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Author post-print (accepted) deposited by Coventry University's Repository

Original citation & hyperlink:

Sherafati, M, Bashiri, M, Tavakkoli-Moghaddam, R & Pishvae, MS 2020, 'Achieving sustainable development of supply chain by incorporating various carbon regulatory mechanisms', Transportation Research, Part D: Transport and Environment, vol. 81, 102253. <https://dx.doi.org/10.1016/j.trd.2020.102253>

DOI 10.1016/j.trd.2020.102253
ISSN 1361-9209

Publisher: Elsevier

NOTICE: this is the author's version of a work that was accepted for publication in Transportation Research, Part D: Transport and Environment. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Transportation Research, Part D: Transport and Environment, 81, (2020) DOI: 10.1016/j.trd.2020.102253

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Achieving sustainable development by incorporating various carbon regulatory mechanisms in supply chains

Abstract- Nowadays, sustainability issues have received considerable attention in supply chain management because of the governmental requirements as well as expectations of the people. This paper introduces a novel supply chain network design problem to cover three dimensions of sustainability, namely economic, environmental, and social. The advantage of the presented model stems from considering the booming development aligned with reduction in environmental impact. In this paper, to achieve the mentioned benefits and to derive a more sustainable supply chain, a novel model in the presence of the most commonly used carbon policies is proposed. This paper, addresses sustainable development through imposing proper carbon regulatory mechanisms. Main contribution of this study is to consider the effect of imposing carbon policies on environmental advantages as well as improving the regional development level in a supply chain network design problem. Moreover, the shipment consolidation decisions are utilized to reduce cost as well as environmental impact. In addition, a novel mixed uncertainty approach is proposed to capture the uncertain emission parameters. The numerical examples and a case study are analyzed to evaluate the performance of the proposed models. It is concluded that, a high-growth economy with low-carbon can be made and also almost global well-being of people is ensured by applying the proposed model. Some managerial insights are provided for the enterprises of supply chains to make the most appropriate sustainable decisions. Finally, proper carbon emission policies are suggested based on the region sustainability characteristics.

Keywords: Sustainability; Supply chain network design; Shipment consolidation; Carbon policies; Robust optimization

1. Introduction

Growing environmental and social concerns are important contemporary issues that have increased pressure from environmental advocacy groups, consumer organizations, and policymakers, enforcing the companies to regard them along with economic performance as three dimensions of sustainability (Abbasi and Nilsson, 2016; Rao et al., 2015). Moreover, enhancing sustainable development can be the only solution to overcome most of the global concerns like poverty, hunger, inequality, climate change, and global warming. So in this paper, three pillars of economy, society, and environment are regarded to design a sustainable supply chain network. Enterprises incur huge costs for shipping their products (Palak et al., 2014) and on the other hand, transportation has a major contribution to greenhouse gas emissions (Li et al., 2019). Therefore, the decrease in the amount of transportation can play an important role in saving costs and keeping the environment cleaner. In addition, since regional development is the most significant issue in social responsibility (Ghaderi, et al. 2018), it is considered in this study to achieve the sustainable development targets.

Carbon footprint can represent the quantification of the impact of a product, process or activity in terms CO₂ emissions (Patella et al., 2019) and it is often applied as a measurement of sustainable performance of the supply chain (Quddus et al., 2017). Many countries strive to mitigate the emission of greenhouse gases by developing carbon emission policies (e.g., carbon cap, carbon tax, carbon cap-and-trade, and carbon offset policies) in order to address the environmental concern. The existing studies in the literature analyzing the impact of the carbon policies have found that these strategies can be useful in emission reduction and protection of environment, and also have more economic benefits for the firms (Mohammed et al., 2017). To the best of authors' knowledge, these policies have not been analyzed in the literature in terms of sustainability. Contrary to the previous studies, the proposed model takes the carbon policies into account to improve all three dimensions of sustainability, as it is illustrated in Figure 1. It is clear that by

imposing carbon regulatory mechanisms, the facilities cannot generate extra greenhouse gases, so the environmental impact is mitigated. On the other hand, the mentioned policies may lead to a balanced regional development, bringing the presented model closer to the sustainable development paradigm. Because for the more developed regions, carbon policies are stricter than for the less developed regions and production rates are more equitable and more fair. Improving of the development level stimulates the economy of country, thus the return on the investment increases and a virtuous circle is seen (Mota et al., 2018) and also the carbon policies provide economic benefits to the companies (Mohammed et al., 2017).

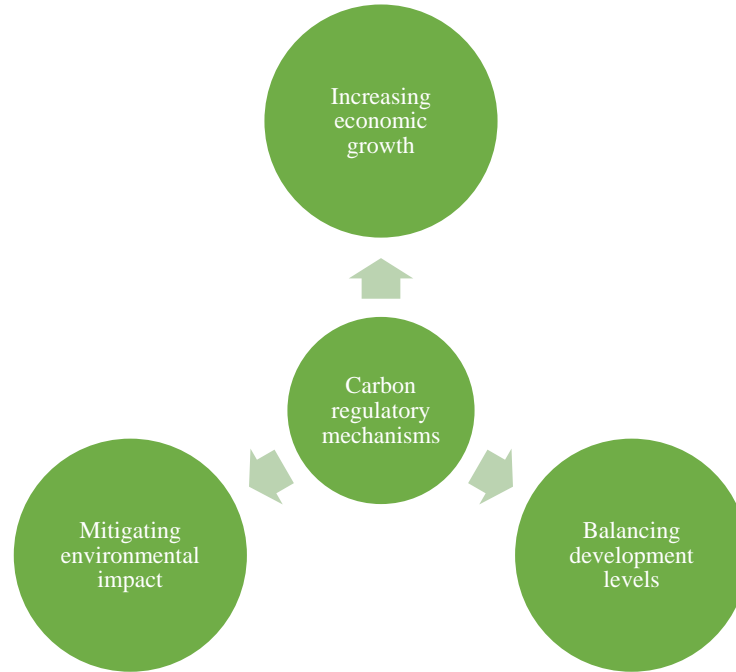


Figure 1. Advantages of the proposed approach based on carbon regulatory mechanisms.

In this paper, some valuable insights to government policy improvement in a more sustainable manner are provided as well. Proper policies are suggested considering environmental, social, and economical situations of countries.

The main contribution of the current paper that can differentiate it from the studies in the related literature is designing of a supply chain network addressing sustainable development through imposing proper carbon regulatory mechanisms; this helps to achieve the sustainability targets. Moreover, this effort applies the shipment consolidation (referred to as ShC here) to reduce total cost and total environmental impact. In this study, development of all regions, especially the less developed ones, is the main goal.

The rest of this research is structured as follows. First, a literature review is presented in section 2. Then, the proposed supply chain network design model with the incorporated carbon regulatory mechanisms and the robust counterpart are described in section 3. Afterwards, in section 4, a computational analysis is presented along with the insights obtained by the results. A case study is analyzed and then, some managerial implications are drawn in section 5. Finally, a discussion on the contributions of the paper for academia and practice as well as findings of the research and outlines for future studies are provided in section 6.

2. Literature review

The papers involving the supply chain network design (SCND) models in various areas have already been reviewed; we refer the readers to the studies presented by Govindan et al. (2015a) and Eskandarpour et al. (2015) to further study.

The SCND models proposed by various studies mostly focus on improving profitability (Govindan et al., 2015b). Increasing public awareness of environmental concerns has attracted attention to the configuration of a “green” supply chain network (Pishvae and Razmi, 2011). Recently, Waltho et al. (2018) studied and reviewed articles related to green supply chain network design and carbon policies. The papers considering design a sustainable supply chain network with environmental protection can be categorized into some groups, including those that focus on minimization of the greenhouse gas (GHG) emissions (such as Allaoui et al., 2018), waste reduction (Arampantzi and Minis, 2017), and other aspects such as fuel consumption and energy (Zhalechian et al., 2016). Eskandarpour et al. (2015), by reviewing some papers, noted that the most appropriate metric to measure environmental impact was carbon footprint. Addressing this factor has been emphasized to reduce the negative environmental, economic, and social impacts by other scholars (e.g., Santibanez-Gonzalez (2017)) as well.

As Xu et al. (2016) noted, the first study containing analyses of the impact of carbon emissions in the SCND problem was presented by Ramudhin et al. (2010). Then, several other scholars continued it, e.g., Wang et al. (2011) and Mallidis et al. (2012). Recently, the researchers tried to minimize the carbon footprint by developing various carbon policies. Benjaafar et al. (2013) first modeled carbon footprint to inform how policies, like mandatory emission caps, taxes on carbon emission, and emission cap-and-trade, would influence decision-making. Jin et al. (2013) investigated carbon cap-and-trade, emission tax, and inflexible cap policies as well as their effect on supply chain design and logistics operations of major retailers. Palak et al. (2014) considered the inventory replenishment decisions at a biorefinery and analyzed the relationships between different carbon policies in a biofuel supply chain. Impacts of the policies on replenishment schedules, costs, and emissions were indicated. Marufuzzaman et al. (2014) captured the trade-off between emissions and costs in supply chain of the biodiesel in a stochastic environment. With respect to this trade-off, under the various carbon regulatory mechanisms, some interesting observations were provided. Mohajeri and Fallah (2015) proposed a closed-loop supply chain network design model with uncertain parameters. Fuzzy programming was used to optimize the problem and to reduce carbon emissions from freight transport. Mohammed et al. (2017) modeled a formulation to design a closed-loop supply chain configuration by incorporating the carbon policies to consider the carbon footprint. Product demand and returns were handled by stochastic scenarios and a robust optimization framework was used to capture uncertain carbon emissions under a box uncertainty set. Haddad-Sisakht and Ryan (2017) formulated a closed-loop supply chain network design model considering a carbon tax with uncertain tax rate. Gao et al. (2018) proposed four models to address transportation cost and carbon cap and then, compared the obtained results. It was concluded that limiting emissions would significantly reduce the carbon footprints without a high cost. Dai et al. (2018) integrated a location-inventory problem into the supply chain network model and used the fuzzy programming approach to tackling capacity and carbon emission constraints. Rad and Nahavandi (2018) designed a closed-loop green supply chain network considering carbon emissions with respect to transportation and production processes. Manupati et al. (2018) investigated a production-distribution-inventory problem with regulatory policies for carbon emissions (strict carbon capping, carbon tax, and carbon cap-and-trade). Halat and Hafezalkotob (2019) developed a bi-level programming models addressing the structure of the green supply chain and the governmental policies, i.e., carbon cap, carbon tax, carbon trade, and carbon offset. Based on the literature review, it is observed that there is no more carbon policies in the previous studies and all of possible four carbon policies are considered in this paper. To the best of our knowledge, in terms of sustainability, the mentioned policies have not been analyzed in the related literature. Beyond the previous studies, the proposed models take the carbon policies into account to improve all three dimensions of sustainability, as illustrated in Table 1. The mentioned policies may lead to balanced regional development, which brings the proposed models closer to the sustainable development paradigm.

