010)	CL	x		x				x						MILP	H	BD
Chaabane et al. (2012)	CL	x	x	x				x				x		MILP	E	CP
Abdallah et al. (2012)	F	x		x						x				MILP	E	CP
Elhedhli and Merrick (2012)	F			x				x			x			MILP	H	LR-based
Diabat et al. (2013)	CL	x		x				x		x				MILP	E	CP
Fahimnia et al. (2013)	CL	x	x	x				x		x				MILP	E	CP
Jin et al. (2014)	F			x				x		x	x	x		LP	E	CP
Cardoso et al. (2013)	FR	x	x		x			x						MILP	E	CP
Marufuzzaman et al. (2014)	F	x			x			x	x	x	x	x	x	MILP	H	LR&L-shaped
Zeballos et al. (2014)	CL	x	x		x			x	x		x			MILP	E	CP
Gao and Ryan (2014)	CL	x	x		x	x		x				x		MILP	E	CP
Choudhary et al. (2015)	FR			x				x		x	x	x		MILP	M	GA
Fahimnia et al. (2015)	F	x	x	x				x	x		x			MINLP	H	Cross-Entropy
Fareeduddin et al. (2015)	CL	x	x	x				x		x	x	x		MILP	E	CP
Mohajeri and Fallah (2016)	CL						x	x	x	x				MILP	E	CP
Rezaee et al. (2015)	F	x			x			x	x			x		MILP	E	CP
Tao et al. (2015)	CL		x	x						x	x			LP	H	LR-based
Zakeri et al. (2015)	F	x	x	x				x	x		x	x		MILP	E	CP
Martí et al. (2015)	F	x		x						x	x	x		ILP	E	CP
Meysam et al. (2016)	CL	x				x		x						MILP	E	CP
Memari et al. (2016)	F	x	x	x				x		x				MILP	M	FFA&NSGA-II
Kumar et al. (2016)	FR		x	x				x						MILP	M	AIS & PSO
Nouira et al. (2016)	F			x				x		x				MILP	E	CP
This research	CL	x	x		x	x		x	x	x	x	x	x	MILP	E	CP

F: Forward; R: Reverse; FR: Forward & Reverse; CL: Closed-loop; E: Exact; H: Heuristic; M: meta-heuristic, CP: Commercial package.

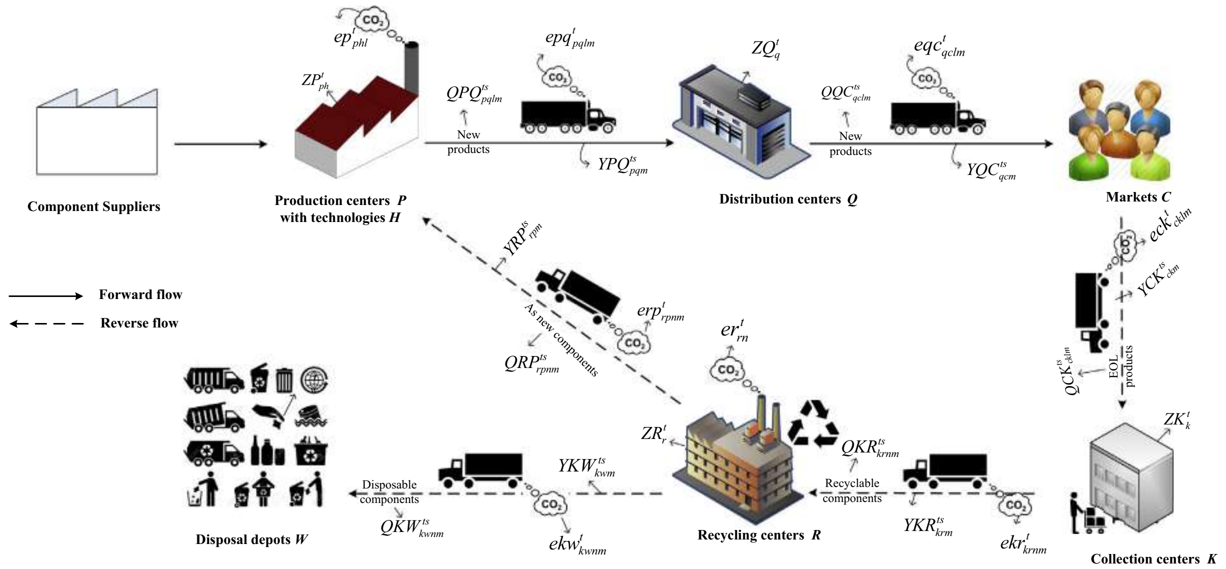

Fig. 1. A general closed-loop supply chain network.

3. Problem description and model formulation

3.1. Problem description

In this paper, we consider a general closed loop supply chain network as shown in Fig. 1. In the forward SC, the network includes multiple production centers (PCs), multiple distribution centers (DCs), and multiple markets. In the reverse SC, the network includes multiple collection centers (CCs), multiple recycling centers (RCs), and multiple disposal depots (DDs). Such a CLSC network could span countries or continents.

In the forward chain, PCs get new components through suppliers and recycled ones through the RC. Each PC could produce multiple product types using technologies that may differ from other producers. Each technology has its own acquisition, operation and production costs as well as carbon emission rate. Finished products are shipped to markets from the DCs. A variety of transportation modes are available for shipping products among facilities at different costs and fuel efficiency rates. In the reverse supply chain, the EOL products are collected by the CCs. Collected products are shipped to RCs. At the RCs, the products are disassembled into components, inspected and sorted into recycled and non-recyclable components. We assume that recycled components are as good as new components. Non-recyclable components are shipped to DDs for disposal.

The problem we study here is to minimize the total system cost by determining the optimal number and location of each facility type, determining the optimal production quantities, transportation quantities, recycling quantities, purchasing quantities, type of transportation mode to be used between the facilities, and type of available technologies to be used at each production center that fulfils the market demand. We assume that there is uncertainty in product demand and return rate.

3.2. Model assumptions and conceptual model outline

The assumptions in modelling are as follows.

(1) The number, capacity and candidate locations of PCs, DCs, CCs, RCs, and DDs are known.
(2) The number and location of markets are known.
(3) Customer demand and EOL products return rate are assumed to be uncertain.
(4) Transportation cost from facility a to b, then from b to c is higher than direct transportation cost from a to c.
(5) Emissions due to processing products at facilities and emissions for shipping products from PCs to end users are known and fixed. These are based on the type of technology used at the PCs and type of transportation mode used in logistic activities (Fahimnia et al., 2013).
(6) The cost of emission for holding/storing products at facilities is assumed to be negligible when compared to the overall supply chain emission (Fahimnia et al., 2013).

Fig. 2 shows a conceptual outline for the proposed CLSC model represented in a block diagram.

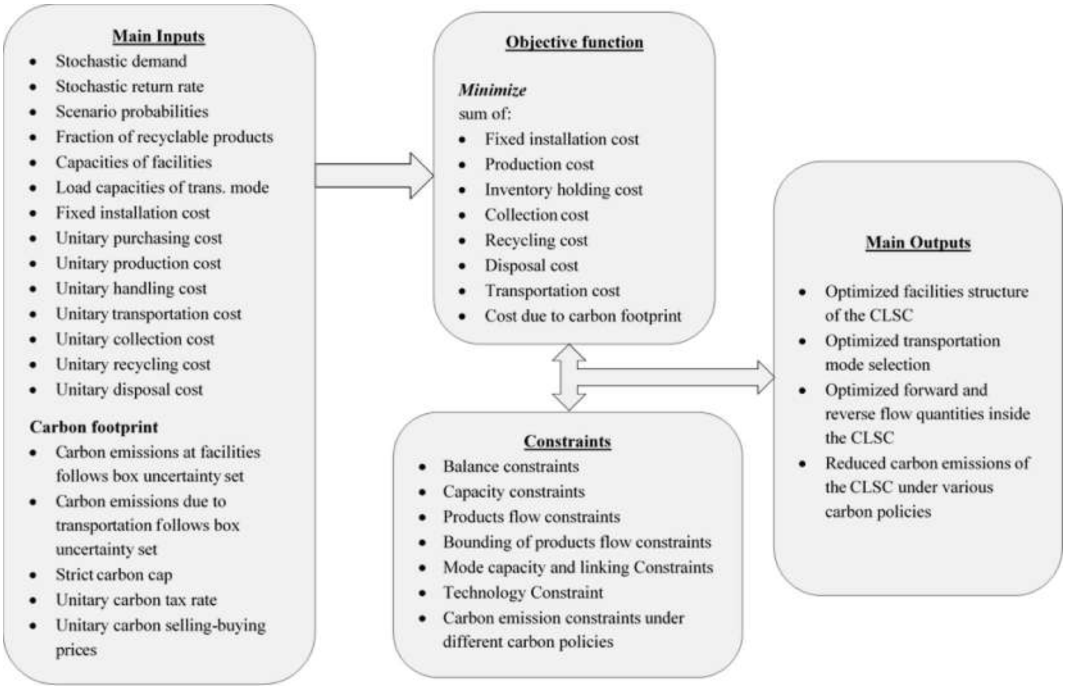

Fig. 2. A conceptual outline of the proposed CLSC model.

3.3. Model notation

The following notation is used for the mathematical formulation of the model.

Sets and subscripts

P	set of candidate locations for production centers PCs $\{1, 2, \ldots p \ldots\}$
Q	set of candidate locations for distribution centers DCs $\{1, 2, \ldots q \ldots\}$
C	set of markets $\{1, 2, \ldots c \ldots\}$
K	set of candidate locations for collection centers CCs $\{1, 2, \ldots k \ldots\}$
R	set of candidate locations for recycling centers RCs $\{1, 2, \ldots r \ldots\}$
W	set of candidate locations for disposal deports DDs $\{1, 2, \ldots w \ldots\}$
L	set of product types $\{1, 2, \ldots l \ldots\}$
N	set of component types $\{1, 2, \ldots n \ldots\}$
M	set of transportation modes $\{1, 2, \ldots m \ldots\}$
H	set of production technologies $\{1, 2, \ldots h \ldots\}$
T	set of periods in the planning horizon $\{1, 2, \ldots t \ldots\}$
S	set of scenarios $\{1, 2, \ldots s \ldots\}$

Parameters

D_{cls}^t	demand for product l by market c in time period t under scenario s
R_{cls}^t	EOL returns of product l from market c in time period t under scenario s
μ_l^f	proportion of EOL product l returned after f years of service, $f = 0$ *means in the same year*, $\sum_{f=0}^{F_l} \mu_l^f \leqslant 1$
F_l	maximum life of product l
φ_{ln}	number of units of component n in a unit of product l
α_n	fraction of component n that could be recycled
Pr_s	probability of occurrence of scenario s
tpl_{lh}	time to produce a unit of product l using technology h
trn_n	time to recycle a component n
vl_l	space required to store a unit of product l
vn_n	space required for disposal of one unit of component n
M	a large scalar

Capacities of facilities

SP_p	production capacity of the PC in location p, in hours
SQ_q	storage capacity of the DC in location q, in m^3
SK_k	storage capacity of the CC in location k, in m^3
SR_r	recycling capacity of the RC in location r, in hours
SW_w	storage capacity of the DD in location w, in m^3

Load capacities of transportation mode

tpq_{pqm}, Tpq_{pqm}	Min. and Max. load capacity of transportation mode m between the PC in location p and DC in location q, in tons
tqc_{qcm}, Tqc_{qcm}	Min. and Max. load capacity of transportation mode m between the DC in location q and market c, in tons
tck_{ckm}, Tck_{ckm}	Min. and Max. load capacity of transportation mode m between market c and in location CC k, in tons
tkr_{krm}, Tkr_{krm}	Min. and Max. load capacity of transportation mode m between the CC in location k and RC in location r, in tons
trp_{rpm}, Trp_{rpm}	Min. and Max. load capacity of transportation mode m between the RC in location r and the PC in location p, in tons
trw_{rwm}, Trw_{rwm}	Min. and Max. load capacity of transportation mode m between the RC in location r and the DD in location w, in tons

Fixed costs

fp_{ph}	fixed cost of constructing a PC in location p with technology h
fq_q	fixed cost of constructing a DC in location q
fk_k	fixed cost of constructing a CC in location k
fr_r	fixed cost of constructing a RC in location r
fw_w	fixed cost of constructing a DD in location w

