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Supply chain network design considering sustainable development paradigm: A case study in cable industry

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A B S T R A C T

The concern about environmental and social impacts of business activities has led to introducing a new paradigm called, sustainable development. It can help to build a low-carbon high-growth global economy and guarantee the global well-being of people. In this paper, three pillars of sustainable development, i.e., economic, environmental, and social, are considered and discussed to design a supply chain network. The proposed model tries to maximize profit primarily while capturing societal community development by prioritizing the less developed regions. Moreover, the model ensures that the environmentally friendly facilities can operate in the supply chain network while others have to be repaired. Furthermore, quantifying the benefits of transportation decisions in terms of both cost and environmental impact savings to improve the sustainability of logistics systems is considered. In addition, the model is regarded as robust programming for the problem to approximate real situations. The proposed model is implemented in some numerical examples and in a real case study. Numerical results and computational analysis are indicative of the significance of the model and through conducting the case study, it is demonstrated that the proposed model can be implemented successfully in practice and it would be beneficial to all the three pillars of sustainable development. Moreover, the managerial insights for the managers of the supply chain networks are provided to make the most appropriate decisions.

1. Introduction

Nowadays, growing environmental concerns and social legislations have enforced the enterprises to consider them along with economic performance as three pillars of sustainability (Kannegiesser et al., 2015). This issue has been emphasized by 2030 Agenda approved by UNCTAD Secretary General's Report (2011) as well as the 2005 World Summit Outcome Document (Mahtaney, 2013 and Basera, 2013). For the first time in 1987, the concept of “Sustainable Development” was introduced in the Brundtland Report and it was discussed with problems such as population growth and lack of sufficient resources in the future. Sustainable development means “meeting the requirements of the present without compromising the ability of future generations to fulfill their own needs” (Brundland Report, 1987) and it considers triple bottom line concept (3Ps “people, planet, profit”) (Elkington and Rowlands, 1999). Promoting sustainable development is the only way to resolve most of the global concerns such as water scarcity, inequality, hunger, poverty, and climate change. According to the previous related studies like Pishvaee et al. (2014) and Arampantzi and Minis (2017), estimating and formulating environmental and social impacts are sophisticated efforts; however, they are valuable and can play a significant role in mitigating the worldwide concerns (Zhalechian et al., 2016). Govindan et al. (2015b) reviewed 328 papers about supply chain network and emphasized that designing this network was a remarkable gap and future research opportunity. It should be noted that, previously, Talaei et al. (2016) had suggested this type of problem under sustainable development

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paradigm as an interesting and important topic for future research.

In this study, three inseparable dimensions of economy, environment, and society are considered to design a sustainable supply chain network. An economically sustainable system should concentrate on equal and balanced economic growth as well as on increase in profit without harming people and the environment. In this paper, a “sustainable development by weighted balanced regional development scheme” is considered for different regions to distribute the wealth and growth. Moreover, it is tried to maximize total network profit, while optimal transportation decisions, like vehicle selection based on the full truckload (FTL) strategy, are made. It should be noted that this strategy is aligned with the environmental concern. Without consideration of these aspects the model imposes more costs and brings more damages to the environment. Moreover, without applying the proposed methodology, there is an unbalanced and unfair economic growth, the more developed regions are more advanced and the less developed regions are deprived. It is clear that under such circumstances, the overall supply chain profit will be reduced significantly. An environmentally sustainable system should conserve the environment, save the water, reduce the effects of greenhouse gases and etc. Thus, here, with respect to the environmental concern, during strategic periods, manufacturers are controlled to have renovation and repair if their environmental impacts exceed their permitted cap. This strategy will assure having a cleaner production inside the supply chain. Overhaul maintenance, improving production methods, and renewing of machinery are some examples of renovation and repair activities. If these aspects are ignored, high environmental impact would result in environmental problems, damages, and disease. A socially sustainable system should include fair and equitable distribution of social services, quality of life, healthcare and education (Lakin and Scheubel, 2010). To resolve the discriminations and differences in a society with harmonious growth and development, economic balance and cohesion in various regions are required. Countries that fail to achieve economic balance between different regions weaken over time and recede from economic development. In this research, development of regions based on their potential capabilities is considered for the supply chain network design (SCND) to achieve a balanced economy in a planning horizon. The previous studies such as Zhalechian et al. (2016), Zahiri et al. (2017), Arampantzi and Minis (2017) and Ghaderi et al. (2018), which considered regional development, only focused on balancing of economic development and ignored some significant and effective criteria. We believe that such development is not just equity and fair. Less developed regions with higher potential for growth (in terms of climate conditions, inhabitants, etc.) or the ability to communicate more closely with neighboring countries should be given greater attention than other less developed regions. This brings the proposed model closer to the sustainable development paradigm than the similar research works.