Decreasing the environmental burden is an important goal of researchers and logistics managers. One of the apt policies to reach this significant goal can be reducing the transportation activities. Using heavy and light vehicles has the greatest impact on the environment pollution and it is the main source of greenhouse gases emissions and noise (Dekker et al., 2012; Wong et al., 2018). As a result, companies have to develop

their supply chains with the least possible transportation activities to provide greener logistics. Furthermore, full transport load (FTL) should behave more economical and significantly reduce the transportation cost. Transportation cost imposes a high percentage of the total logistics cost (often between one-third and two-third) (Hosseini et al., 2014). Managing the transportation activities can dramatically reduce the cost. One of the best policies to reduce transportation activity can be the shipment consolidation strategy in which small shipments are aggregated into larger ones to achieve the benefits of the economies of scale. The studies that have considered the shipment consolidation policy are listed as follows. Cetinkaya and Bookbinder (2003) analyzed quantity-based and time-based shipment consolidation policies. In the first policy, products are accumulated to achieve a specified quantity to ship. Shipments are consolidated and dispatched in every T periods by the second policy. Çapar (2013) considered shipment consolidation decisions in a supply chain with a distribution center, multiple retailers, and a supplier. Periodic-review inventory policy and stock policy were utilized at the distribution center and by the retailers, respectively. Howard and Marklund (2011) considered a warehouse with N-retailer inventory system utilizing a shipment consolidation policy at a warehouse. Ülkü (2012) introduced time-based shipment consolidation to analyze the advantages of consolidation policy in terms of both cost and CO₂ emissions. It was demonstrated that shipment consolidation as a powerful logistics strategy could decrease carbon and energy waste. Qin et al. (2014) proposed a freight allocation and consolidation problem concerning selection of shipping routes for shipments with different sizes and costs.

Researchers have frequently proposed consolidation policies as a means of raising truck payload utilization and mitigating externalities created by freight transportation. The majority of the related studies have not considered any shipment consolidation policy in designing of the supply chain network and have determined only the timing and quantity of the shipments. However, in the current study, supply chain network is configured with shipment consolidation. Accordingly, shipment consolidation with sustainability targets using four carbon emission regulatory mechanisms is the major contribution of the current study.

The studies that consider social aspects of the network design models can be classified as those that focus on increasing regional development (Arampantzi and Minis., 2017), achieving balanced regional development (Zahiri et al., 2017; Ghaderi et al., 2018), addressing customer satisfaction (Zhang et al., 2016; Tsao et al., 2018), employee satisfaction (Ramos et al., 2014; Arampantzi and Minis., 2017), creating job opportunities (Mota et al., 2015; Mota et al., 2018), and reducing the number of lost working days due to occupational accidents (Devika et al., 2014; Sahebjamnia et al., 2018). The most significant aspect in social responsibility dimension is the regional development, that has received little attention (Sherafati et al., 2019); therefore, this research focuses on the remarkable gap.

Another considerable issue in the supply chain network design problems can be uncertainty of parameters. Many scholars, such as Bairamzadeh et al. (2015) and Sherafati and Bashiri (2014), believe that uncertainties should be considered in these problems due to the nature of them and the characteristics of their parameters, and robustness is essential for ensuring sustainability (Klibi et al., 2010) which leads to the higher reliability (Miralinaghi and Peeta, 2019) as well. Some SCND models under uncertainty were reviewed and comprehensively classified in a review paper presented by Klibi et al. (2010) and Govindan et al. (2017). Moreover, the interested readers can refer to the research by Daghighi et al. (2018), in which the sustainable SCND models and solution approaches in the uncertain environments were well reviewed.

Most of the previous studies have considered regular parameters like demand as the source of uncertainty, and carbon emission has generally been regarded as a deterministic parameter (Waltho et al., 2018) and only a little papers, such as Mohammed and Wang (2017), Mohammed et al. (2017) and Mohammed et al. (2019), formulated the carbon emission as an uncertain parameter. However, in real situations, uncertainty of carbon emission is inevitable. Thus, in the current research, the uncertainty of parameters related to carbon emission is captured. In this study, the demand is considered as a deterministic parameter for simplification and because it does not affect on the main idea of the research.

Table 1- A summarized comparison of the related supply chain network design studies considering sustainability aspects.

Reference	Social aspects	Economic aspects alongside the environmental concern	Carbon policies				Sustainable development by imposing carbon policies	Shipment consolidation	Tackling uncertainty		
			Carbon cap	Carbon tax	Carbon cap-and-trade	Carbon offset			Robust	Fuzzy	Stochastic
Pishvae et al. (2014)	✓									✓	
Zhalechian et al. (2016)	✓									✓	✓
Soleimani et al. 2017	✓		✓E							✓	
Zahiri et al.2017	✓				✓E						
Arampantzi and Minis, 2017	✓	✓									
Ghaderi et al. (2018)	✓								✓		✓
Mirzapour Al-e-hashem et al. (2013)			✓E								✓
Jin et al. (2013)			✓E	✓E	✓E						
Palak et al. (2014)		✓	✓E	✓E	✓E	✓E					
Baud-Lavigne et al. (2014)			✓E								
Choudhary et al. (2015)			✓E	✓E	✓E						
Bing et al. (2015)					✓E						
Peng et al. (2016)			✓E	✓E							
Rezaee et al. (2017)			✓E		✓E						✓
Xu et al. (2017)			✓E	✓E	✓E						
Qudduset al. (2017)					✓E						
Mohammed et al. (2017)		✓	✓E	✓E	✓E	✓E			✓		✓
Haddad-Sisakht and Ryan (2017)		✓		✓E					✓		✓
Gao et al. (2018)			✓E								
Dai et al. 2018			✓E							✓	
Rad and Nahavandi (2018)	✓	✓	✓E							✓	
Manupati et al. (2018)	✓		✓E	✓E	✓E						
Shuang et al. (2019)		✓		✓E	✓E						✓
Current research	✓	✓	✓S	✓S	✓S	✓S	✓	✓	✓	✓	

E: Environmental target, S: Sustainability target

3. Problem description and formulation

In this section, a mathematical programming model is proposed for the design of the supply chain regarding to four carbon regulatory mechanisms. The network is supposed to be multi-period and multi-product, and comprises two echelons of manufacturers and customers, as it is shown in Figure 2. The main idea of this research has been illustrated in mentioned figure, too. Most of the focus is on manufacturers, since their production and transportation activities have the greatest impact on the environment and on development level among the supply chain elements.

Four carbon policy regulatory mechanisms, namely, Carbon cap policy (CCP), Carbon tax policy (CTP), Carbon cap-and-trade policy (CCTP), and Carbon offset policy (COP), are considered in the proposed models. The main advantage of the proposed model is considering four carbon policies, to achieve sustainable development targets.

In this study, maximization of the total profit is the only objective function, and the reduction of the environmental impact and carbon emissions generated by the facilities and transportation activities is under the carbon regulatory mechanisms. Such as similar studies, a constraint in CCP, CCTP and COP and a cost in CTP are considered to limit the environmental impact as the previous scholars have carried out. To do so, without consideration of an objective function to minimize environmental impact, all carbon emissions

are reduced as far as possible. In fact, the emissions are integrated with the costs by multiplying a parameter, and a preferred solution is extracted. It should be noted that previously, some researchers for example Muñoz-Villamizar et al. (2017) formulated a single objective function with two different weights for cost and CO₂ emissions. Moreover, the previous scholars such as Jin et al., (2014), Palak et al., (2014), Marufuzzaman et al., (2014), Bing et al. (2015), Xu et al. (2017), Mohammed et al., (2017) and etc., imposing carbon policies similar to this paper, considered an objective containing economic and environmental costs.