Unit costs

cpo^t_{np}	unit purchasing cost of new component n from suppliers for the PC in location p in time period t
cmp^t_{phl}	unit production cost of product l at the PC in location p using technology h in time period t
chp^t_{pn}	unit holding cost of component n at the PC in location p in time period t
chq^t_{ql}	unit holding cost of product l at the DC in location q in time period t
ccc^t_{kl}	unit collection cost of EOL product l at CC in location k in time period t
crc^t_{rn}	unit recycling cost of component n at the RC in location r in time period t
cdw^t_{wn}	unit disposal cost of scrapped component n at the DD in location w in time period t
tpq^t_{pqlm}	cost of shipping a unit of product l from the PC in location p to the DC in location q using transportation mode m in time period t
tqc^t_{qclm}	cost of shipping a unit of product l from the DC in location q to market c using transportation mode m in time period t
tck^t_{cklm}	cost of shipping a unit of retuned product l from market c to the CC in location k using transportation mode m in time period t
tkr^t_{krlm}	cost of shipping a unit of returned product l from the CC in location k to the RC in location r using transportation mode m in time period t
trp^t_{rpnm}	cost of shipping a unit of recycled component n from the RC in location r to the PC in location p using transportation mode m in time period t
trw^t_{rwnm}	cost of shipping a unit of scrapped component n from the RC in location r to the DD in location w using transportation mode m in time period t

Parameters related to carbon emission

ep^t_{phl}	carbon emission in kg due to production of one unit of product l at the PC in location p with technology h in time period t
eq^t_{ql}	carbon emission in kg due to storing of one unit of product l at the DC in location q in time period t
ek^t_{kl}	carbon emission in kg due to collection of one unit of returned product l at the CC in location k in time period t
er^t_{rn}	carbon emission in kg due to recycling of one unit of component n at the RC in location r in time period t
ew^t_{wn}	carbon emission in kg due to disposal of one unit of component n at the DD in location w in time period t
epq^t_{qplm}	carbon emission in kg due to shipping one unit of product l from the PC in location p to DC in location q using transportation mode m in time period t.
eqc^t_{qclm}	carbon emission in kg due to shipping product l from the DC in location q to market in location c using

(continued on next page)

	transportation mode m in time period t
eck^t_{cklm}	carbon emission in kg due to shipping returned product l from market in location c to the CC in location k using transportation mode m in time period t
ekr^t_{krlm}	carbon emission in kg due to shipping returned product l from the CC in location k to the RC in location r using transportation mode m in time period t
erp^t_{rpnm}	carbon emission in kg due to shipping recycled component n from the RC in location r to the PC in location p using transportation mode m in time period t
erw^t_{rwnm}	carbon emission in kg due to shipping scrapped component n from the RC in location r to the DD in location w using transportation mode m in time period t
C^{cap}	carbon cap on emissions over the entire planning horizon
δ	the carbon tax rate per unit (amount of tax paid per unit emitted)
p^+	buying price of one kg of carbon in the carbon market
p^-	selling price of one kg of carbon in the carbon market
p^o	the carbon offset price per kg

Decision variables

Binary variables

ZP_{ph}	1 if a PC is constructed in candidate location p that uses technology h, 0 otherwise
ZQ_q	1 if a DC is constructed in candidate location q, 0 otherwise
ZK_k	1 if CC is constructed in candidate location k, 0 otherwise
ZR_r	1 if RC is constructed in candidate location r, 0 otherwise
ZW_w	1 if DD is constructed in candidate location w, 0 otherwise
YPQ^{ts}_{pqm}	1 if transportation mode m is used between the PC in location p and the DC in location q in time period t under scenario s, 0 otherwise
YQC^{ts}_{qcm}	1 if transportation mode m is used between the DC in location q and the market in location c in time period t under scenario s, 0 otherwise
YCK^{ts}_{ckm}	1 if transportation mode m is used between the market in location c and the CC in location k in time period t under scenario s, 0 otherwise
YKR^{ts}_{krm}	1 if transportation mode m is used between the CC in location k and the RC in location r in time period t under scenario s, 0 otherwise
YRP^{ts}_{rpm}	1 if transportation mode m is used between the RC in location r and the PC in location p in time period t under scenario s, 0 otherwise
YRW^{ts}_{rwm}	1 if transportation mode m is used between the RC in location r and the DD in location w in time period t under scenario n, 0 otherwise

Continuous variables

QE^{ts}_{np}	quantity of new component n purchased by the PC in location p in time period t under scenario s
QP^{ts}_{phl}	quantity of product l produced in the PC in location p using technology h in time period t under scenario s
QPQ^{ts}_{pqlm}	quantity of product l shipped from the PC in location p to the DC in location q using transportation mode m in time period t under scenario s
QQC^{ts}_{qclm}	quantity of product l shipped from the DC in location q to the market in location c using transportation mode m in time period t under scenario s
QCK^{ts}_{cklm}	quantity of returned product l shipped from the market in location c to the CC in location k using transportation mode m in time period t under scenario s
QKR^{ts}_{krlm}	quantity of returned product l shipped from the CC in location k to the RC in location r using transportation mode m in time period t under scenario s
QRP^{ts}_{rpnm}	quantity of component n shipped from the RC in location r to the PC in location p using transportation mode m in time period t under scenario s
QRW^{ts}_{rwnm}	quantity of disposable component n shipped from the RC in location r to the DD in location w using transportation mode m in time period t under scenario s
IP^{ts}_{pn}	inventory of component n at the PC in location p in time period t under scenario s
IQ^{ts}_{ql}	inventory of product l at the DC in location q in time period t under scenario s
e^+_{ts}	the amount of carbon credit purchased in time period t under scenario s
e^-_{ts}	the amount of carbon credit sold in time period t under scenario s

3.4. Formulation of scenario-based stochastic programming model without carbon emissions considerations (base model)

The CLSC network design problem under uncertainty is formulated as a multi-period multi-product MILP model. The scenario-based stochastic programming approach is used to deal with uncertainty arising from customer demand and

EOL product return. This approach covers strategic/tactical and operational decisions. Strategic decisions such as facility location are made at the beginning of the planning horizon (prior to observing the actual demand and returns). Once these decisions are made, then the tactical and operational decisions; production, distribution, storage, and transportation mode selection are made at each time periods. These allow for revising decisions in each time period in order to avoid infeasibilities due to uncertainty previously realized. The proposed formulation is capable of representing the time-varying nature of the network.

In the this approach, uncertainties of demand and return are modeled independently. We define a scenario of demand and return as a combination of these two random quantities for all time periods. For example, suppose that the demand of a product, at any time period, could assume one of four values, d_1, d_2, d_3, and d_4. Similarly, assume that the EOL product return at any time period, could assume one of three values, r_1, r_2, and r_3. Then a scenario for 3 periods is given by; (D^1, R^1, D^2, R^2, D^3, R^3) where $D^t \in \{d_1, d_2, d_3\}$ and $R^t \in \{r_1, r_2, r_3\}$. In this case, there are $4^3 \times 3^3$ possible scenarios. Let $P(D^t = d_j)$ be the probability that the demand in period t is equal to d_j. where t = 1, 2, 3 and j = 1, . . . , 4 and $P(R^t = r_j)$ be the probability that the return in period t is equal to r_j where t = 1, 2, 3 and j = 1, . . . , 3. Then the probability of a particular scenario is the product of these probabilities.

A base model will exclude carbon emission consideration, where strategic and tactical/operational decisions are solely based on economic performance.

3.4.1. The objective function

The total expected cost of the CLSC is derived from the opening of facilities, production, inventory, collection, recycling, disposal, and transportation.

$$\text{Total fixed cost (TFC)} = \sum_{p\in P}\sum_{h\in H} ZP_{ph} + \sum_{q\in Q} cfq_q ZQ_q + \sum_{k\in K} cfk_k ZK_k + \sum_{r\in R} cfr_r ZR_r + \sum_{w\in W} cfw_w ZW_w$$

$$\text{Expected total material and production costs (ETPRC)} = \sum_{s\in S} Pr_s\left[\sum_{n\in N}\sum_{p\in P}\sum_{t\in T} cpo^t_{np} QE^{ts}_{np} + \sum_{p\in P}\sum_{h\in H}\sum_{l\in L}\sum_{t\in T} cmp^t_{phl} QP^{ts}_{phl}\right]$$

$$\text{Expected total inventory holding costs (ETHC)} = \sum_{s\in S} Pr_s\left[\sum_{p\in P}\sum_{n\in N}\sum_{t\in T} chp^t_{pn} IP^{ts}_{pn} + \sum_{q\in Q}\sum_{l\in L}\sum_{t\in T} chq^t_{ql} IQ^{ts}_{ql}\right]$$

$$\text{Expected total collection cost (ETCC)} = \sum_{s\in S} Pr_s\left[\sum_{c\in C}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} ccc^t_{kl} QCK^{ts}_{cklm}\right]$$

$$\text{Expected total recycling cost (ETRC)} = \sum_{s\in S} Pr_s\left[\sum_{r\in R}\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T} crc^t_{rn} QRP^{ts}_{rpnm}\right]$$

$$\text{Expected total disposal cost (ETDC)} = \sum_{s\in S} Pr_s\left[\sum_{r\in R}\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T} cdw^t_{wn} QRW^{ts}_{rwnm}\right]$$

$$\begin{aligned}\text{Expected total transportation cost (ETTC)} = \sum_{s\in S} Pr_s\Bigg[&\sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} tpq^t_{qplm} QPQ^{ts}_{pqlm}\\ &+\sum_{q\in Q}\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} tqc^t_{qclm} QQC^{ts}_{qclm}\\ &+\sum_{c\in C}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} tck^t_{cklm} QCK^{ts}_{cklm} + \sum_{k\in K}\sum_{r\in R}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} tkr^t_{krlm} QKR^{ts}_{krlm}\\ &+\sum_{r\in R}\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T} trp^t_{rpnm} QRP^{ts}_{rpnm}\\ &+\sum_{r\in R}\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T} trw^t_{rwnm} QRW^{ts}_{rwnm}\Bigg]\end{aligned}$$

The objective function, Expected Total Cost (ETC) to be minimized is thus as given in (1):

$$\textit{Minimize}\ \text{ETC} = \text{TFC} + \text{ETPRC} + \text{ETHC} + \text{ETCC} + \text{ETRC} + \text{ETDC} + \text{ETTC} \quad (1)$$

3.4.2. The constraints

This sub-section provides the constraints of the proposed model:

3.4.2.1. Balance constraints. Constraints (2)–(9) are called balance constraints. The left hand side of (2) gives the quantity of component n that are generated by all RCs, the number of new components acquired from suppliers, and previous period inventory at the PC in location p in time period t. The right hand side gives quantity of component n that are needed for manufacturing product l that is produced in the PC in location p in time t in addition to end of period inventory.

$$\sum_{r\in R}\sum_{m\in M} QRP^{ts}_{rpnm} + QE^{ts}_{np} + IP^{t-1,s}_{pn} = \sum_{l\in L}\sum_{h\in H} \varphi_{ln} QP^{ts}_{phl} + IP^{ts}_{pn}, IP^{0,s}_{pn} = 0, \quad p\in P, \quad n\in N, \quad t\in T, \quad s\in S \tag{2}$$

The left hand side of the following constraint gives the quantity of product l produced by the PC in location p at time period t. The right side gives the sum of the shipments of the same product and same PC to the DCs in time period t.

$$\sum_{h\in H} QP^{ts}_{phl} = \sum_{q\in Q}\sum_{m\in M} QPQ^{ts}_{pqlm} \quad \text{for } p\in P, \quad l\in L, \quad t\in T, \quad s\in S \tag{3}$$

The left hand side of (4) is equal to the quantity of product l that the DC in location q receives from all PCs in addition to last period ending inventory. The right side gives the quantity of the same product that has been shipped to the markets in the same time period.

$$IQ^{t-1,s}_{ql} + \sum_{p\in P}\sum_{m\in M} QPQ^{ts}_{pqlm} = IQ^{ts}_{ql} + \sum_{c\in C}\sum_{m\in M} QQC^{ts}_{qclm}, IQ^{0,s}_{ql} = 0 \quad \text{for } q\in Q, \quad l\in L, \quad t\in T, \quad s\in S \tag{4}$$

The following constraint ensures that the demand for each market is satisfied through shipments from the distribution centers for each time period.

$$\sum_{q\in Q}\sum_{m\in M} QQC^{ts}_{qclm} = D^{t}_{cls} \quad \text{for } c\in C, \quad l\in L, \quad t\in T, \quad s\in S \tag{5}$$

The constraint below shows that for each time period, the EOL returns of each product equal the shipments of these returns to the collection centers.

$$\sum_{k\in K}\sum_{m\in M} QCK^{ts}_{cklm} = R^{t}_{cls}, \quad c\in C, \quad l\in L, \quad t\in T, \quad s\in S \tag{6}$$

$$R^{t}_{cls} = \sum_{f=0}^{F_l} \mu^{f}_{l} D^{t-f}_{cls}, t \geqslant F_t, \quad c\in C, \quad l\in L, \quad t\in T, \quad s\in S$$

where $D^{g}_{cls} = 0$ for $g \leqslant 0$.