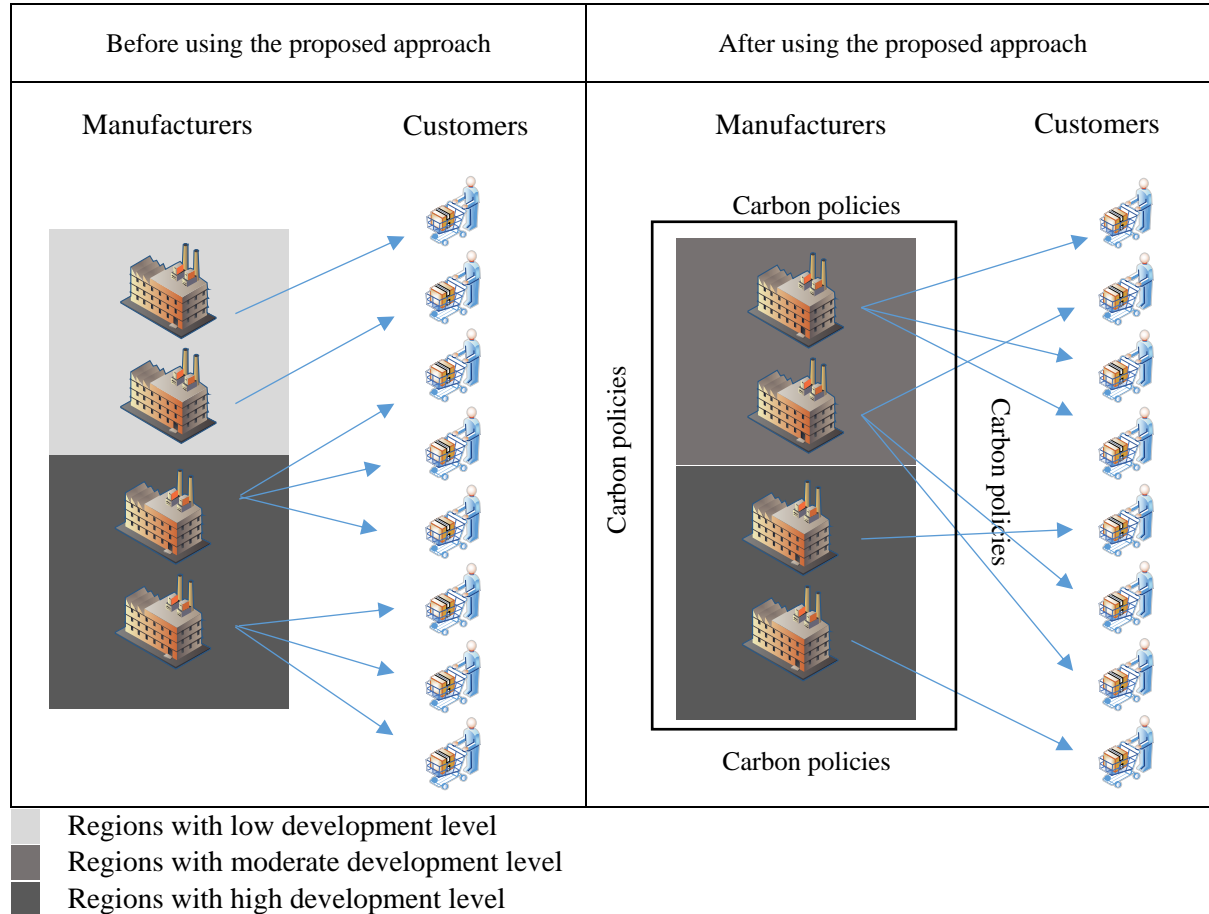


Figure 2- An illustration of the proposed approach to achieve a sustainable supply chain.

Another innovative properties of the model is that these policies vary from region to region. In fact, it is stricter for more developed regions and more permissive for the less developed regions to reduce the difference between the development levels and balance the community. The carbon policy constraints consider the social aspects, too, because by such mechanisms, development level of regions and the whole society will be balanced.

The most significant aspect in the social responsibility dimension is the regional development, because it has significant effects on other social aspects. Thus, the social aspect is considered as the carbon policies equations.

Many researchers used the City Development Index (CDI) to indicate the development level of regions and evaluate sustainability (Yang and Li, 2019). CDI is one of the major sustainability indicators (Mori and Christodoulou, 2012), in fact its main advantage among indicators used in the related literature assessing the three dimensions of sustainability, it can evaluate all of environment, economy, and society pillars

(Huang et al., 2016). To calculate this index, the same formulas considered in the UNDP Human Development Report (1999), namely, product, health, education, infrastructure, and waste indicators are used. So, the CDI is a well-known indicators and can be considered to evaluate of sustainability. One of the main criteria to measure of this indicator is amounts of production, which it is applied in this paper, because it is related to the studied problem. Other criteria such as health, education and so on can be considered as a future study.

Another property and contribution of this paper is consideration of mixed uncertainty. As suggested by Mohammed et al. (2017) and Waltho et al. (2018), uncertainty consideration is highly necessary for designing a supply chain network with carbon footprint. Addressing the inherent uncertain emission parameters, the approach proposed by Bertsimas and Sim (2004) is utilized to tackle the uncertainty and present a set of protected solutions against uncertainty. In the robust counterpart of the proposed model, there is a parameter Γ (protection level) which adjust the robustness against the level of conservatism of the solution. This important parameter is determined by the decision maker. Since there is a vagueness in the opinions of the decision maker and fuzzy set theory is used to handle vagueness and human subjectivity in decision making (Garg and Kashav, 2019), thus, it is proposed that this parameter is considered as a trapezoidal fuzzy parameter ($\tilde{\Gamma}$). By using fuzzy chance constraint programming and necessity measure (Pishvae et al, 2012), the protection level is considered as a trapezoidal fuzzy number in the model ($[\Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4]$). Subsequently, the proposed model is presented with mixed uncertainty or deep uncertainty.

In the classic model, there is no shipment consolidation decision so that all orders of the customers are delivered on time. The drawback of the classic model is that some vehicles may transport in LTL (Less than Truck Load) form. One of the properties of the proposed model is that by considering ShC, if the number of products is equal to the capacity of the vehicle, and the vehicle is fully filled up, they can be sent directly to the customer and the quantities less than the capacity are transferred to the warehouse to be consolidated with the products of other periods. If products are transferred to the warehouse, a penalty should be paid for each unit of product because of the delayed delivery. In the logistic literature, this is very well-known concept and many papers consider aggregate demands assuming full-truck-load transportation. So, this logistics strategy is used in this paper to develop a more general model which makes the proposed model closer to the sustainability targets.

In this paper, demand is assumed as a price-response function similar to Fattahi et al. (2015), so it is considered as a deterministic parameter to reduce the computational complexities.

The main assumptions of this study are as follows:

- The shortage is taken into account as a backorder and it bears a penalty cost.
- Products with higher priority in shipment have more backorder costs.
- Each manufacturer has a warehouse to transfer excess products to the vehicle capacity.
- In the warehouse, the products are labeled to each specific customer.
- The development status of regions are considered as determined parameters at the beginning of the planning horizon (b_{or}). For the remaining periods of the time horizon (beyond the first one), it is assumed as a decision variable.

The following notation sets, parameters, and decision variables are considered for the mathematical formulation of the model.

Sets

R : Set of region's category ($r1$: regions with the less development level, $r2$: regions with the more development level).

I' : Set of candidate locations for manufacturers in the regions with r^{th} development category.

I : Set of all possible candidate locations for manufacturers ($I = I'^1 \cup I'^2$), $i \in I$.

J : Set of customers, $j \in J$.

P : Set of products, $p \in P$.

T : Set of time periods, $t \in T$.
 L : Set of price levels, $l \in L$.

Parameters

Pr_{plt} : Price per unit of product p at price level l in time period t .
 D_{jplt} : Demand of customer j in time period t for product p with price level l .
 tc_{ij} : Transportation cost from manufacturer i to customer j .
 pc_{ip} : Production cost per unit of product p at manufacturer i .
 fc_i : Fixed cost for opening of manufacturer i .
 M_{ip} : Production capacity of manufacturer i for product p .
 vc : Vehicle capacity
 lc_{jp} : Penalty cost per unit of product p borne for delay in delivery to customer j .
 ic_{ip} : Inventory cost per unit of product p at manufacturer i .
 ep_i : Carbon emission in tons for opening of manufacturer i .
 et_{ij} : Carbon emission in tons for transportation of a vehicle from manufacturer i to customer j .
 eh_{ip} : Carbon emission in tons for inventory per unit of product p at the warehouse of manufacturer i .
 em_{ip} : Carbon emission in tons for production per unit of product p at manufacturer i .
 CC_r : Maximum permitted amounts of carbon that can be emitted in regions with development category r .
 μ_r : Amounts of tax paid per unit emitted in regions with development category r .
 p^b_r : Carbon buying prices per ton in the carbon market in regions with development category r .
 p^s_r : Carbon selling prices per ton in the carbon market in regions with development category r .
 p^o_r : Carbon offset prices per ton in regions with development category r .
 β_r : Realization rate of development for regions with development category r .

Continues decision variables:

z'_{ijpt} : Assigned capacity ratio to consolidated product p in a vehicle transporting from manufacturer i to customer j in time period t .
 e_r^b : Amounts of carbon credit bought in a carbon trade market in regions with development category r .
 e_r^s : Amounts of carbon credit sold in a carbon trade market in regions with development category r .
 b_{ir} : Development level of regions with development category r in time period t .

Integer decision variables:

g_{ijpt} : Allocated portion of the demand of customer j to manufacturer i in time period t for product p .
 n_{ijt} : Number of vehicles transporting from manufacturer i to customer j in time period t .
 x_{ijpt} : Quantity of product p transported from manufacturer i to customer j in time period t directly.
 y_{ijpt} : Quantity of product p related to customer j consolidated in manufacturer i in time period t .
 h_{ijpt} : Quantity of product p related to customer j hold at the warehouse of manufacturer i in time period t .

Binary decision variables:

o_i : 1 if manufacturer i is opened, otherwise 0.
 δ_{plt} : 1 if price level l per unit product p is selected in period t , otherwise 0.
 z_{ijt} : 1 if a vehicle transports the consolidated products from manufacturer i to customer j in time period t , otherwise 0.

In the following, two models with and without shipment consolidation are presented, respectively and then, the models containing carbon regulatory mechanisms are provided.