Constraint (7) gives inventory balance equation of returned products at each CC in each time period.

$$\sum_{c\in C}\sum_{m\in M} QCK^{ts}_{cklm} = \sum_{r\in R}\sum_{m\in M} QKR^{ts}_{krlm}, \quad k\in K, \quad l\in L, \quad t\in T, \quad s\in S \tag{7}$$

Constraint (8) shows inventory balance equation of recycled components at each RC in time period t.

$$\sum_{p\in P}\sum_{m\in M} QRP^{ts}_{rpnm} = \sum_{k\in K}\sum_{l\in L}\sum_{m\in M} \alpha_n \varphi_{ln} QKR^{ts}_{krlm}, \quad r\in R, \quad n\in N, \quad t\in T, \quad s\in S \tag{8}$$

Constraint (9) shows inventory balance equation of disposable components at each RC in time period t.

$$\sum_{w\in W}\sum_{m\in M} QRW^{ts}_{kwnm} = \sum_{k\in K}\sum_{l\in L}\sum_{m\in M} (1-\alpha_n)\varphi_{ln} QKR^{ts}_{krlm}, \quad r\in R, \quad n\in N, \quad t\in T, \quad s\in S \tag{9}$$

3.4.2.2. Capacity constraints. Constraints (10)–(14) are called capacity constraints of the facilities. The left side of (10) gives the total production time of the PC in location p, of all products, during time period t using technology h. The right side is the capacity of the same PC if the same technology is used.

$$\sum_{l\in L} tpl_{lh} QP^{ts}_{phl} \leqslant SP_p ZP_{ph}, \quad p\in P, \quad h\in H, \quad t\in T, \quad s\in S \tag{10}$$

The left side of (11) gives the volume of carryover inventory of the previous period and volume of products shipped from the PCs to each DC. The right side is the storage capacity of the same DC at the same time period.

$$\sum_{l\in L} vl_l IQ^{t-1,s}_{ql} + \sum_{p\in P}\sum_{l\in L}\sum_{m\in M} vl_l QPQ^{ts}_{pqlm} \leqslant SQ_q ZQ_q, IQ^{0,s}_{ql} = 0, \quad q\in Q, \quad t\in T, \quad s\in S \tag{11}$$

Constraint (12) ensures that the volume of EOL products shipped from all markets does not exceed the capacity of CC in location k at time period t.

$$\sum_{c\in C}\sum_{l\in L}\sum_{m\in M} vl_l QCK^{ts}_{cklm} \leqslant SK_k ZK_k, \quad k\in K, \quad t\in T, \quad s\in S \tag{12}$$

The left side of constraint (13) gives the number of components of all types that are processed at the RC in location r in time period t.

$$\sum_{k\in K}\sum_{l\in L}\sum_{n\in N}\sum_{m\in M} trn_n\varphi_{ln}QKR^{ts}_{krlm} \leqslant SR_rZR_r, \qquad r\in R,\quad t\in T,\quad s\in S \tag{13}$$

The left side of constraint (14) gives the volume of all scrapped components at the DD in location w in time period t.

$$\sum_{k\in K}\sum_{n\in N}\sum_{m\in M} vn_nQRW^{ts}_{rwnm} \leqslant SW_wZW_w, \qquad w\in W,\quad t\in T,\quad s\in S \tag{14}$$

Constraint (15) ensures that if location p is used for constructing a PC, then, only one technology is adopted and this will be done at most once.

$$\sum_{t\in T}\sum_{h\in H} ZP^t_{ph} \leqslant 1, \qquad p\in P \tag{15}$$

3.4.2.3. Constraints on the flow of items in and out of a facility. The following constraints (16)–(29) are included to make sure that if a flow takes place at time period t, then the facility must have been constructed at t or prior to it.

$$\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} QPQ^{ts}_{pqlm} \leqslant MM(t)\sum_{h\in H} ZP_{ph}, \qquad p\in P \tag{16}$$

$$\sum_{n\in N}\sum_{s\in S} QE^{ts}_{np} \leqslant MM(t)\sum_{h\in H} ZP_{ph}, \qquad p\in P \tag{17}$$

$$\sum_{h\in H}\sum_{l\in L}\sum_{t\in T}\sum_{s\in S} QP^{ts}_{phl} \leqslant MM(t)\sum_{h\in H} ZP_{ph}, \qquad p\in P \tag{18}$$

$$\sum_{n\in N}\sum_{t\in T}\sum_{s\in S} IP^{ts}_{pn} \leqslant MM(t)\sum_{h\in H} ZP_{ph}, \qquad p\in P \tag{19}$$

$$\sum_{l\in L}\sum_{t\in T}\sum_{s\in S} IQ^{ts}_{ql} \leqslant MM(t)ZQ_q, \qquad q\in Q \tag{20}$$

$$\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} QCK^{ts}_{cklm} \leqslant MM(t)ZK_k, \qquad k\in K \tag{21}$$

$$\sum_{r\in R}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} QRP^{ts}_{rpnm} \leqslant MM(t)\sum_{h\in H} ZP_{ph}, \qquad p\in P \tag{22}$$

$$\sum_{p\in P}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} QPQ^{ts}_{pqlm} \leqslant MM(t)ZQ_q, \qquad q\in Q \tag{23}$$

$$\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} QQC^{ts}_{qclm} \leqslant MM(t)ZQ_q, \qquad q\in Q \tag{24}$$

$$\sum_{r\in R}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} QKR^{ts}_{krlm} \leqslant MM(t)ZK_k, \qquad k\in K \tag{25}$$

$$\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} QKR^{ts}_{krlm} \leqslant MM(t)ZR_r, \qquad r\in R \tag{26}$$

$$\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} QRP^{ts}_{rpnm} \leqslant MM(t)ZR_r, \qquad r\in R \tag{27}$$

$$\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} QRW^{ts}_{rwnm} \leqslant MM(t)ZR_r, \qquad r\in R \tag{28}$$

$$\sum_{r\in R}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} QRW^{ts}_{rwnm} \leqslant MM(t)ZW_w, \qquad w\in W \tag{29}$$

The value of $MM(t)$ should be large enough so that the right side is guaranteed to be less than the left side. We use $MM(t) = \sum_{l\in L}\sum_{c\in C} max_s(D^t_{cls})$.

3.4.2.4. Constraints on the transportation between facilities. Constraints (30)–(39) permit the transportation between a pair of facilities at time t if these facilities are part of the network at t or prior to it.

$$YPQ^{ts}_{pqm} \leqslant \sum_{h \in H} ZP_{ph}, \quad \text{for } p \in P, \quad q \in Q, \quad m \in M, \quad t \in T, \quad s \in S \tag{30}$$

$$YRP^{ts}_{rpm} \leqslant \sum_{h \in H} ZP_{ph}, \quad \text{for } r \in R, \quad p \in P, \quad m \in M, \quad t \in T, \quad s \in S \tag{31}$$

$$YPQ^{ts}_{qpm} \leqslant ZQ_q, \quad p \in P, \quad q \in Q, \quad m \in M, \quad t \in T, \quad s \in S \tag{32}$$

$$YQC^{ts}_{qcm} \leqslant ZQ_q, \quad q \in Q, \quad c \in C, \quad m \in M, \quad t \in T, \quad s \in S \tag{33}$$

$$YCK^{ts}_{ckm} \leqslant ZK_k, \quad c \in C, \quad k \in K, \quad m \in M, \quad t \in T, \quad s \in S \tag{34}$$

$$YKR^{ts}_{krm} \leqslant ZK_k, \quad k \in K, \quad r \in R, \quad m \in M, \quad t \in T, \quad s \in S \tag{35}$$

$$YKR^{ts}_{krm} \leqslant ZR_r, \quad k \in K, \quad r \in R, \quad m \in M, \quad t \in T, \quad s \in S \tag{36}$$

$$YRP^{ts}_{rpm} \leqslant ZR_r, \quad r \in R, \quad p \in P, \quad m \in M, \quad t \in T, \quad s \in S \tag{37}$$

$$YRW^{ts}_{rwm} \leqslant ZR_r, \quad r \in R, \quad w \in W, \quad m \in M, \quad t \in T, \quad s \in S \tag{38}$$

$$YRW^{ts}_{rwm} \leqslant ZW_w, \quad r \in R, \quad w \in W, \quad m \in M, \quad t \in T, \quad s \in S \tag{39}$$

3.4.2.5. Transportation mode capacity constraints. Constraints (40)–(51) ensure that if a specific transportation mode is used then the shipment must be between the minimum and maximum capacity of this mode.

$$\sum_{l \in L} QPQ^{ts}_{pqlm} \geqslant tpq_{pqm} YPQ^{ts}_{pqm} \quad \text{for } p \in P, \quad q \in Q, \quad m \in M, \quad t \in T, \quad s \in S \tag{40}$$

$$\sum_{l \in L} QPQ^{ts}_{pqlm} \leqslant Tpq_{pqm} YPQ^{ts}_{pqm} \quad \text{for } p \in P, \quad q \in Q, \quad m \in M, \quad t \in T, \quad s \in S \tag{41}$$

$$\sum_{l \in L} QQC^{ts}_{qclm} \geqslant tqc_{qcm} YQC^{ts}_{qcm} \quad \text{for } q \in Q, \quad c \in C, \quad m \in M, \quad t \in T, \quad s \in S \tag{42}$$

$$\sum_{l \in L} QQC^{ts}_{qclm} \leqslant Tqc_{qcm} YQC^{ts}_{qcm} \quad \text{for } q \in Q, \quad c \in C, \quad m \in M, \quad t \in T, \quad s \in S \tag{43}$$

$$\sum_{l \in L} QCK^{ts}_{cklm} \geqslant tck_{ckm} YCK^{ts}_{ckm} \quad \text{for } c \in C, \quad k \in K, \quad m \in M, \quad t \in T, \quad s \in S \tag{44}$$

$$\sum_{l \in L} QCK^{ts}_{cklm} \leqslant Tck_{ckm} YCK^{ts}_{ckm} \quad \text{for } c \in C, \quad k \in K, \quad m \in M, \quad t \in T, \quad s \in S \tag{45}$$

$$\sum_{l \in L} QKR^{ts}_{krlm} \geqslant tkr_{krm} YKR^{ts}_{krm} \quad \text{for } k \in K, \quad r \in R, \quad m \in M, \quad t \in T, \quad s \in S \tag{46}$$

$$\sum_{l \in L} QKR^{ts}_{krlm} \leqslant Tkr_{krm} YKR^{ts}_{krm} \quad \text{for } k \in K, \quad r \in R, \quad m \in M, \quad t \in T, \quad s \in S \tag{47}$$

$$\sum_{n \in N} QRP^{ts}_{rpnm} \geqslant trp_{rpm} YRP^{ts}_{rpm} \quad \text{for } r \in R, \quad p \in P, \quad m \in M, \quad t \in T, \quad s \in S \tag{48}$$

$$\sum_{n \in N} QRP^{ts}_{rpnm} \leqslant Trp_{rpm} YRP^{ts}_{rpm} \quad \text{for } r \in R, \quad p \in P, \quad m \in M, \quad t \in T, \quad s \in S \tag{49}$$

$$\sum_{n \in N} QRW^{ts}_{rwnm} \geqslant trw_{rwm} YRW^{ts}_{rwm} \quad \text{for } r \in R, \quad w \in W, \quad m \in M, \quad t \in T, \quad s \in S \tag{50}$$

$$\sum_{n \in N} QRW^{ts}_{rwnm} \leqslant Trw_{rwm} YRW^{ts}_{rwm} \quad \text{for } r \in R, \quad w \in W, \quad m \in M, \quad t \in T, \quad s \in S \tag{51}$$

4. Model extensions under various carbon policies

In this section, we present four extensions of the base model presented above with carbon emission constraints and costs to study the impact of various carbon policies on the CLSC design and planning decisions. These policies are carbon cap policy, carbon tax policy, carbon cap-and-trade policy, and carbon offset policy. Each policy is described below. These extensions were motivated by recent work by Benjaafar et al. (2013) and Palak et al. (2014) on classical economic lot-sizing problem, Jin et al. (2014) on supply chain design and mode choice for major retailers, Marufuzzaman et al. (2014) on design and management of the biodiesel supply chain, Fareeduddin et al. (2015) on CLSC design and planning decisions. These authors explore the impact of the above policies on lot-sizing decisions and supply chain design decisions respectively. This research is a contribution in this direction.