3.1. Classic model

$$\begin{aligned} \max \quad z1 = & \sum_{j \in J} \sum_{p \in P} \sum_{l \in L} \sum_{t \in T} \text{Pr}_{plt} \times D_{jplt} \times \delta_{plt} \\ & - \sum_{i \in I} fc_i \times o_i \end{aligned} \quad (1)$$

$$\begin{aligned} & - \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} tc_{ij} \times n_{ijt} \\ & - \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} pc_{ip} \times g_{ijpt} \end{aligned}$$

$$\sum_{i \in I} g_{ijpt} = \sum_{l \in L} (D_{jplt} \times \delta_{plt}) \quad \forall j \in J, p \in P, t \in T \quad (2)$$

$$\sum_{l \in L} \delta_{plt} = 1 \quad \forall p \in P, t \in T \quad (3)$$

$$\sum_{j \in J} g_{ijpt} \leq M_{ip} \times o_i \quad \forall i \in I, p \in P, t \in T \quad (4)$$

$$n_{ijt} \geq \frac{\sum_{p \in P} g_{ijpt}}{vc} \quad \forall i \in I, j \in J, t \in T \quad (5)$$

$$n_{ijt} < \frac{\sum_{p \in P} g_{ijpt}}{vc} + 1 \quad \forall i \in I, j \in J, t \in T \quad (6)$$

$$g_{ijpt}, n_{ijt} \geq 0 \text{ and Integer} \quad \forall i \in I, j \in J, p \in P, t \in T \quad (7)$$

$$o_i, \delta_{plt} \in \{0,1\} \quad \forall i \in I, l \in L, p \in P, t \in T \quad (8)$$

The classic model for supply chain network design is defined by equations (1) – (8). Objective function (1) seeks to maximize profit and minimize opening, transportation, and production costs. Constraint (2) is considered to balance the amounts of production and customer demand. According to constraint (3), only one price level is selected for each product in each period. Constraint (4) ensures that the amount of production at each manufacturer does not exceeded its capacity. The number of required vehicles is determined according to constraints (5) and (6). Finally, constraints (7) and (8) define the type of variables.

3.2. Shipment consolidation model

$$\begin{aligned} \max \quad z2 = & \sum_{j \in J} \sum_{p \in P} \sum_{l \in L} \sum_{t \in T} \text{Pr}_{plt} \times D_{jplt} \times \delta_{plt} \\ & - \sum_{i \in I} fc_i \times o_i \\ & - \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} lc_{jp} \times y_{ijpt} \end{aligned} \quad (9)$$

$$- \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} tc_{ij} \times (n_{ijt} + z_{ijt})$$

$$- \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} ic_{ip} \times h_{ijpt}$$

$$- \sum_{i \in I} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} pc_{ip} \times g_{ijpt}$$

Constraints 2 - 4

$$\sum_{p \in P} (x_{ijpt} + y_{ijpt}) = \sum_{p \in P} g_{ijpt} \quad \forall i \in I, j \in J, t \in T \quad (10)$$

$$\sum_{p \in P} y_{ijpt} < vc \quad \forall i \in I, j \in J, t \in T \quad (11)$$

$$\sum_{p \in P} y_{ijpt} + \sum_{p \in P} h_{ijp,t-1} - vc \leq z_{ijt} \times BN \quad \forall i \in I, j \in J, t \geq 2 \in T \quad (12)$$

$$\sum_{p \in P} y_{ijpt} + \sum_{p \in P} h_{ijp,t-1} - vc \geq -(1 - z_{ijt}) \times BN \quad \forall i \in I, j \in J, t \geq 2 \in T \quad (13)$$

$$\sum_{p \in P} h_{ijpt} < vc \quad \forall i \in I, j \in J, t \geq 2 \in T \quad (14)$$

$$z'_{ijpt} \times vc + h_{ijpt} = h_{ijp,t-1} + y_{ijpt} \quad \forall i \in I, j \in J, p \in P, t \geq 2 \in T \quad (15)$$

$$\sum_{p \in P} z'_{ijpt} = z_{ijt} \quad \forall i \in I, j \in J, t \geq 2 \in T \quad (16)$$

$$h_{ijp1} = y_{ijp1} \quad \forall i \in I, j \in J, p \in P, t = 1 \quad (17)$$

$$\sum_{p \in P} x_{ijpt} = vc \times n_{ijt} \quad \forall i \in I, j \in J, t \in T \quad (18)$$

$$n_{ijt} \leq \frac{\sum_{p \in P} g_{ijpt}}{vc} \quad \forall i \in I, j \in J, t \in T \quad (19)$$

$$n_{ijt} > \frac{\sum_{p \in P} g_{ijpt}}{vc} - 1 \quad \forall i \in I, j \in J, t \in T \quad (20)$$

$$z'_{ijpt} \geq 0 \quad \forall i \in I, j \in J, p \in P, t \in T \quad (21)$$

$$g_{ijpt}, n_{ijt}, x_{ijpt}, y_{ijpt}, h_{ijpt} \geq 0 \text{ and Integer} \quad \forall i \in I, j \in J, p \in P, t \in T \quad (22)$$

$$o_i, \delta_{plt}, z_{ijt} \in \{0, 1\} \quad \forall i \in I, j \in J, p \in P, l \in L, t \in T \quad (23)$$

The objective function (equation (9)) is similar to equation (1), in which penalty and inventory cost of transferred products to warehouses are added. Based on constraints (10) and (11), the amount of demand is divided into two parts: one directly sent to the customers and the other transferred to the warehouses for consolidation with products of the previous periods. According to constraints (12) – (14), decisions about the products shipped from the warehouse to the customers or kept in the warehouse are made. Constraint (15) is the inventory balance constraint in each warehouse. The ratio of each product to the total capacity of the vehicle being sent from the warehouse is determined by constraint (16). Constraint (17) assures that there is no initial inventory in the first period. Number of required vehicles is determined by constraints (18) – (20). The type of decision variables is determined by constraints (21) – (23).

Finally, it should be noted that a social constraint (24) is considered to measure the development level of regions in each time period as follows.

$$b_r \leq b_{t-1,r} + \beta_r \sum_{i \in I'} \sum_{j \in J} \sum_{p \in P} g_{ijpt} \quad \forall r \in R, t \geq 2 \in T \quad (24)$$

3.3. The proposed model under carbon cap policy

In this model, a strict carbon cap is assigned to control emissions. Two types of carbon cap are considered in order to achieve sustainability concerns. In fact, tighter carbon cap limits the carbon emitted by more developed regions.

max z2

s.t.

Constraints (2) – (4)

Constraints (10) – (24)

$$\sum_{i \in I'} ep_i \times o_i + \sum_{i \in I'} \sum_{j \in J} \sum_{t \in T} et_{ij} \times (n_{ijt} + z_{ijt}) + \sum_{i \in I'} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} eh_{ip} \times h_{ijpt} + \sum_{i \in I'} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} em_{ip} \times g_{ijpt} \leq CC_r \quad \forall r \in R \quad (25)$$

Constraints 25 limit emissions for less and more developed regions.

The robust counterpart of the proposed model with uncertain carbon emissions is presented as follows. It is assumed that the uncertain parameter \tilde{e} is a bounded and symmetric random variable in the interval $[e - \bar{e}, e + \bar{e}]$, in which e and \bar{e} are the nominal value and perturbation amplitude of the uncertain parameter, respectively. Constraint 26-30 are robust counterpart of 25 and are substituted it.

max z2

s.t.

Constraints (2) – (4)

Constraints (10) – (24)

$$\begin{aligned} & \sum_{i \in I'} ep_i \times o_i + \sum_{i \in I'} k_{ir}^1 \\ & + \sum_{i \in I'} \sum_{j \in J} \sum_{t \in T} et_{ij} \times (n_{ijt} + z_{ijt}) + \sum_{i \in I'} \sum_{j \in J} k_{ijr}^2 \\ & + \sum_{i \in I'} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} eh_{ip} \times h_{ijpt} + \sum_{i \in I'} \sum_{p \in P} k_{ipr}^3 \\ & + \sum_{i \in I'} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} em_{ip} \times g_{ijpt} + \sum_{i \in I'} \sum_{p \in P} k_{ipr}^4 \\ & + \tilde{\Gamma}^r \lambda^r \leq CC_r \end{aligned} \quad \forall r \in R \quad (26)$$

$$\lambda^r + k_{ir}^1 \geq \overline{ep}_i \times o_i \quad \forall i \in I', r \in R \quad (27)$$

$$\lambda^r + k_{ijr}^2 \geq \overline{et}_{ij} \sum_{t \in T} (n_{ijt} + z_{ijt}) \quad \forall i \in I', j \in J, r \in R \quad (28)$$

$$\lambda^r + k_{ipr}^3 \geq \overline{eh}_{ip} \sum_{j \in J} \sum_{t \in T} h_{ijpt} \quad \forall i \in I', p \in P, r \in R \quad (29)$$

$$\lambda^r + k_{ipr}^4 \geq \overline{em}_{ip} \sum_{j \in J} \sum_{t \in T} g_{ijpt} \quad \forall i \in I', p \in P, r \in R \quad (30)$$

Variables k and λ are two decision variables related to the dual model and Γ is the protection level (uncertainty budget, or conservatism level) determined by the decision maker.

Fuzzy chance constraint programming and necessity measure (Pishvae et al, 2012) is applied to handle fuzzy protection level as constraint (31). α is defined as minimum feasibility degree for the constraint. The proposed model under CCP is reformulated as follows:

max z2

s.t.

Constraints (2) – (4)

Constraints (10) – (24)

$$\begin{aligned}
& \sum_{i \in I^r} ep_i \times o_i + \sum_{i \in I^r} k_{ir}^1 \\
& + \sum_{i \in I^r} \sum_{j \in J} \sum_{t \in T} et_{ij} \times (n_{ijt} + z_{ijt}) + \sum_{i \in I^r} \sum_{j \in J} k_{ijr}^2 \\
& + \sum_{i \in I^r} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} eh_{ip} \times h_{ijpt} + \sum_{i \in I^r} \sum_{p \in P} k_{ipr}^3 \\
& + \sum_{i \in I^r} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} em_{ip} \times g_{ijpt} + \sum_{i \in I^r} \sum_{p \in P} k_{ipr}^4 \\
& + \lambda^r \left[(1 - \alpha) \Gamma_3^r + \alpha \Gamma_4^r \right] \leq CC_r
\end{aligned} \quad \forall r \in R \tag{31}$$

Constraints (27)-(30)

3.4. The proposed model under carbon tax policy

The companies must pay a fee for each unit of carbon generated under a carbon tax policy (Palak et al., 2014). The carbon tax value should be selected carefully, because the tax high enough decreases emission while increases total cost (Waltho et al., 2018). Here, it is proposed that the companies in more developed regions pay a higher tax than those in the less developed regions. The fuzzy-robust counterpart of the ShC model under CTP can be presented as follows:

Max σ

Constraints (2) – (4)

Constraints (10) – (24)

$$\begin{aligned}
\sigma & \leq z2 - \sum_{r \in R} \mu_r \left(\sum_{i \in I^r} ep_i \times o_i + \sum_{i \in I^r} k_{ir}^1 \right. \\
& + \sum_{i \in I^r} \sum_{j \in J} \sum_{t \in T} et_{ij} \times (n_{ijt} + z_{ijt}) + \sum_{i \in I^r} \sum_{j \in J} k_{ijr}^2 \\
& + \sum_{i \in I^r} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} eh_{ip} \times h_{ijpt} + \sum_{i \in I^r} \sum_{p \in P} k_{ipr}^3 \\
& + \sum_{i \in I^r} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} em_{ip} \times g_{ijpt} + \sum_{i \in I^r} \sum_{p \in P} k_{ipr}^4 \\
& \left. + \lambda^r \left[\alpha \Gamma_1^r + (1 - \alpha) \Gamma_2^r \right] \right)
\end{aligned} \quad \forall r \in R \tag{32}$$

Constraints (27)-(30)

3.5. The proposed model under carbon cap-and-trade policy

There is another mechanism to limit the emissions, namely carbon cap-and-trade. Based on this policy, if a company generates less emissions than the determined carbon cap, then, the gap between the emitted carbon and the permitted cap can be sold in a carbon market to those firms that generate more emissions than their cap level (Xu et al., 2016).

In this study, two various carbon buying and selling prices are taken into account for different regions based on their development status. The fuzzy-robust counterpart of the proposed model under carbon cap-and-trade policy is considered as follows:

$$\max \quad z2 - \sum_{r \in R} (p_r^b \times e_r^b - p_r^s \times e_r^s)$$

Constraints (2) – (4)

Constraints (10) – (24)

$$\begin{aligned} & \sum_{i \in I'} ep_i \times o_i + \sum_{i \in I'} k_{ir}^1 \\ & + \sum_{i \in I'} \sum_j \sum_t et_{ij} \times (n_{ijt} + z_{ijt}) + \sum_{i \in I'} \sum_j k_{ijr}^2 \\ & + \sum_{i \in I'} \sum_j \sum_p \sum_t eh_{ip} \times h_{ijpt} + \sum_{i \in I'} \sum_p k_{ipr}^3 \\ & + \sum_{i \in I'} \sum_j \sum_p \sum_t em_{ip} \times g_{ijpt} + \sum_{i \in I'} \sum_p k_{ipr}^4 \\ & + \lambda^r [(1 - \alpha) \Gamma_3^r + \alpha \Gamma_4^r] \\ & + e_r^s \leq CC_r + e_r^b \end{aligned} \quad \forall r \in R \quad (33)$$

Constraints (27)-(30)

3.6. The proposed model under carbon offset policy

Carbon offset regulatory mechanism is almost similar to CCTP, except that the companies cannot sell unused carbon credits to others. The fuzzy-robust counterpart of the considered model under COP is taken into account as follows:

$$\max \quad z2 - \sum_{r \in R} (p_r^o \times e_r^b)$$

Constraints (2) – (4)

Constraints (10) – (24)

$$\begin{aligned} & \sum_{i \in I'} ep_i \times o_i + \sum_{i \in I'} k_{ir}^1 \\ & + \sum_{i \in I'} \sum_{j \in J} \sum_{t \in T} et_{ij} \times (n_{ijt} + z_{ijt}) + \sum_{i \in I'} \sum_{j \in J} k_{ijr}^2 \\ & + \sum_{i \in I'} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} eh_{ip} \times h_{ijpt} + \sum_{i \in I'} \sum_{p \in P} k_{ipr}^3 \\ & + \sum_{i \in I'} \sum_{j \in J} \sum_{p \in P} \sum_{t \in T} em_{ip} \times g_{ijpt} + \sum_{i \in I'} \sum_{p \in P} k_{ipr}^4 \\ & + \lambda^r [(1 - \alpha) \Gamma_3^r + \alpha \Gamma_4^r] \\ & \leq CC_r + e_r^b \end{aligned} \quad \forall r \in R \quad 34$$

Constraints (27)-(30)

The properties of the proposed models are presented in summary in Table 2 and Table 3. Some carbon regulatory mechanisms can be converted to each other by setting the parameters as presented in Table 3.

Table 2- Summary of the properties related to the proposed models under various carbon regulatory mechanisms.

Model name	Policy	Objective function	Constraints	Special parameters	Special constraint	Special variables
Classic model	No carbon policy	Max $Z1$	(2)-(8)	-	-	-
ShC model	No carbon policy	Max $Z2$	(2)-(4) and (10)-(23)	-	-	-
CCP model	Inflexible carbon cap	Max $Z2$	(2)-(4), (10)-(23), (31) and (27)-(30)	Carbon cap (CC_r)	31	-
CTP model	Carbon tax	Max σ	(2)-(4), (10)-(23), (32) and (27)-(30)	Carbon tax (μ_r)	32	-
CCTP model	Carbon trade market to meet the cap	Max $Z2$ $-\Sigma(p_r^b \cdot e_r^b - p_r^s \cdot e_r^s)$	(2)-(4), (10)-(23), (33) and (27)-(30)	Carbon cap and carbon prices (CC_r, p_r^b, p_r^s)	33	carbon credit bought and sold (e_r^b, e_r^s)
COP model	Carbon offset	Max $Z2 - \Sigma(p_r^o \cdot e_r^b)$	(2)-(4), (10)-(23), (34) and (27)-(30)	Carbon cap and carbon offset (CC_r, p_r^o)	34	carbon credit bought (e_r^b)

Table 3- A comparison of the proposed models and their convertibility to each other.

Model name	Shipment consolidation	Carbon cap	Carbon tax	Carbon price	Carbon offset	Convertibility to another carbon policy model
ShC model	✓					
CCP model	✓	✓ (Hard)				
CTP model	✓		✓			
CCTP model	✓	✓ (Soft)		✓		If $p_r^b = \infty$ and $p_r^s = 0$, it will perform as a CCP model; If $p_r^s = 0$ and $p_r^b = p_r^o$, it will perform as a COP model
COP model	✓	✓ (Soft)			✓	If $p_r^o = \infty$, it will perform as a CCP model

4. Numerical examples

This section discusses remarkable observations related to the proposed sustainable supply chain network design, including the total cost, development status, and carbon emissions considering various carbon policies. The performance of the proposed model is analyzed and a sensitivity analysis is performed for a dataset adopted from Mohammed et al. (2017). Moreover, the method developed by Fahimnia et al. (2013) is used to calculate the transportation-related emissions and costs as functions of the distance traveled. Processing costs in more developed regions are assumed to be lower than those in less developed ones. Carbon policies decisions are more stringent for more developed regions than for less developed ones.

The proposed MILP formulations are solved using an optimization software, i.e. GAMS 24.1. An Intel Core i3 M380 CPU (2.53 GHz) laptop with 4.00 GB of RAM is applied to carry out of all the numerical examples.

Comparative sensitivity analysis are conducted in three steps. The first sensitivity analysis is performed to demonstrate the superiority of the proposed model in the ShC decisions to the classic one, which does not include these decisions. Such a sensitivity analysis can present worthwhile information on the economic and environmental benefits of the proposed model. In the second sensitivity analysis, the impact of uncertainty on the performance of the supply chain is investigated under carbon cap policy. The third sensitivity analysis is designed to study the change rate of the performance (cost, development status, and emissions) by the mentioned parameters of carbon policies.

It should be noted that a social measure which is difference between the development level of the more developed regions and the development level of the less developed regions after the planning horizon (Δ) is evaluated in this study. It is calculated using equation (35).

$$\Delta \geq b_{T,r2} - b_{T,r1} \quad \forall r \quad 35$$

4.1. Supply chain as usual

Here, economic and environmental performances of the proposed model with shipment consolidation (ShC) and the classic one without carbon policies are analyzed.

Figure 3 illustrates the effect of the vehicle capacity on the transportation cost. Moreover, the total costs of both models are compared in Figure 4. The same sensitivity analysis is considered for the emissions, which is depicted in Figure 5. The results confirm that by considering full truck load, the proposed model will lead to low total and transportation costs as well as emissions compared to the classic model. Additionally, it can be realized that total consolidation cost may increase by the enlargement of the vehicle capacity. Therefore, as it can be observed in Figure 4, FTL is not preferable for high-capacity vehicles, especially with perishable products.

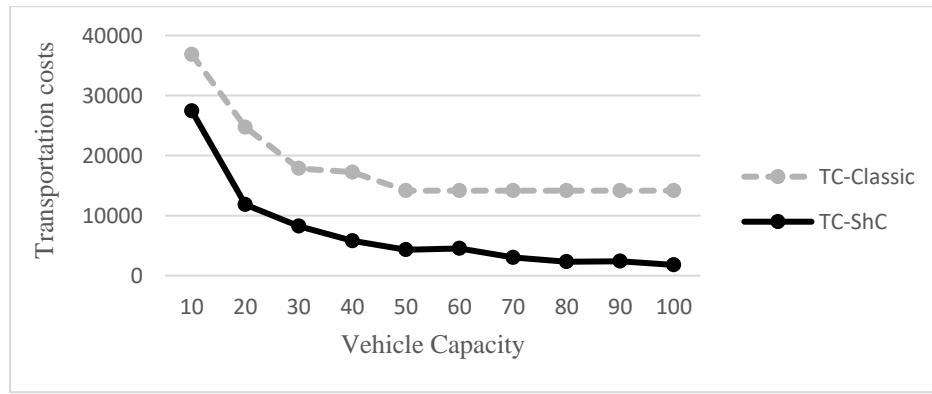


Figure 3. Comparison of transportation costs of two classic and ShC models.