4.1. Model formulation of carbon cap policy

Under this policy, a firm is allowed to emit a limited amount of carbon emissions over the planning horizon. The carbon emissions included are those due to production, storage, and transportation activities. The imposed carbon allowance is referred to as the carbon cap, C^{cap}. Constraint (53) gives the sum of emissions within the facilities, and emissions due to logistic activities. The model to be solved in this case is given by by Eq. (52) where Z is the total cost given by Eq. (1):

$$\text{Minimize } Z_1 = Z \tag{52}$$

Subject to:
Constraints (2)–(51) and

$$\begin{aligned}
&\sum_{p\in P}\sum_{h\in H}\sum_{l\in L}\sum_{t\in T} ep^t_{phl}ZP_{ph} + \sum_{q\in Q}\sum_{l\in L}\sum_{t\in T} eq^t_{ql}ZQ_q + \sum_{k\in K}\sum_{l\in L}\sum_{t\in T} ek^t_{kl}ZK_k + \sum_{r\in R}\sum_{n\in N}\sum_{t\in T} er^t_{rn}ZR_r \\
&+ \sum_{w\in W}\sum_{n\in N}\sum_{t\in T} ew^t_{wn}ZW_w + \sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} epq^t_{qplm}QPQ^{ts}_{pqlm} + \sum_{q\in Q}\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} eqc^t_{qclm}QQC^{ts}_{qclm} \\
&+ \sum_{c\in C}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} eck^t_{cklm}QCK^{ts}_{cklm} + \sum_{k\in K}\sum_{r\in R}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} ekr^t_{krlm}QKR^{ts}_{krlm} \\
&+ \sum_{r\in R}\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T} erp^t_{rpnm}QRP^{ts}_{rpnm} + \sum_{r\in R}\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} erw^t_{rwnm}QRW^{ts}_{rwnm} \\
&\leqslant C^{cap}, \qquad s\in S
\end{aligned} \tag{53}$$

4.2. Model formulation of carbon tax policy

This policy is an alternative to strict carbon cap policy. Under this policy, a financial penalty is incurred per unit of CO_2 emission in supply chain operations. The penalty assumes a linear relationship. The objective function in this case comprises the sum of economic costs given by Eq. (1) and penalty times the total environmental costs, Z_{em}. The model to be solved in this case is given by Eq. (54) where Z is the cost given by Eq. (1).

$$\text{Minimize } Z_2 = Z + \delta Z_{em} \tag{54}$$

Eq. (55) represents the total environmental costs, where

$$\begin{aligned}
Z_{em} = &\sum_{p\in P}\sum_{h\in H}\sum_{l\in L}\sum_{t\in T} ep^t_{phl}ZP_{ph} + \sum_{q\in Q}\sum_{l\in L}\sum_{t\in T} eq^t_{ql}ZQ_q + \sum_{k\in K}\sum_{l\in L}\sum_{t\in T} ek^t_{kl}ZK_k + +\sum_{r\in R}\sum_{n\in N}\sum_{t\in T} er^t_{rn}ZR_r \\
&+ \sum_{w\in W}\sum_{n\in N}\sum_{t\in T} ew^t_{wn}ZW_w + \sum_{s\in S}Pr_s\Bigg[\sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} epq^t_{qplm}QPQ^{ts}_{pqlm} + \sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} epq^t_{qplm}QPQ^{ts}_{pqlm} \\
&+ \sum_{q\in Q}\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} eqc^t_{qclm}QQC^{ts}_{qclm} + \sum_{c\in C}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} eck^t_{cklm}QCK^{ts}_{cklm} \\
&+ \sum_{k\in K}\sum_{r\in R}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} ekr^t_{krlm}QKR^{ts}_{krlm} + \sum_{r\in R}\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T} erp^t_{rpnm}QRP^{ts}_{rpnm} \\
&+ \sum_{r\in R}\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T} erw^t_{rwnm}QRW^{ts}_{rwnm}\Bigg]
\end{aligned} \tag{55}$$

Subject to: Constraints (2)–(51)

4.3. Model formulation of carbon cap-and-trade policy

Under this policy, a firm has a carbon cap as in the previous policy. However, it is allowed to trade its carbon allowance. If a firm emits less than its prescribed carbon cap, then it sells the unused amount of carbon emission. On the other hand, if a firm emits more than its prescribed carbon cap then it purchases additional carbon emission credit in order to maintain its supply chain activities. In this model, e^+_{ts} and e^-_{ts} are two new variables representing amount of bought and sold carbon credit in time period t and scenario s and the objective function becomes Z_3 as given by Eq. (56).

$$Minimize\ Z_3 = Z + \sum_{t\in T}\sum_{s\in S} Pr_s(p^+e^+_{ts} - p^-e^-_{ts}) \tag{56}$$

Subject to:
Constraints (2)–(51) and constraint (57), which is modification of constraint (53);

$$\begin{aligned}&\sum_{p\in P}\sum_{h\in H}\sum_{l\in L}\sum_{t\in T} ep^t_{phl}ZP_{ph} + \sum_{q\in Q}\sum_{l\in L}\sum_{t\in T} eq^t_{ql}ZQ_q + \sum_{k\in K}\sum_{l\in L}\sum_{t\in T} ek^t_{kl}ZK_k + \sum_{r\in R}\sum_{n\in N}\sum_{t\in T} er^t_{rn}ZR_r + \sum_{w\in W}\sum_{n\in N}\sum_{t\in T} ew^t_{wn}ZW_w\\ &+ \sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} epq^t_{qplm}QPQ^{ts}_{pqlm} + \sum_{q\in Q}\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} eqc^t_{qclm}QQC^{ts}_{qclm} + \sum_{c\in C}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} eck^t_{cklm}QCK^{ts}_{cklm}\\ &+ \sum_{k\in K}\sum_{r\in R}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} ekr^t_{krlm}QKR^{ts}_{krlm} + \sum_{r\in R}\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T} erp^t_{rpnm}QRP^{ts}_{rpnm} + \sum_{r\in R}\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T} erw^t_{rwnm}QRW^{ts}_{rwnm}\\ &+ \sum_{t\in T} e^-_{ts} \leqslant C^{cap} + \sum_{t\in T} e^+_{ts}, \qquad s\in S\end{aligned} \tag{57}$$

4.4. Model formulation of carbon offset policy

This policy is similar to the carbon cap-and-trade policy with one exception, the firm cannot sell unused carbon credit. A firm, under this policy, can buy carbon credit. In other words, a firm cannot make additional profit by selling unused carbon credit. Thus, there is no motivation for a firm to emit less carbon than the assigned carbon cap.

Let, p^o denotes the price per unit offset and e^+_{ts} denotes the amount of carbon offset purchases by the firm in time period t and scenario s (in units of carbon emissions). The model formulation becomes Eq. (58);

$$Minimize\ Z_4 = Z + p^o\sum_{t\in T}\sum_{s\in S} Pr_s e^+_{ts} \tag{58}$$

Subject to:
Constraints (2)–(51) and (59)

$$\begin{aligned}&\sum_{p\in P}\sum_{h\in H}\sum_{l\in L}\sum_{t\in T} ep^t_{phl}ZP_{ph} + \sum_{q\in Q}\sum_{l\in L}\sum_{t\in T} eq^t_{ql}ZQ_q + \sum_{k\in K}\sum_{l\in L}\sum_{t\in T} ek^t_{kl}ZK_k + \sum_{r\in R}\sum_{n\in N}\sum_{t\in T} er^t_{rn}ZR_r + \sum_{w\in W}\sum_{n\in N}\sum_{t\in T} ew^t_{wn}ZW_w\\ &+ \sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} epq^t_{qplm}QPQ^{ts}_{pqlm} + \sum_{q\in Q}\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} eqc^t_{qclm}QQC^{ts}_{qclm} + \sum_{c\in C}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} eck^t_{cklm}QCK^{ts}_{cklm}\\ &+ \sum_{k\in K}\sum_{r\in R}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} ekr^t_{krlm}QKR^{ts}_{krlm} + \sum_{r\in R}\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T} erp^t_{rpnm}QRP^{ts}_{rpnm} + \sum_{r\in R}\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S} erw^t_{rwnm}QRW^{ts}_{rwnm}\\ &\leqslant C^{cap} + \sum_{t\in T} e^+_{ts}, \qquad s\in S\end{aligned} \tag{59}$$

5. Robust counterpart mathematical model

To develop the robust counterpart of the proposed carbon footprint based CLSC network model, carbon emissions due to facilities as well as due to transportation are considered as uncertain parameters. Each of these uncertain parameters is assumed to vary in a specified closed bounded box (Ben-Tal et al., 2009; Pishvaee et al., 2011). The general form of this box as follows:

$$u_{Box} = \{\xi \in \Re^n : |\xi_t - \overline{\xi_t}| \leqslant \rho G_t, t = 1, \ldots n\}, \tag{60}$$

where $\overline{\xi_t}$ is the nominal value of ξ_t as tth parameter of vector ξ (n-dimentional vector) and the positive numbers G_t represent uncertainty scale and $\rho > 0$ is the uncertainty level. A particular case of interest is $G_t = \overline{\xi_t}$, which corresponds to a simple case where the box contains ξ_t whose relative deviation from the nominal data is of size up to ρ. Some researchers studied robust optimization in details (Ben-Tal and Nemirovski, 1999; Ben-Tal et al., 2009; Pishvaee et al., 2011).

5.1. Model formulation of carbon cap policy (M1) under uncertainty

The model formulation of carbon cap policy is presented in Section 4.1. In this section, we consider robust counterpart of the proposed MILP formulation by considering bounded box set of uncertain parameters (carbon emissions). The robust counterpart of the model in Section 4.1 with box sets is equivalent to the following MILP problem.

$$Minimize\ Z_1 = Z \tag{61}$$

Subject to

$$\begin{aligned}
&\sum_{p\in P}\sum_{h\in H}\sum_{l\in L}\sum_{t\in T}\left(\overline{ep}^t_{phl}ZP_{ph}+\eta^P_{phlt}\right)+\sum_{q\in Q}\sum_{l\in L}\sum_{t\in T}\left(\overline{eq}^t_{ql}ZQ_q+\eta^Q_{klt}\right)+\sum_{k\in K}\sum_{l\in L}\sum_{t\in T}\left(\overline{ek}^t_{kl}ZK_k+\eta^K_{klt}\right)\\
&+\sum_{r\in R}\sum_{n\in N}\sum_{t\in T}\left(\overline{er}^t_{rn}ZR_r+\eta^R_{rnt}\right)+\sum_{w\in W}\sum_{n\in N}\sum_{t\in T}\left(\overline{ew}^t_{wn}ZW_w+\eta^W_{wnt}\right)\\
&+\sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{epq}^t_{pqlm}QPQ^{ts}_{pqlm}+\eta^{PQ}_{pqlmt}\right)+\sum_{q\in Q}\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{eqc}^t_{qclm}QQC^{ts}_{qclm}+\eta^{QC}_{qclmt}\right)\\
&+\sum_{c\in C}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{eck}^t_{cklm}QCK^{ts}_{cklm}+\eta^{CK}_{cklmt}\right)+\sum_{k\in K}\sum_{r\in R}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{ekr}^t_{krlm}QKR^{ts}_{krlm}+\eta^{KR}_{krlmt}\right)\\
&+\sum_{r\in R}\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\left(\overline{erp}^t_{rpnm}QRP^{ts}_{rpnm}+\eta^{RP}_{rpnmt}\right)+\sum_{r\in R}\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S}\left(\overline{erw}^t_{rwnm}QRW^{ts}_{rwnm}+\eta^{RW}_{rwnmt}\right)\\
&\leqslant C^{cap},\qquad s\in S
\end{aligned}\tag{62}$$