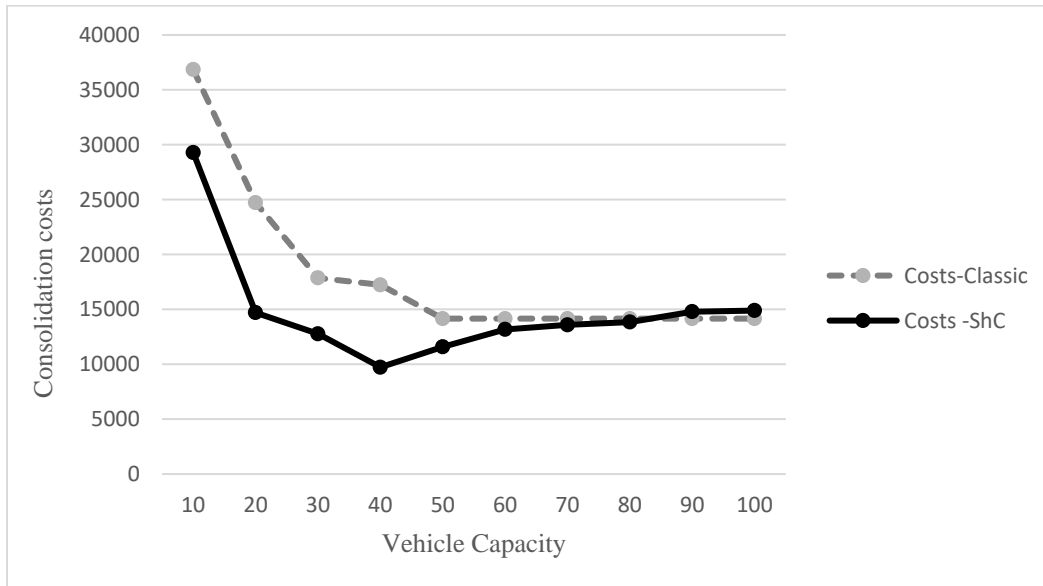


Figure 4. Comparison of the consolidation-related costs of classic and ShC models.

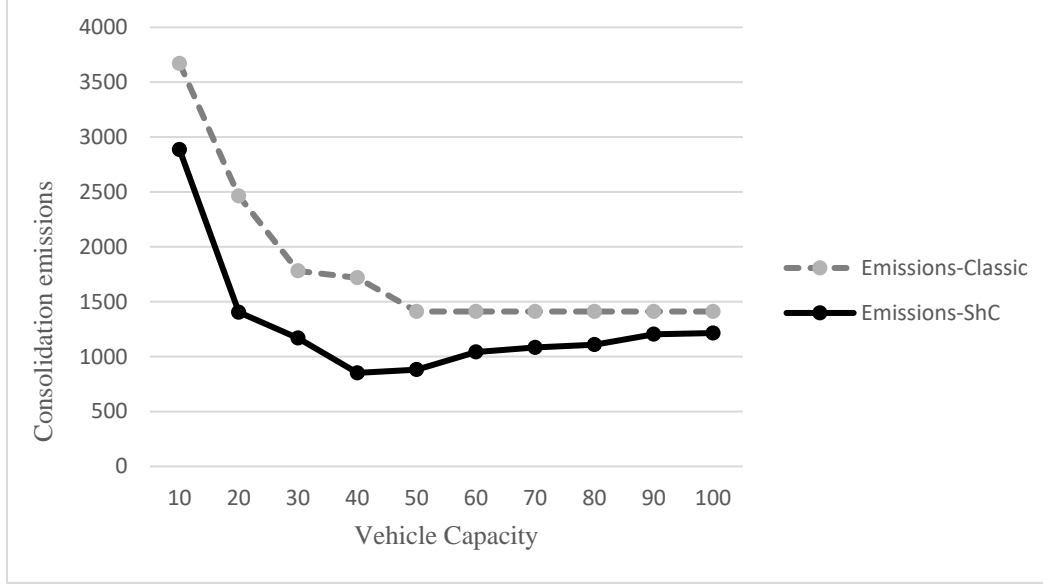


Figure 5. Comparison of the total emissions for both classic and ShC models.

4.2. Uncertainty analysis

Initially, sensitivity analysis is carried out for robustness parameters to demonstrate the performance of a robust model. As shown in Figure 6, when these parameters are zero, the extracted solution will be same as the result of the deterministic model, and by increase in uncertainty, costs increase. In fact, we have to reach a trade-off between cost and protection level. The more conservative the decision, the higher the cost. The impact of uncertainty on balancing can be seen in Figure 7.

To ensure validity of the proposed fuzzy method for uncertain budget, a sensitivity analysis is conducted for various values of α and the results are reported in Figure 8. The results demonstrate that with increase in α , the feasible region deteriorates; thus, the total cost and the difference between the development levels decrease.

Moreover, it is shown that by consideration of fuzziness for the protection level parameter (I), the model is capable to improve the performance of the designed network regarding to the both total cost and difference between the development levels, which are improved almost 0.5% and 2.2%, respectively, comparing to the robust model with deterministic protection level.

4.3. Impact of the carbon cap policy

By ignoring the carbon cap constraint in the model, the network will perform economically without requiring to pay attention to the environment and sustainability. The numerical analysis confirms that by setting a proper carbon cap for various regions, the supply chain will activate supply elements in less developed regions. It will lead to a balanced regional development. As depicted in Figure 9, as long as the carbon cap of the more developed regions is not constrained, all production occurs in the more developed regions (due to lower cost), so the development level of the less developed regions becomes zero; but, with reduction in the carbon cap of the more developed regions, the amount of production and the development level of less developed regions begin to increase.

Limiting emissions and motivating less developed regions are advantages of the carbon cap policy. It means that the proposed model would be beneficial in terms of all the three pillars of sustainability. Also,

it is concluded that determining the appropriate carbon cap in this policy is very important and proper decision will lead to favorable sustainability results.

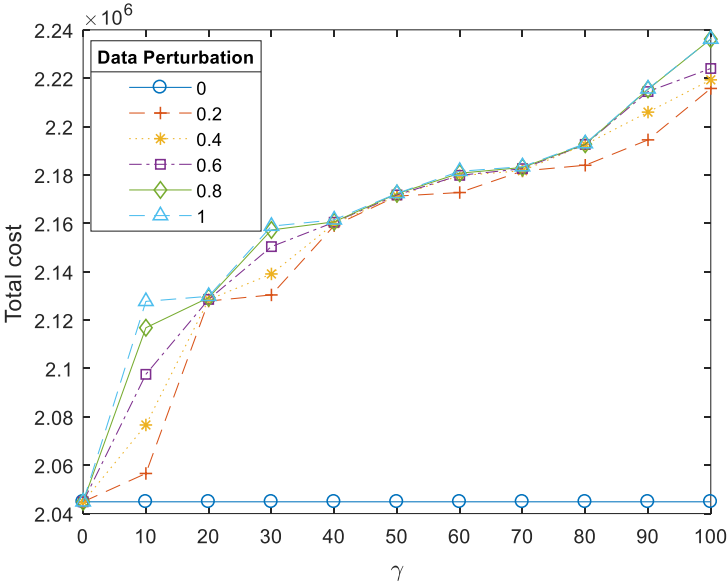


Figure 6. Effect of the robust parameters on the total cost.

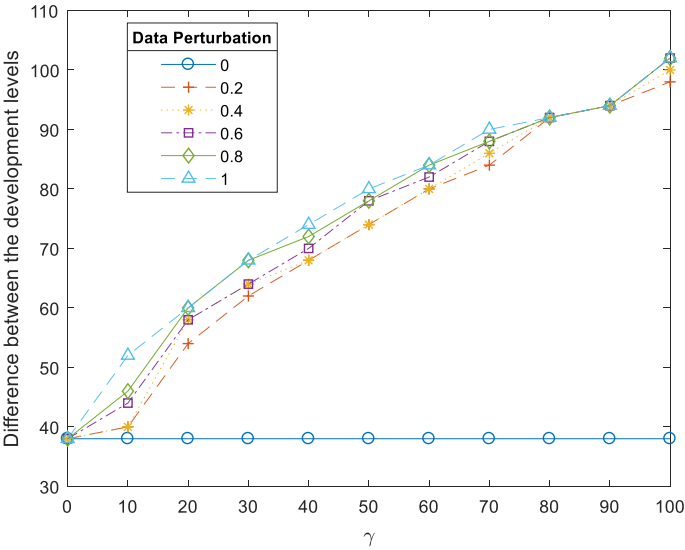


Figure 7. Effect of the robust parameters on the balanced development.

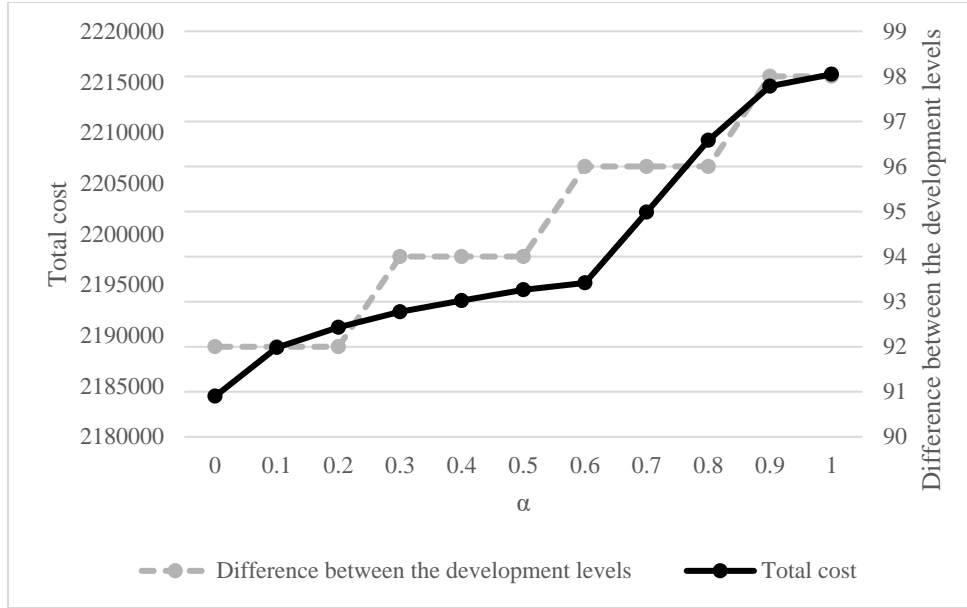


Figure 8. Sensitivity analysis of α for total cost and development sustainability.

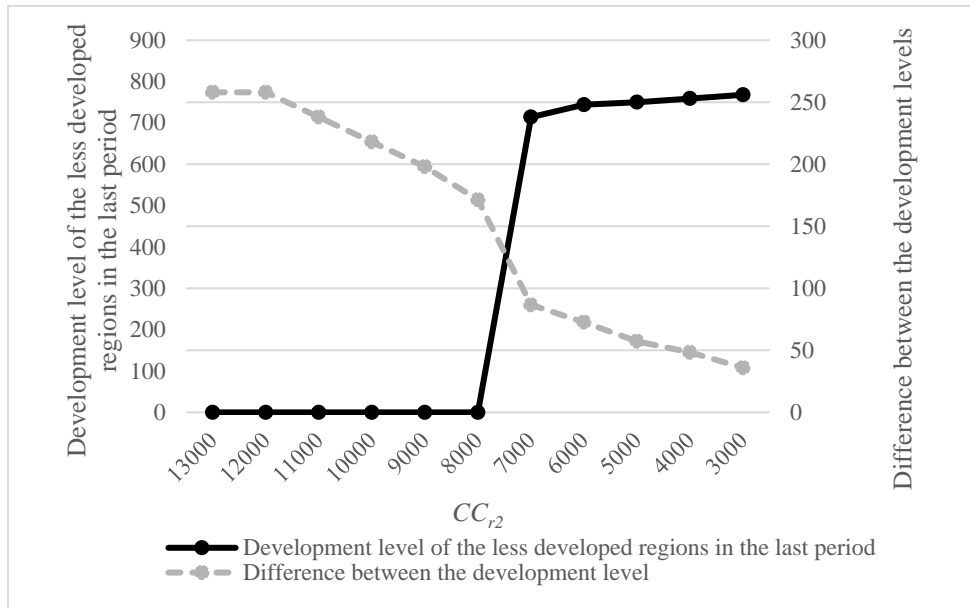


Figure 9. Developmental variations in the less developed regions and balancing the more developed regions by tightening the carbon cap .

4.4. Impact of carbon tax policy

The carbon tax rate for the less developed regions was set to 10 and we analyzed sensitivity of the carbon tax rate in the more developed regions. The results are shown in **Figure 10**.

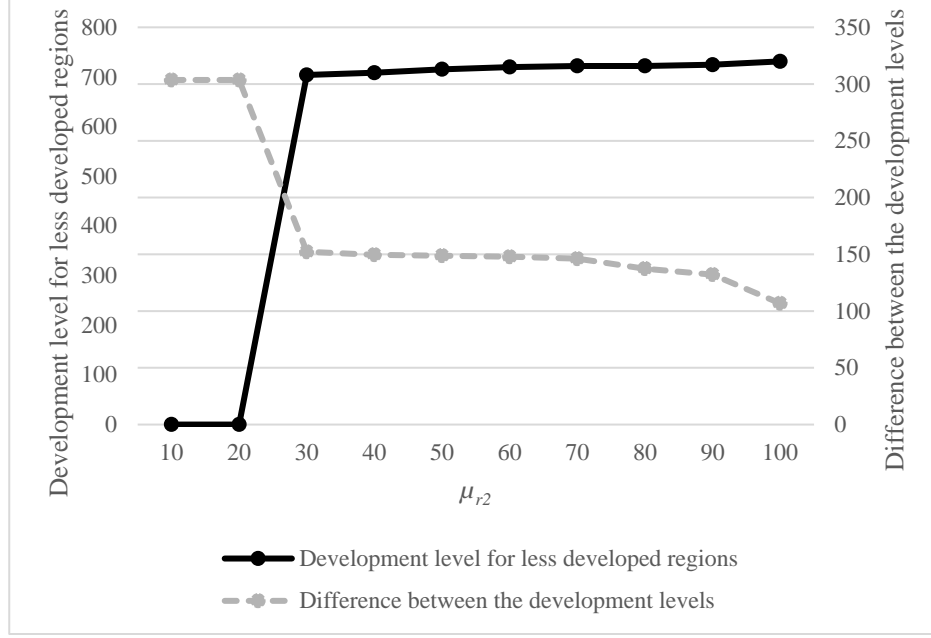


Figure 10. Impact of carbon tax of the more developed regions on development of the less developed ones.

An increase in μ_{r2} will reduce the difference between the development levels of the two regions. Therefore, it is concluded that carbon tax in the less developed regions should be lower than that in the more developed ones, because by setting μ_{r2} more than μ_{r1} , the network will tend to activate elements of the less developed regions, leading to a balanced regional development.

4.5. Impact of carbon cap-and-trade policy

Carbon prices are one of the most important success factors in the carbon policies (Chao et al., 2019). Some researches, such as Xu et al. (2016) and Mohammed et al. (2017), assumed the buying and selling prices equal, while others, like Jin et al. (2013), stated that the carbon buying price would be higher than carbon selling price. In this study, it is proposed that the buying price in the less developed regions should be lower and, similarly, the selling price in such regions should be higher than those in the more developed regions.

The effect of buying price for developed regions is analyzed. As depicted in figures 10 and 11, by setting a proper value for the buying price, emissions can be limited and there is a positive impact on the balanced regional development. Based on the numerical analysis, it was concluded that by setting the carbon credit parameters in the order of $p_{r2}^s < p_{r1}^s < p_{r1}^b < p_{r2}^b$, the best results would be achieved.

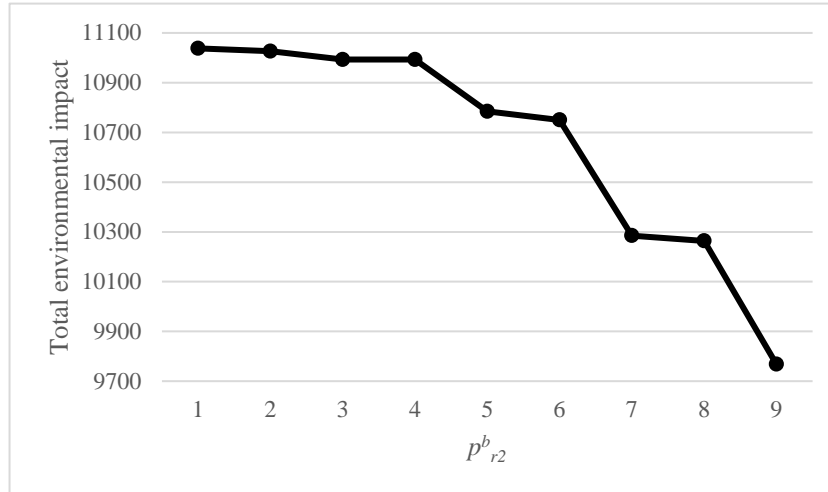


Figure 11. Impact of carbon buying price of the more developed regions on total environmental impact.

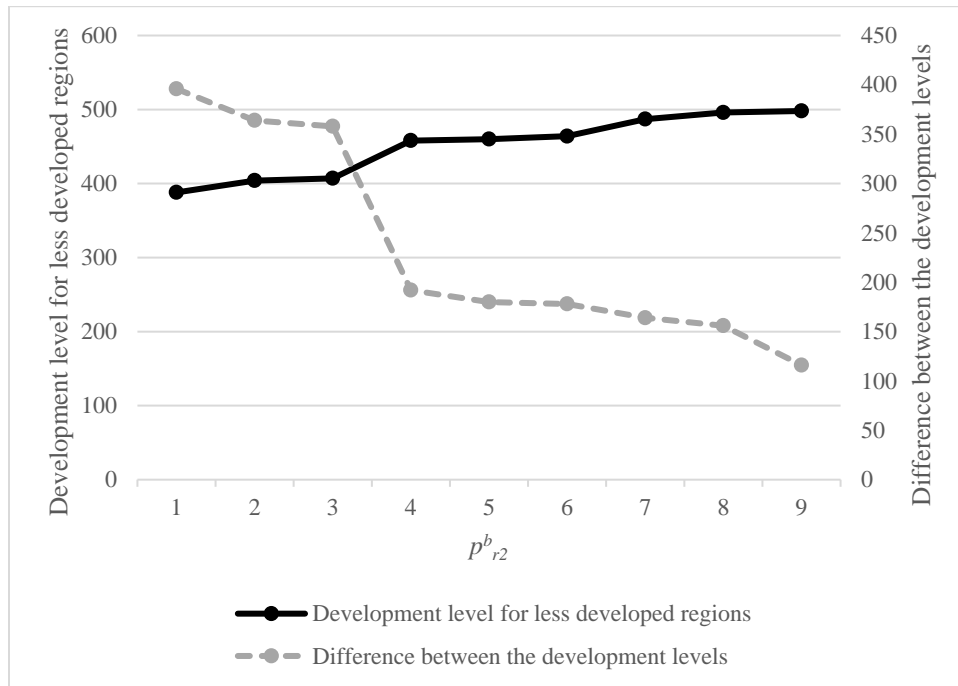


Figure 12. Impact of carbon buying price of the more developed regions on development of the less developed regions.