$$\rho_P G^P_{phlt}\ ZP_{ph}\leqslant \eta^P_{phlt},\qquad p\in P,\quad h\in H,\quad l\in L,\quad t\in T \tag{63}$$

$$\rho_P G^P_{phlt}\ ZP_{ph}\geqslant -\eta^P_{phlt},\qquad p\in P,\quad h\in H,\quad l\in L,\quad t\in T \tag{64}$$

$$\rho_Q G^Q_{qlt}\ ZQ_q\leqslant \eta^Q_{qlt},\qquad q\in Q,\quad l\in L,\quad t\in T \tag{65}$$

$$\rho_Q G^Q_{qlt}\ ZQ_q\geqslant -\eta^Q_{qlt},\qquad q\in Q,\quad l\in L,\quad t\in T \tag{66}$$

$$\rho_K G^K_{klt}\ ZK_k\leqslant \eta^K_{klt},\qquad k\in K,\quad l\in L,\quad t\in T \tag{67}$$

$$\rho_K G^K_{klt}\ ZK_k\geqslant -\eta^K_{klt},\qquad k\in K,\quad l\in L,\quad t\in T \tag{68}$$

$$\rho_R G^R_{rnt}\ ZR_r\leqslant \eta^R_{rnt},\qquad r\in R,\quad n\in N,\quad t\in T \tag{69}$$

$$\rho_R G^R_{rnt}\ ZR_r\geqslant -\eta^R_{rnt},\qquad r\in R,\quad n\in N,\quad t\in T \tag{70}$$

$$\rho_W G^W_{wnt}\ ZW_w\leqslant \eta^W_{wnt},\qquad w\in W, n\in N, t\in T \tag{71}$$

$$\rho_W G^W_{wnt}\ ZW_w\geqslant -\eta^W_{wnt},\qquad w\in W,\quad n\in N,\quad t\in T \tag{72}$$

$$\rho_{PQ} G^{PQ}_{pqlmt}\ QPQ^{ts}_{pqlm}\leqslant \eta^{PQ}_{pqlmt},\qquad p\in P,\quad q\in Q,\quad l\in L,\quad m\in M,\quad t\in T \tag{73}$$

$$\rho_{PQ} G^{PQ}_{pqlmt}\ QPQ^{ts}_{pqlm}\geqslant -\eta^{PQ}_{pqlmt},\qquad p\in P,\quad q\in Q,\quad l\in L,\quad m\in M,\quad t\in T \tag{74}$$

$$\rho_{QC} G^{QC}_{qclmt}\ QQC^{ts}_{qclm}\leqslant \eta^{QC}_{qclmt},\qquad q\in Q,\quad c\in C,\quad l\in L,\quad m\in M,\quad t\in T \tag{75}$$

$$\rho_{QC} G^{QC}_{qclmt}\ QQC^{ts}_{qclm}\geqslant -\eta^{QC}_{qclmt},\qquad q\in Q,\quad c\in C,\quad l\in L,\quad m\in M,\quad t\in T \tag{76}$$

$$\rho_{CK} G^{CK}_{cklmt}\ QCK^{ts}_{cklm}\leqslant \eta^{CK}_{cklmt},\qquad c\in C,\quad k\in K,\quad l\in L,\quad m\in M,\quad t\in T \tag{77}$$

$$\rho_{CK} G^{CK}_{cklmt}\ QCK^{ts}_{cklm}\geqslant -\eta^{CK}_{cklmt},\qquad c\in C,\quad k\in K,\quad l\in L,\quad m\in M,\quad t\in T \tag{78}$$

$$\rho_{KR} G^{KR}_{krlmt}\ QKR^{ts}_{krlm}\leqslant \eta^{KR}_{krlmt},\qquad k\in K,\quad r\in R,\quad l\in L,\quad m\in M,\quad t\in T \tag{79}$$

$$\rho_{KR} G^{KR}_{krlmt}\ QKR^{ts}_{krlm} \geqslant -\eta^{KR}_{krlmt}, \quad k \in K, \quad r \in R, \quad l \in L, \quad m \in M, \quad t \in T \tag{80}$$

$$\rho_{RP} G^{RP}_{rpnmt}\ QRP^{ts}_{rpnm} \leqslant \eta^{RP}_{rpnmt}, \quad r \in R, \quad p \in P, \quad n \in N, \quad m \in M, \quad t \in T \tag{81}$$

$$\rho_P \rho_{RP} G^{RP}_{rpnmt}\ QRP^{ts}_{rpnm} \geqslant -\eta^{RP}_{rpnmt}, \quad r \in R, \quad p \in P, \quad n \in N, \quad m \in M, \quad t \in T \tag{82}$$

$$\rho_{RW} G^{RW}_{rwnmt}\ QRW^{ts}_{rwnm} \leqslant \eta^{RW}_{rwnmt}, \quad r \in R, \quad w \in W, \quad n \in N, \quad m \in M, \quad t \in T \tag{83}$$

$$\rho_{RW} G^{RW}_{rwnmt}\ QRW^{ts}_{rwnm} \geqslant -\eta^{RW}_{rwnmt}, \quad r \in R, \quad w \in W, \quad n \in N, \quad m \in M, \quad t \in T \tag{84}$$

where emission parameter $\overline{ep}^t_{phl}$ is nominal value of ep^t_{phl}, G^P_{phlt} represents uncertainty scale and ρ_P is the uncertainty level. The same definition applies to the rest of the parameters. Also, constraints (64), (66), (68) etc are included in the model formulation for the sake of its completion.

5.2. Model formulation of carbon tax policy (M2) under uncertainty

The model formulation of carbon tax policy has been presented in Section 4.2. Its robust counterpart with box sets is equivalent to the following MILP model;

$$Minimize\ Z_2 = Z + \delta Z_{em} \tag{85}$$

where Z is the objective function of the base model which is given by the Eq. (1) and Constraint (86) represents robust counterpart of Constraint (54);

$$\begin{aligned}
&\sum_{p\in P}\sum_{h\in H}\sum_{l\in L}\sum_{t\in T}\left(\overline{ep}^t_{phl} ZP_{ph} + \eta^P_{phlt}\right) + \sum_{q\in Q}\sum_{l\in L}\sum_{t\in T}\left(\overline{eq}^t_{ql} ZQ_q + \eta^Q_{klt}\right) + \sum_{k\in K}\sum_{l\in L}\sum_{t\in T}\left(\overline{ek}^t_{kl} ZK_k + \eta^K_{klt}\right)\\
&\quad + \sum_{r\in R}\sum_{n\in N}\sum_{t\in T}\left(\overline{er}^t_{rn} ZR_r + \eta^R_{rnt}\right) + \sum_{w\in W}\sum_{n\in N}\sum_{t\in T}\left(\overline{ew}^t_{wn} ZW_w + \eta^W_{wnt}\right)\\
&\quad + \sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{epq}^t_{pqlm} QPQ^{ts}_{pqlm} + \eta^{PQ}_{pqlmt}\right) + \sum_{q\in Q}\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{eqc}^t_{qclm} QQC^{ts}_{qclm} + \eta^{QC}_{qclmt}\right)\\
&\quad + \sum_{c\in C}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{eck}^t_{cklm} QCK^{ts}_{cklm} + \eta^{CK}_{cklmt}\right) + \sum_{k\in K}\sum_{r\in R}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{ekr}^t_{krlm} QKR^{ts}_{krlm} + \eta^{KR}_{krlmt}\right)\\
&\quad + \sum_{r\in R}\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\left(\overline{erp}^t_{rpnm} QRP^{ts}_{rpnm} + \eta^{RP}_{rpnmt}\right) + \sum_{r\in R}\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\sum_{s\in S}\left(\overline{erw}^t_{rwnm} QRW^{ts}_{rwnm} + \eta^{RW}_{rwnmt}\right) \leqslant Z_{em}
\end{aligned} \tag{86}$$

Constraints (2)–(51) and Constraints (63)–(84).

5.3. Model formulation of carbon cap-and-trade policy (M3) under uncertainty

The model formulation of the carbon cap-and-trade policy is presented in Section 4.3. Thus, its robust counterpart with box sets is equivalent to the following MILP model.

$$Minimize\ Z_3 = Z + \sum_{t\in T}\sum_{s\in S} Pr_s (p^+_t e^+_{ts} - p^-_t e^-_{ts}) \tag{87}$$

where Z is the objective function of the base model given by Eq. (1)

Subject to Constraints (2)–(51), Constraints (63)–(84), and Constraint (88);

$$\begin{aligned}
&\sum_{p\in P}\sum_{h\in H}\sum_{l\in L}\sum_{t\in T}\left(\overline{ep}^t_{phl} ZP_{ph} + \eta^P_{phlt}\right) + \sum_{q\in Q}\sum_{l\in L}\sum_{t\in T}\left(\overline{eq}^t_{ql} ZQ_q + \eta^Q_{klt}\right) + \sum_{k\in K}\sum_{l\in L}\sum_{t\in T}\left(\overline{ek}^t_{kl} ZK_k + \eta^K_{klt}\right)\\
&\quad + \sum_{r\in R}\sum_{n\in N}\sum_{t\in T}\left(\overline{er}^t_{rn} ZR_r + \eta^R_{rnt}\right) + \sum_{w\in W}\sum_{n\in N}\sum_{t\in T}\left(\overline{ew}^t_{wn} ZW_w + \eta^W_{wnt}\right) + \sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{epq}^t_{pqlm} QPQ^{ts}_{pqlm} + \eta^{PQ}_{pqlmt}\right)\\
&\quad + \sum_{q\in Q}\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{eqc}^t_{qclm} QQC^{ts}_{qclm} + \eta^{QC}_{qclmt}\right) + \sum_{c\in C}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{eck}^t_{cklm} QCK^{ts}_{cklm} + \eta^{CK}_{cklmt}\right)\\
&\quad + \sum_{k\in K}\sum_{r\in R}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{ekr}^t_{krlm} QKR^{ts}_{krlm} + \eta^{KR}_{krlmt}\right) + \sum_{r\in R}\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\left(\overline{erp}^t_{rpnm} QRP^{ts}_{rpnm} + \eta^{RP}_{rpnmt}\right)\\
&\quad + \sum_{r\in R}\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\left(\overline{erw}^t_{rwnm} QRW^{ts}_{rwnm} + \eta^{RW}_{rwnmt}\right) + \sum_{t\in T} e^-_{ts} \leqslant C^{cap} + \sum_{t\in T} e^+_{ts}, \quad s \in S
\end{aligned} \tag{88}$$

Constraints (2)–(51) and Constraints (63)–(84)

5.4. Model formulation of carbon offset policy (M4) under uncertainty

The model formulation of the carbon offset policy is presented in Section 4.4. Thus, its robust counterpart with box sets is equivalent to the following MILP model.

$$\text{Minimize } Z_3 = Z + p^o \sum_{t\in T}\sum_{s\in S} Pr_s e^+_{ts} \tag{89}$$

where Z is the objective function of the base model given by Eq. (1)

Subject to Constraints (2)–(51), Constraints (63)–(84), and Constraint (90);

$$\begin{aligned}
&\sum_{p\in P}\sum_{h\in H}\sum_{l\in L}\sum_{t\in T}\left(\overline{ep}^t_{phl}ZP_{ph}+\eta^P_{phlt}\right)+\sum_{q\in Q}\sum_{l\in L}\sum_{t\in T}\left(\overline{eq}^t_{ql}ZQ_q+\eta^Q_{klt}\right)+\sum_{k\in K}\sum_{l\in L}\sum_{t\in T}\left(\overline{ek}^t_{kl}ZK_k+\eta^K_{klt}\right)\\
&+\sum_{r\in R}\sum_{n\in N}\sum_{t\in T}\left(\overline{er}^t_{rn}ZR_r+\eta^R_{rnt}\right)+\sum_{w\in W}\sum_{n\in N}\sum_{t\in T}\left(\overline{ew}^t_{wn}ZW_w+\eta^W_{wnt}\right)\\
&+\sum_{p\in P}\sum_{q\in Q}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{epq}^t_{pqlm}QPQ^{ts}_{pqlm}+\eta^{PQ}_{pqlmt}\right)+\sum_{q\in Q}\sum_{c\in C}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{eqc}^t_{qclm}QQC^{ts}_{qclm}+\eta^{QC}_{qclmt}\right)\\
&+\sum_{c\in C}\sum_{k\in K}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{eck}^t_{cklm}QCK^{ts}_{cklm}+\eta^{CK}_{cklmt}\right)+\sum_{k\in K}\sum_{r\in R}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T}\left(\overline{ekr}^t_{krlm}QKR^{ts}_{krlm}+\eta^{KR}_{krlmt}\right)\\
&+\sum_{r\in R}\sum_{p\in P}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\left(\overline{erp}^t_{rpnm}QRP^{ts}_{rpnm}+\eta^{RP}_{rpnmt}\right)+\sum_{r\in R}\sum_{w\in W}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\left(\overline{erw}^t_{rwnm}QRW^{ts}_{rwnm}+\eta^{RW}_{rwnmt}\right)\\
&\leqslant C^{cap}+\sum_{t\in T}e^+_{ts},\qquad s\in S
\end{aligned} \tag{90}$$

For convenience, Table 2 summarizes all five models with their respective objective functions and constraints.

6. Numerical results

This section discusses important observations related to design and planning of CLSC, SC total cost, and carbon emissions related decisions while considering various carbon policies. It is assumed that fuel efficiency of trucks remains the same while varying policy parameters such as carbon cap, carbon tax rate, and carbon market prices.

To investigate the impact of carbon emission policies on the design of a multi-period multi-product CLSC under uncertainty, a numerical example is used. Specifically, we analyze the impact of policy parameters on CLSC strategic design, expected total cost, and total carbon emission.

We consider a hypothetical firm that manufactures a wide range of products are used in the automotive industry. The firm decided to convert the existing supply chain to a CLSC by collecting and recycling activities of EOL products due to high volume of damaged and returned products. The firm is now considering carbon regulatory policies in order to investigate the effect of these policies on their production and distribution strategies.

The firm has two PCs ($P = 2$), that produce four different types of products ($L = 4$), using two technology options at each PC ($H = 2$). Assuming that technology one has less investment cost but produce high carbon emissions, technology two has more investment cost but produce less carbon emissions. Selection of technologies has trade-off between investment cost and amount of emissions. The production is used to satisfy customers that are located at five locations ($C = 5$) through DCs ($Q = 3$). In the reverse chain, returned products are collected at five CCs ($K = 5$). After inspection carried out at CCs, recyclable products and scrap products are separated. Scrapped products are sent to two disposal centers ($W = 2$) and recyclable products are sent to three RCs ($R = 3$). Finally, recycled components are sent to PCs for manufacturing new products. Each product consists of six components ($N = 6$). For logistic activities between the facilities, three alternative transportation modes are available ($M = 3$). It is well known that different transportation modes have a significant difference in carbon emission per ton-mile (Wang et al., 2011). For example, rail and water transport have much higher energy efficiency than air and road transport. In this work only road transportation modes are available for logistic activities and each mode has specific size,

Table 2
Summary of the five models under various carbon policies.

Model name	Policy	Objective function	Constraints
Base Model	No carbon policy	(1)	(2)–(51)
Carbon Cap Model (M1)	Inflexible carbon cap policy	(61)	(2)–(51) and (62)–(84)
Carbon Tax Model (M2)	Carbon tax policy	(85)	(2)–(51), (63)–(84) and (86)
Carbon cap-and-trade Model (M3)	Carbon cap-and-trade policy	(87)	(2)–(51), (63)–(84) and (88)
Carbon Offset Model (M4)	Carbon offset policy	(89)	(2)–(51), (63)–(84) and (90)

Table 3
Values of model parameters.

Values of various model parameters

Parameter	Values
fp_{ph}	Uniform (30000, 60000)
fq_q	Uniform (10000, 12000)
fk_k	Uniform (2500, 5000)
fr_r	Uniform (20000, 30000)
fw_w	Uniform (4000, 5000)
SP_p	Uniform (40000, 48000)
SQ_q	Uniform (50000, 60000)
SK_k	Uniform (18000, 24000)
SR_r	Uniform (400000, 600000)
SW_w	Uniform (500000, 600000)
cpo^t_{np}	Uniform (11, 13)
cmp^t_{phl}	Uniform (21, 24)
chp^t_{pn}	Uniform (2, 4)
chq^t_{ql}	Uniform (2, 5)
ccc^t_{kl}	Uniform (6, 9)
crc^t_{rn}	Uniform (7, 9)
cdw^t_{wn}	Uniform (2, 4)
tpl_{lh}	Uniform (8, 12)
trn_n	Uniform (1, 5)
vl_l	Uniform (12, 16)
vn_n	Uniform (1, 5)
φ_{ln}	6
α_n	60%
M	Large scalar

Values of transportation modes capacities

Mode Type	Min. Capacity	Max. Capacity
Heavy duty truck	100	14000
Mid-size truck	100	10000
Light truck	100	5000

The cost and carbon emissions of transportation modes

Mode	Cost ($ / ton-km)	CO_2 emission factor (kg/ton-km)
Heavy duty truck	0.125	0.297
Mid-size truck	0.118	0.0252
Light truck	0.110	0.048

Parameter values of carbon emissions by various facilities

Parameter	Values
ep^t_{ph1l}	Uniform (2.1, 2.3)
ep^t_{ph2l}	Uniform (1.2, 1.4)
eq^t_{ql}	Uniform (0.6, 0.9)
ek^t_{kl}	Uniform (0.2, 0.4)
er^t_{rn}	Uniform (0.7, 1.1)
ew^t_{wn}	Uniform (0.5, 0.8)

carbon emission and cost of transportation. We consider a planning horizon of three periods ($T = 3$). The data used in the example are randomly generated from the uniform distribution. Table 3 shows the parameters of the distribution for all model parameters, namely, fixed costs for opening and operating facilities, capacities of facilities, unit costs, transportation mode capacities, carbon emission by various facilities, transportation emission and costs, and parameter values related to robust uncertainty. Also we consider three uncertainty levels for carbon emission related parameters ($\rho = 0.2, 0.5, 0.8$) for analysis purpose.

All the five models as summarized in Table 2 were solved using GAMS 24.5.6 and ILOG CPLEX 12.6 MIP solver on a laptop with Intel core i5 with 2.40 GHz processor and 4.0 GB of RAM.

6.1. CLSC network design

This section presents strategic design of CLSC network with respect to (i) no carbon policy and (ii) various carbon policies.

The optimal CLSC network structure under no carbon policy (without consideration of carbon emissions) is as follows: Two PCs (p_1, p_2) with technology option one, i.e., (h_1) and two DCs (q_1, q_3) are opened in the forward direction. In the reverse direction, three CCs (k_1, k_2, k_4), three RCs (r_1, r_2, r_3) and two disposal centers (w_1, w_2) are opened. The objective value (total cost) is $5396994.168. The solution time is 471.61 seconds. The model statistics are 2,256,424 non-zero elements, 800,331 single equations, 98,765 single variables, and 17,756 discrete variables. Prior to performing CLSC network design and sensitivity analysis for each carbon policy, we need to find the minimum and maximum carbon required by SC activities. To find the minimum carbon emission, we minimize the expression for carbon emission subject to constraints (1)–(51) of the base model. The maximum carbon emission is found by solving the base model and computing the corresponding carbon emission. We found that SC requires at least 50 tons of carbon for operating its activities and requires 52.2 tons in order to satisfy customer's demand and maintain SC operations Therefore, we consider strict carbon cap that ranges between 50 and 55 tons for the three planning periods.

Facility selection decisions of the CLSC network under different policies vary with respect to changes in supply chain total cost and carbon emissions as shown in Table 4 where the value 1 represents that a facility is opened and 0, otherwise.

Table 4(a) presents the optimal CLSC network for different values of carbon caps under carbon cap policy. From Table 4(a), as carbon cap increases new facilities are opening. The new facilities result in less operational cost at the expense of increasing carbon emission. Once the carbon cap reaches 52.2 tons, the total cost reaches its lowest value. Higher carbon caps exceed the maximum emissions of the firm hence do not result in any further reduction in the cost. The SC network structure does not change in this case.

Table 4
CLSC network design under different carbon policies.

Facility type	Carbon cap in tons		
	50	51	⩾52
(a) Carbon cap policy			
PCs	[1 1]	[1 1]	[1 1]
DCs	[1 0 0]	[1 0 0]	[1 0 1]
CCs	[1 1 0 1 0]	[1 1 0 1 0]	[1 1 1 1 0]
RCs	[1 0 0]	[1 0 1]	[1 1 1]
DDs	[1 0]	[1 1]	[1 1]

Facility type	Carbon tax rate, δ $/ton					
	0	5	10	15	20	⩾25
(b) Carbon tax policy						
PCs	[1 1]	[1 1]	[1 1]	[1 1]	[1 1]	[1 1]
DCs	[1 0 1]	[1 0 1]	[1 0 1]	[1 0 1]	[1 0 1]	[1 0 1]
CCs	[1 1 0 1 0]	[1 1 0 1 0]	[1 1 0 1 0]	[1 1 0 1 0]	[1 1 0 1 0]	[1 1 0 1 0]
RCs	[1 1 1]	[1 0 1]	[1 0 0]	[1 0 0]	[1 0 0]	[1 0 0]
DDs	[1 1]	[1 1]	[1 1]	[1 0]	[1 0]	[1 0]

Facility type	Carbon cap ⩾ 30 tons		
	p^-, p^+ = 5 $/kg	p^-, p^+ = 10 $/kg	p^-, p^+ = 15 $/kg
(c) Carbon cap-and-trade policy			
PCs	[1 1]	[1 1]	[1 1]
DCs	[1 0 1]	[1 0 1]	[1 0 0]
CCs	[1 1 0 1 0]	[1 1 0 1 0]	[1 1 0 1 0]
RCs	[1 1 1]	[1 0 1]	[1 0 1]
DDs	[1 1]	[1 0]	[1 0]

Facility type	p^o = 5 $/kg & carbon cap		p^o = 10, 15 $/kg & carbon cap		
	30–50	⩾52	30–40	50	⩾52
(d) Carbon offset policy					
PCs	[1 1]	[1 1]	[1 1]	[1 1]	[1 1]
DCs	[1 0 1]	[1 0 1]	[1 0 1]	[1 0 1]	[1 0 1]
CCs	[1 1 0 1 0]	[1 1 0 1 0]	[1 1 0 1 0]	[1 1 0 1 0]	[1 1 0 1 0]
RCs	[1 0 1]	[1 1 1]	[1 0 1]	[1 1 1]	[1 1 1]
DDs	[1 1]	[1 1]	[1 1]	[1 1]	[1 1]

PCs = production centers; DCs = distribution centers; CCs = collection centers; RCs = recycling centers; DDs = disposal centers; 1 = a facility is opened and 0, otherwise.

Table 4(b) shows the optimal CLSC network structure for different values of carbon tax rates under carbon tax policy. When there is no carbon tax, the CLSC network structure is the same as the base model network structure. As carbon tax rate increases, the SC uses one less RC and on less DD. This reduction is needed to cut the cost of carbon tax, but results in higher costs, see Figs. 5 and 6.

Optimal CLSC network structure at different values of carbon caps and carbon market prices under carbon cap-and-trade policy is presented in Table 4(c). In this policy, a firm buys and sells carbon credit in order to minimize cost. From Table 4(c), at a particular carbon market price the optimal CLSC network structure is the same for all carbon caps. At higher level of carbon market prices, some of the opened facilities are to be closed. The reason for this is that at higher carbon market prices, the firm has enough incentive to sell carbon credit and make profit at the expense of other costs.

The optimal CLSC network structure for different carbon caps and offset prices under carbon offset policy is presented in Table 4(d). This policy is similar to the carbon cap policy, in addition, the policy allows for buying additional carbon credit. At a particular carbon offset price, as carbon cap increases additional facilities are to be opened in order to minimize the total cost and reduce the carbon emissions. When the carbon cap reaches 52.2 tons, the total cost becomes the lowest irrespective of carbon offset prices. At this cap, the optimal CLSCN design structure is the same as the base model regardless of increase in carbon cap and/or offset price.