4.6. Impact of carbon offset policy

Similar to previous policies, the carbon offset policy is analyzed. The impact of carbon offset policy on the development level for various values of the carbon offset price follows the same pattern as that in figure 11.

4.7. Comparison of the four investigated policies

Here, performances of four carbon regulatory mechanisms are analyzed and compared. The related parameters are set according to Table 4. The results of the comparison are reported in Table 5.

Table 4- Values of the parameters related to carbon policies.

$CC1$	$CC2$	$\mu1$	$\mu2$	$p1^s$	$p2^s$	$p1^b$	$p2^b$
6000	5000	50	50	10	8	12	13

Table 5- Numerical comparison of four investigated carbon policies.

Carbon policies	Total cost corresponding to			Emissions emitted by			Total development level for			Difference between the development levels
	Less developed regions	More developed regions	Whole regions	Less developed regions	More developed regions	Whole regions	Less developed regions	More developed regions	Whole regions	
CCP	1333025	807163	2140188	6000	5000	11000	300	492	792	192
CTP	1436009	952407	2388416	7338	6634	13972	395	437	832	42
CCTP	1263021	739221	2002242	4123	4635	8758	374	428	802	54
COP	1332572	806330	2138902	6000	5000	11000	301	491	792	190

The performed analysis demonstrates that a proper carbon regulatory mechanism should be selected based on sustainability characteristics of the region as well as the targeted sustainability direction. For instance, if achieving a balanced development is the most important sustainability target, then, the carbon tax policy is a more effective mechanism. On the other hand, if the total cost and environmental impact are critical sustainability factors, then, the carbon cap-and-trade is a more efficient and desirable carbon policy.

5. Case study and managerial implications

In this section, a case study is conducted to better understand how different carbon regulatory mechanisms influence the SCND. The studied case is adopted from Xu et al. (2016), which is inspired by the plastic industry with four potential manufacturers, four customers, two types of product, three price levels and twenty time periods. Regional development change over the planning horizon is depicted for each carbon policy in Figure 13. The results confirm that by applying CTP and CCTP, a more balanced regional development is achieved.

Total costs and carbon emissions of the classic model, the proposed model without carbon policies, CCP, CTP, CCTP, and COP (by setting their parameters to appropriate levels) are reported in Table 6. It is obvious that imposing carbon policies decreases the carbon emission while increases the total cost. The proposed model is the most cost effective one and it has lower emissions than the classic model. In adopting the carbon policies, it is concluded that CTP leads to the highest cost (similar to the observations of Marti (2015), Fareeduddin et al. (2015), and Zakeri (2015)) and the lowest emissions are achieved by imposing the CCTP (like the comparisons presented by Mohammed et al. (2017) and Marufuzzaman et al. (2014)).

The managerial implications of this research as well as the findings in practice and theory are presented as follows.

First, one of the most remarkable research gaps, namely, achieving sustainable development of supply chain and analyzing the impact of the SCND model on the total profit of the supply chain, is filled. This leads that the managers by considering profit, development level, and carbon emissions, design the optimal configuration of a sustainable supply chain and maximize their profit.

Second, introducing carbon policies and optimizing the total profit for less and more developed regions extends the traditional supply chain network design problem to a comprehensive sustainable model. This research reveals that the emissions and total cost from both sides can be reduced and consequently more customers can be attracted. The companies also do not need to spend too much cost to obtain the environmental, economic and social targets.

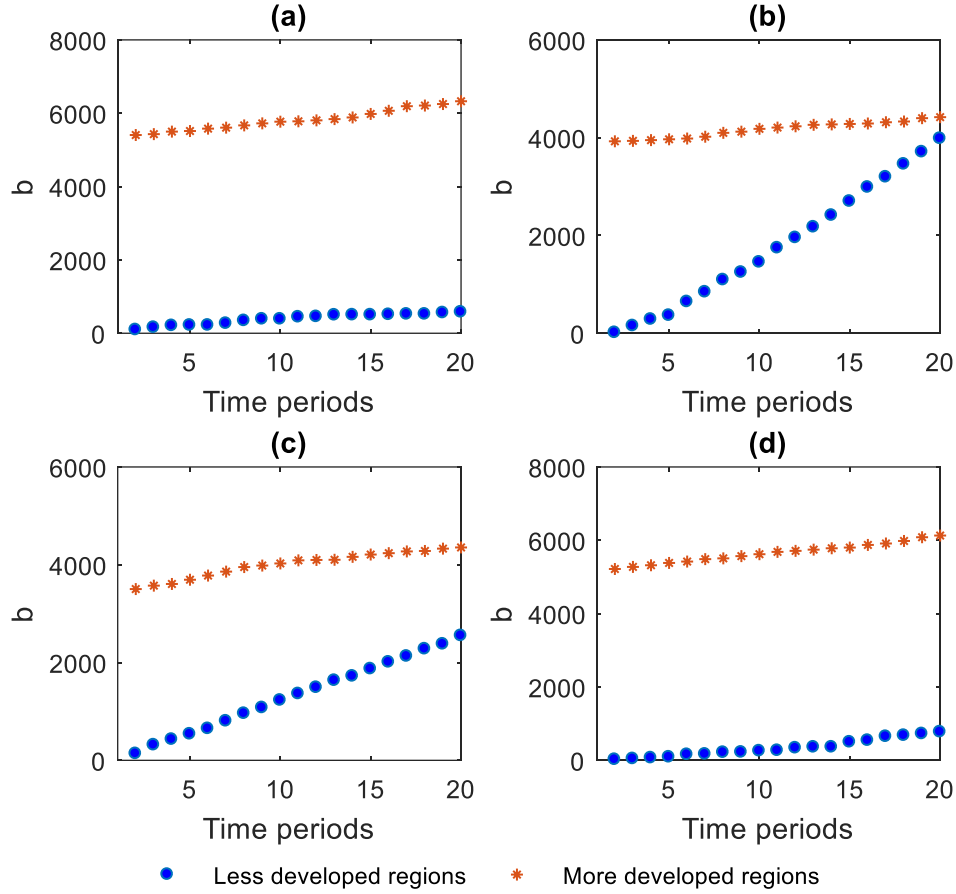


Figure 13. Regional development levels during the planning horizon for (a) CCP, (b) CTP, (c) CCTP and (d) COP.

Table 6- Comparison of total costs and carbon emissions by four carbon policies and without policy for the studied case.

Carbon policy	Total cost	Carbon emissions
CCP	30708230	9622
CTP	31708230	10034
CCTP	29209050	9444
COP	30209320	9569
ShC	25211500	10133
Classic	28321420	10486

Third, as it is shown, by applying the propped model the country's developmental level improves. As a consequence, unemployment rate, crimes, corruption, delinquency, etc. decrease and motivation, hope, and general welfare of the society will be enhanced. Moreover, improving of the development level stimulates the economy of country, thus the return on the investment increases and a virtuous circle is seen (Mota et al., 2018).

Fourth, a relationship between demand and price is presented. It can help the managers to maximize the total profit of the supply chain.

Fifth, to design an almost realistic supply chain network, a novel multi-period and multi-product SCND model considering shipment consolidation is proposed. This can be a cost-effective way to save money as well as an advisable tool to protect environment. Generally, it can be claimed that investing as well as designing a supply chain network by applying of the presented paper would be economically and environmentally advantageous.

Finally, this research can present a guidance on environmentally friendly behavior of companies to enhance the consumers attractiveness and it is also a reference for the government in considering carbon policies.

6. Conclusions

This paper presents an optimization model to address a novel multi-product and multi-period supply chain network design problem considering shipment consolidation. An adequate literature review is carried out and relevant knowledge gaps are identified. The proposed model properly contributes to fill the identified gaps. The proposed model covers dimensions of sustainability, namely economic, environmental, and social. It is extended to consider the carbon footprint of supply chain facilities and transportation. For a deeper understanding of emissions, four carbon regulatory mechanisms, namely carbon cap, carbon tax, carbon cap-and-trade, and carbon offset policies, are modeled and then, their potential structural and financial impacts on the supply chain are analyzed in a more sustainable manner. The main contribution of this paper is designing of a supply chain network addressing sustainable development through imposing proper carbon regulatory mechanisms. Moreover, in this study, development of all regions, especially the less developed ones, is the main goal. To make supply chain needs more realistic, carbon emissions generated from the activities are considered as uncertain parameters using a hybridized approach of robust optimization and fuzzy programming. Through the experimental analysis, it is concluded that carbon policies, in addition to reducing environmental impacts, would affect the behavior of the system, development level, and supply chain network design. As the carbon cap of the more developed regions decreases or the carbon tax, market price of carbon or the carbon offset in these regions increases, the amount of production in the less developed regions and their development level as well as the development level of the community will improve. As a consequence, unemployment rate, crimes, corruption, delinquency, etc. decrease and instead motivation, hope, and general welfare of the society will be enhanced. The performed analysis demonstrates that a proper carbon regulatory mechanism can be selected based on sustainability characteristics of the region as well as the targeted sustainability direction. For example, the lowest total cost and the lowest emissions are achieved by imposing the CCTP. If achieving a balanced development is the most important sustainability target, then, the CTP is a more effective mechanism. Moreover, based on the analyzed numerical example, it is found out that the use of shipment consolidation decisions can reduce cost and environmental impacts, so the model applying of these decision is very economically and environmentally beneficial.

Some extensions of this study can be considered in the future research. For example, optimization of carbon policies regulations through a mathematical model might be a proper direction. Moreover, considering the carbon policies regulation problem in a bi-level programming structure can be another valuable direction. Furthermore, the demand function can be handled as an uncertain parameter. Other criteria of CDI such as health, education and so on can be considered as a future study to measure development level of regions and to evaluate sustainability.

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