6.2. Results of carbon-cap policy

Figs. 3 and 4 depict the results of both deterministic solution and mixed model (a model with two different types of uncertainties) solution respectively. It shows the impact of varying carbon cap on the total cost as well as carbon emission. Fig. 3 has two lines; (i) the line on primary axis represents the total cost versus carbon cap, (ii) the line on the secondary axis

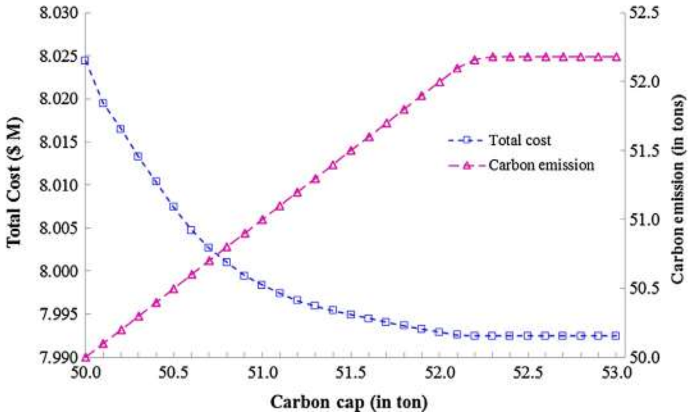

Fig. 3. Carbon cap policy (deterministic) – carbon cap vs total cost and carbon emission.

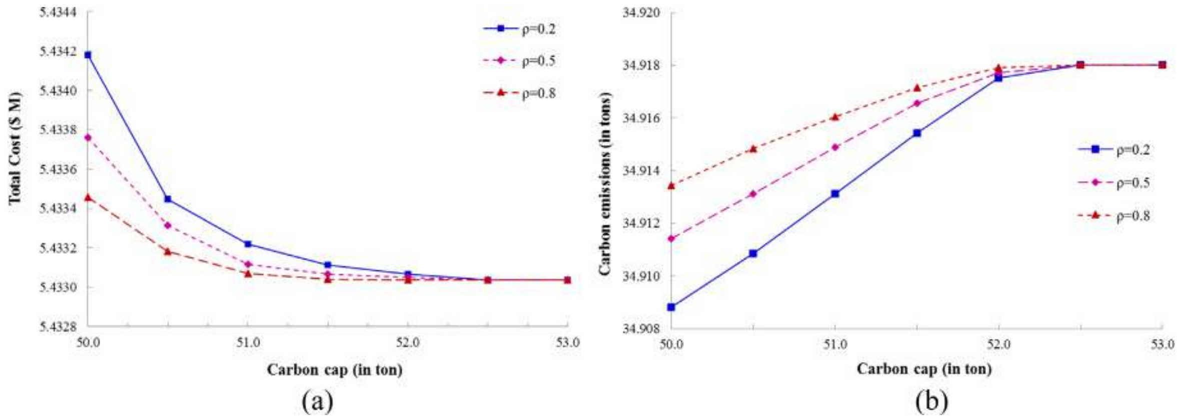

Fig. 4. Carbon cap policy (mixed model): (a) total cost vs carbon cap, (b) carbon emission vs carbon cap.

represents carbon emission versus carbon cap. Similarly, Fig. 4 has two figures in which Fig. 4(a) represents total cost versus carbon cap at different uncertainty levels of the box uncertainty set and Fig. 4(b) represents total carbon emission versus carbon cap at different uncertainty levels of the box uncertainty set.

Fig. 3 indicates that while increasing the carbon cap, the total cost decreases but carbon emissions increase. The shape of the carbon emission curve indicates that carbon cap is linearly related to the total emissions i.e., carbon emissions can be reduced significantly with slight increase in the total cost. In the model (M1), the carbon cap constraint (62) is a tight constraint hence it directly impacts on the total carbon emissions. By reducing the carbon cap from 53 tons to 50 tons, a reduction of carbon emissions of 6% results in a total cost increase of 0.2% only. This indicates that a slight increase in transportation and inventory costs play a significant role in reducing emissions. As the carbon cap increases, the emission curve becomes almost linear. This result suggests that supply chain operations are more flexible to use what is allowed by the cap, once the cap reaches 52.2 tons, the curve becomes constant and the firm reaches the minimum total cost. Further increase in carbon cap value will not effect the total cost.

Similar to the explanation provided in Fig. 3 about the behavior of total cost and carbon emissions with respect to carbon cap, Fig. 4 depicts the same behavior in the case of mixed uncertainty. Moreover, we plotted additional lines at different uncertainty levels to study the impact of the uncertainty level on total cost and carbon emission. As can seen in Fig. 4(a) and 4(b) that lines have the same trend the uncertainty level effects both total cost and carbon emission. In Fig. 4(a), as the uncertainty level increases the total cost decreases, carbon emission increases, which implies that the robust strategy has a better performance on higher uncertainty levels versus the deterministic one.

6.3. Results of carbon tax policy

Figs. 5 and 6 show the effect of carbon tax rate on the total cost and carbon emissions under the carbon tax policy of both deterministic solution and mixed model solution with different uncertainty levels respectively.

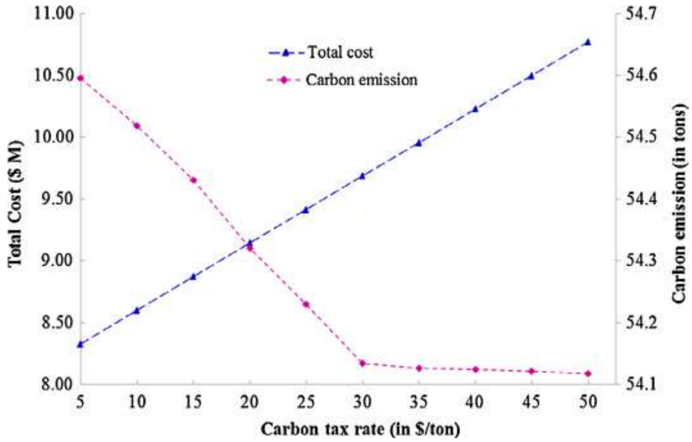

Fig. 5. Carbon tax policy (deterministic solution) – total cost and carbon emissions vs carbon tax rate.

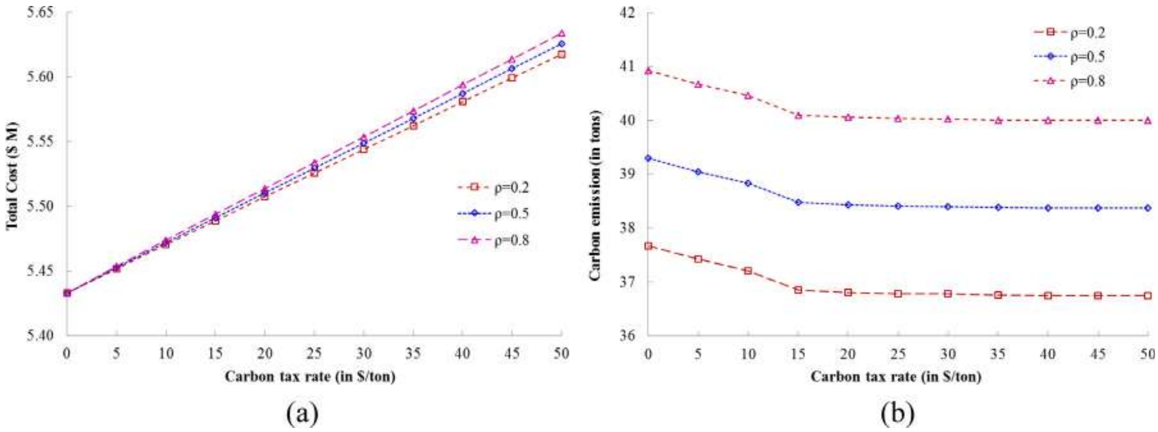

Fig. 6. Carbon tax policy (mixed model solution): (a) total cost vs carbon tax rate, (b) carbon emission vs carbon tax rate.

In Fig. 5, the increase in carbon tax rate results in an increase in SC total cost. For the problem on hand, total cost increases linearly with carbon tax rate. On the other hand, carbon emissions decrease significantly as carbon tax rate increases. The emission curve eventually becomes almost flat at carbon tax rate 15 $/ton. This indicates that the carbon footprint of the firm has reached its minimum.

Fig. 6(a) and (b) show the effect of uncertainty on the total cost and carbon emissions of mixed model respectively. As the uncertainty level increases the total cost increases but carbon emission decreases which is similar to the trend in Fig. 5. This implies that uncertainty is not immune to the total cost and carbon emissions.

6.4. Results of carbon cap-and-trade policy

Fig. 7(a) and (b) shows the relationship between carbon cap and the total cost of both deterministic solution and mixed model solution respectively. Each curve in Fig. 7(a), represents a different value of carbon price. For a fixed carbon cost, an increase in the carbon caps allows the firm to buy less carbon hence the total cost drops. As the carbon cap increases further, the firm starts to sell carbon and hence the total cost keeps decreasing. Next, we investigate the effect of the carbon price on the total cost. For carbon cap less than 51 tons, the firm is a net buyer of carbon; hence, the total cost is higher for high carbon price. At a carbon cap of 51 tons, the firm is not trading carbon, hence the total cost at all carbon prices is identical. For carbon caps greater than 52 tons, the firm is actually selling carbon. In this case, higher carbon selling prices result in lower total costs.

Next, we compare the policy of this section with the carbon cap policy of section 6.2. As can be seen in Figs. 3 and 4, carbon emissions could be as low as 50 for the deterministic model and less than 34.9 for the mixed model. In the current policy, carbon emission is almost fixed at each value of the carbon cost. As shown in Fig. 7(c), carbon emission is at most 32.95 which is smaller than the emission under carbon cap policy. This proves that carbon trading results in lesser emissions. Comparing with the results of carbon cap policy in Figs. 3 and 4, initially emission curve is almost linear with carbon cap but after

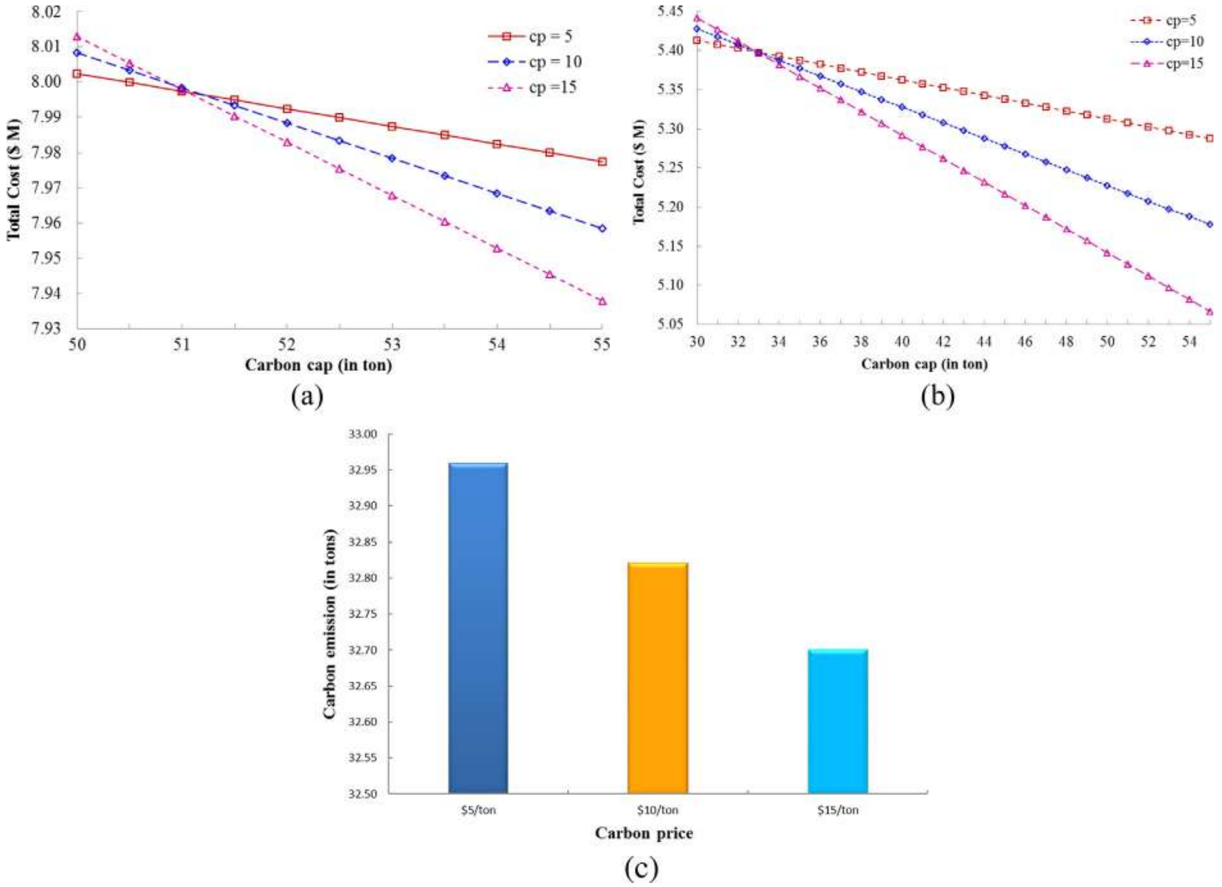

Fig. 7. Carbon cap-and-trade policy – total cost vs carbon cap at different values of carbon prices (a) deterministic solution, (b) mixed model solution. (c) Carbon cap-and-trade policy – carbon emission vs carbon prices.

reaching cap value 52.2 tons, it becomes constant. However, in carbon cap-and-trade policy, carbon emissions maintain constant level though varying carbon cap as shown in Fig. 7(c). This result proof that there is a carbon market exists under this policy that a firm can sell unused carbon credit to the market. This enables firm to generate additional income and also can buy the carbon credit from the market.

6.5. Results of carbon offset policy

Fig. 8(a) represents the relationship between the total cost and carbon cap of both deterministic solution and mixed model solution respectively. Each curve in the graph represents a different value of the carbon price. The lines in the figures show that the carbon cap and corresponding market prices have impact on total cost. As offset price increases the total cost also increases when carbon cap is at low level (steeper lines at smaller cap and at high offset prices). At low carbon cap level, a firm may consider using transportation modes and adopt technologies that generate less carbon emission. As the carbon cap level increases, the three curves approach one another and converge to the same total cost. When the cap reaches 52.2 tons the SC achieves minimum total cost regardless of any offset prices and additional carbon credit becomes redundant. Similar to Fig. 8(a), Fig. 8(b) represents total cost versus carbon cap at different uncertainty levels which shows that there is no effect of uncertainty on SC total cost.

Fig. 9(a) and (b) shows the effect of carbon offset price on the carbon emissions while varying carbon cap. At low carbon caps, carbon emissions are low. As the cap increases, emission increase but reach a constant level once the cap reaches 52.2 tons. When the carbon offset price large, the firm will generate less emissions. This is because there is no motivation for a firm to reduce carbon emissions and make additional income by selling unused carbon credit in the market.

6.6. Comparison of the four investigated policies

Comparisons of the four investigated policies based on total cost and total carbon emission under particular set of parameters is shown in Table 5. For the sake of comparison of different policies, we run the models and fixed the carbon cap to

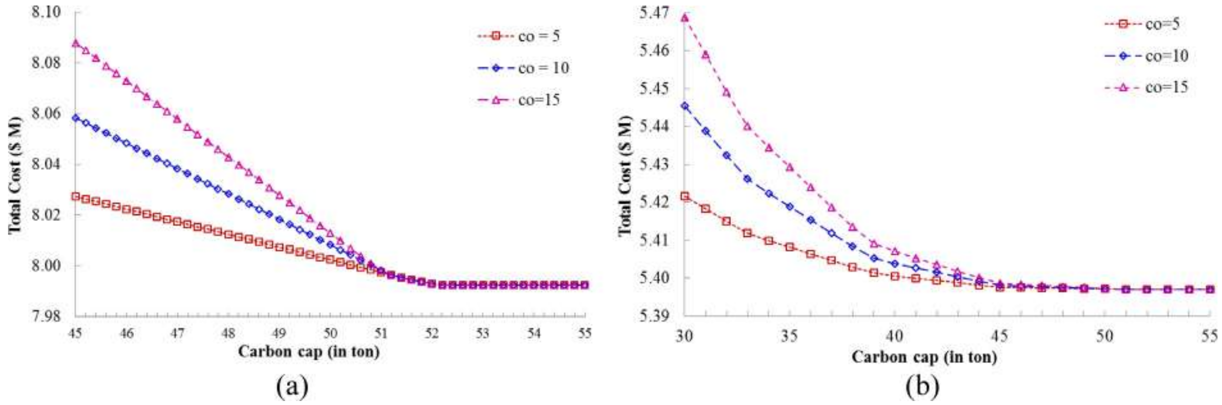

Fig. 8. Carbon offset policy – total cost vs carbon cap at different values of carbon offset prices; (a) deterministic, (b) mixed model.

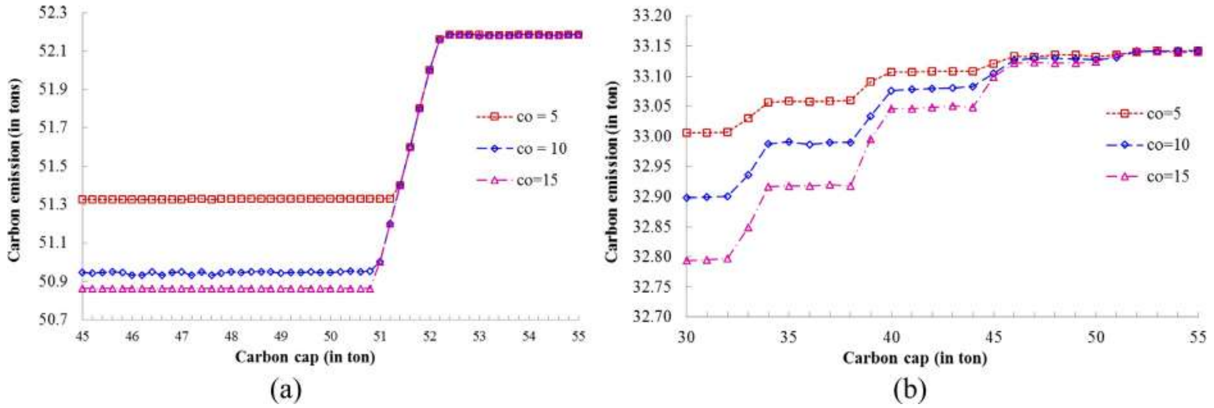

Fig. 9. Carbon offset policy – carbon emission vs carbon cap at different values of carbon offset prices; (a) deterministic, (b) mixed model.

Table 5
Comparison of total cost and carbon emission under four proposed policies with different parameters.

Carbon Policy	Deterministic model		Proposed mixed model	
	Total cost ($M)	Carbon emissions (in tons)	Total cost ($M)	Carbon emissions (in tons)
Carbon cap	7.99	52.00	5.43	34.92
Carbon tax	10.23	54.12	5.59	36.75
Carbon cap-and-trade	7.98	50.94	5.30	32.82
Carbon offset	7.99	52.00	5.40	33.14

52 tons, carbon tax rate to 40 $/ton, and carbon buying/selling prices to 10 $/ton. Table 5 shows that Carbon cap-and-trade policy has the lowest total cost and carbon emission compared to other policies in both deterministic and mixed models solutions.

Carbon cap-and-trade policy has more flexibility to buy and sell carbon in the carbon market compared to carbon tax and carbon offset policies. The decision makers may decide depending on whether their priority is to minimize the total cost or to minimize the total carbon emission. If one wants to minimize both total cost and carbon emissions, carbon cap-and-trade policy will be the best option in this case. However, all these decisions are dependent on the particular data set used. The findings in Table 4 (CLSC network design) and Table 5 (comparison of carbon policies) may vary if data sets in Table 3 are changed.

7. Conclusions and future research

This paper proposes an optimization model to address a multi-period and multi-product CLSC network design problem. A MILP formulation is used to handle the problem. To design a realistic network, some of the parameters of the proposed model are regarded as uncertain parameters with two different types of uncertainties; (i) products demand and return rate uncertainties are considered by means of stochastic scenarios whose probability of occurrence are known, (ii) carbon emissions due to facilities and transportation are considered as uncertain parameters by means of a set-based methodology which leads to robust optimization. To make supply chain requirements become more realistic, we incorporated decisions on selection of technologies at facilities and transportation modes options, as well as capacity limits on production, distribution and storage. We have extended our model in order to account for carbon footprint considerations due to supply chain activities. We model the impact of most common carbon policies namely, strict carbon cap policy, carbon tax policy, carbon cap-and-trade policy, and carbon offset policy on the design and planning of CLSC. Numerical results provide some insightful observations about the impact of the different policies on optimal design of CLSC, SC total costs, and carbon emissions.

Observation (1): Optimal CLSCN structure under different carbon policies was examined. Under carbon cap and carbon offset policies, as carbon cap increases, decision to open new facilities should be made until carbon cap reaches 52.2 tons. This decision may be preferred for firm that is willing to minimize SC total cost and reduce carbon emissions by utilizing allocated carbon allowances. When carbon cap is at low levels, generally firm may prefer to buy additional carbon credit (in carbon offset policy) to maintain its SC operations. SC total cost is the lowest at the carbon cap 52.2 tons. On the other hand, under carbon cap-and-trade policy, a firm allows to sell unused carbon credit and make additional income. It may buy additional carbon credit (usually at low carbon caps) to main SC operations. Due to this buying and selling flexibility, firm strategic activity (open new facilities) is the same for all carbon cap levels at particular carbon credit price (from Table 4). In carbon tax rate policy, due to SC total cost is directly (linearly) proportional to carbon tax. Strategic activities of the firm are significantly reduced (closing the opened facilities) as carbon tax rate increases that is to minimize SC total cost and reduce carbon emissions.

Observation (2): In carbon cap policy, a strict carbon emission constraint imposes on the amount of carbon emissions generated in SC activities. Under this policy, carbon emissions can be reduced significantly with slightly increase in the total cost. Also emissions are the lowest under this policy. The effectiveness of this policy heavily depends on the cap size impose on the firm.

Observation (3): Carbon tax policy provides more flexibility but impose huge financial burden on the firms in order to reach certain emission target compared to other three policies. However, once tax policy is adopted, supply chain total cost is insensitive to targeted emission goal, which is different from other three policies.

Observation (4): Cap-and-trade policy heavily depends on carbon market price and cap allocation. Results indicate that among three carbon cap policies, carbon cap-and-trade policy is more flexible and efficient than the other two policies. Under this policy, firms can sell unused carbon units to the market and make additional income when carbon cap size is large. In other words, this policy motivates the firms to emit less carbon units even when the carbon allowance is available more than needed. However, in carbon offset policy, firms need to purchase additional carbon units if they exceed the carbon cap limit (smaller cap) in order to maintain SC operations. When the carbon cap size is large, no reward for emitting less carbon units than the allocated cap i.e., there is no motivation for firms to emit less carbon units. Due to the existence of carbon market in the carbon cap-and-trade policy, it is more favorable among all other policies and attractive to many countries (Fahimnia et al., 2015; Palak et al., 2014; Zakeri et al., 2015). However, the big challenge for a firm or a policy maker is how to decide cap size in cap-based policies.

The proposed optimization model with different carbon policies can be valuable to the companies, researchers, and decision makers by choosing proper combination among different parameters to predict the impact of these policies on overall costs and carbon emissions in supply chain activities. The decision makers can decide what are the best policies (under the specified range of certain parameters) to be chosen to minimize both cost as well as carbon footprint across the supply chain.

Our modelling effort and analysis come with limitations that can provide numerous avenues for further research. Future research can consider complex supply chain networks and large number of operational problems that could be integrated with carbon footprint consideration. Such investigations may more broadly evaluate efficient policy interventions for emissions reduction and controlled use of natural resources. Since the multi-stage scenario-based stochastic approaches for practical problems are mostly large scale, whose size increases with the number of scenarios, it is desirable to reduce the scenario tree. The present model considers few facilities operating with three level (low, medium, high) of parameters uncertainty with three-time periods settings leads to 27 scenarios and were able to solve in reasonable amount of time. However, in real life, supply chain networks become more complex and multiple time period settings lead to large number of scenarios. As such, scenario reduction methods are necessary for this purpose and could be considered as a possible future research opportunity. Another future research direction could be incorporating risk measures to the existing the model that make it to risk-averse model. The current model is risk-neutral which considers the expectation of random variables in its objective function where decision making is solely based on a cost-minimization approach. Wherein a risk-averse approach that considers the effects of the variability of random outcomes, should provide more robust solutions compared to a risk-neutral approach.

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