Another important concern in the network design is uncertainty of parameters. Many researchers such as Sherafati and Bashiri (2016) and Bairamzadeh et al. (2015) believe that uncertainty should be addressed in the SCND due to the nature of the model and its parameters and it is never possible to make decisions certainly about the supply chain plans. It is clear that modeling of supply chain without taking uncertainty into account cannot be actual and the need for a model overcoming the drawbacks of using deterministic optimization models has frequently been emphasized (Pishvaee et al., 2012; Yu and Solvang, 2018). Due to the fact that the prices of components and raw materials are not precise and readily available, the procurement cost and, consequently, the manufacturing cost should be considered as uncertain parameters. To do so, a new formulation based on Bertsimas and Sim (2004) is developed in this study to make decisions closer to the real-world situations.

In general, the advantages of the proposed model in comparison with other studies are shown through the numerical examples and a case study. For example, the proposed model is more environmentally friendly than the model in which the repair decisions are ignored. Since the best arrangement of vehicles is selected using the proposed FTL strategy, this study can be an advisable option to reduce the imposed costs and bring less damages to the environment. This paper, which devises a weighted balanced regional development scheme, can improve the development level as well as the well-being of people significantly compared to the classic models that have not addressed this sustainability concern. Finally, we can claim that the proposed model can provide the more reliable solutions in comparison to the deterministic model.

Main contribution of this study that distinguishes our efforts from the existing published works in the literature is design of a supply chain network by considering of sustainable development with a few aspects which are summarized as follows:

- Consideration of a growth potential scheme in the proposed mathematical model to reach a weighted balanced regional development at the end of the planning horizon. It may lead to a balanced improvement on general welfare, unemployment rate and finally crimes and corruption levels.
- Consideration of clean transportation in the network utilizing the FTL strategy.
- Allowing environmentally friendly manufacturers to be activated in the supply chain while others have to be repaired and renovated.
- Tackling the manufacturing cost as an uncertain parameter and applying robust optimization to create a protected solution against uncertainty.

The remainder of this research is organized as follows. First, a literature review for the related studies is presented in section 2. The proposed SCND model is described in detail in section 3. The mixed integer nonlinear programming (MINLP) model is converted to a mixed integer programming (MIP). Then, the robust counterpart of the proposed model and the applied approach to handle the multi-objective model are presented. In section 4, several numerical examples are analyzed to verify the proposed approach and model. Moreover, a real case study is presented and analyzed and then, some managerial insights are drawn in section 5. Finally, the concluding remarks are made and outlines for future studies are presented in the last section.

2. Literature review

Studies involving the SCND models have already been reviewed in some papers, e.g., Govindan et al. (2015b) and Eskandarpour et al. (2015), the interested readers can refer to them to further study. In this section, the studies taking into account all the three dimensions of the triple bottom line (TBL) are presented separately based on the aspects of sustainability. Afterwards, some researches considering their proposed models in the uncertain environments are provided.

2.1. Social aspects

One of the dimensions of the TBL is socially responsible, which has attracted considerable attention for recent years in both academia and the industrial world. The various studies involving this concern in supply chain network design models are divided into three categories: Societal commitment, consumer issues and work conditions (Eskandarpour et al., 2015). Table 1 summarizes

Table 1
Summary of related supply chain network design containing TBL approach literature.

Reference	Social aspects	Environmental aspects	Economic aspects	Tackling with uncertainty
Pishvaee et al. (2014)	D, C, W	OEn		F
Ramos et al. (2014)	W	GHG		
Devika et al. (2014)	W	OEn	OEc	
Mota et al. (2015)	W	OEn		
Zhang et al. (2016)	C	OEn		
Zhalechian et al. (2016)	D, W	GHG	OEc	F, S
Tsao et al. (2016)	C, W	GHG		F
Soleimani et al. (2017)	C, W	GHG, PC		F
Zahiri et al. (2017)	D, W	GHG, PC		
Arampantzi and Minis (2017)	D, W	GHG, OEn		
Babazadeh et al. (2017a)	W	OEn	OEc	F
Babazadeh et al. (2017b)	D	OEn, WFP	OEc	
Feitó-Cespón et al. (2017)	C	OEn, WFP	OEc	S
Rahimi and Ghezavati (2018)	W	GHG		S
Govindan et al. (2018)	C, W	OEn	OEc	
Fattahi and Govindan (2018)	D, W	OEn	OEc	S
Ghaderi et al. (2018)	D, W	OEn		R, S
Allaoui et al. (2018)	W	GHG, WFP		
Mota et al. (2018)	W	OEn		S
Sahebjamnia et al. (2018)	W	OEn		
Rahimi et al. (2019)	W	OEn		S
Current research	WBD,C, W	GHG, WTP, PC, Rp	OEc	R

D: Development/Balanced development, WBD: Weighted balanced development, C: Consumer issues, W: Work conditions, GHG: Greenhouse gas, WFP: Water footprint, PC: Permitted cap, OEn: Others environmental aspects, Rp: Repair, OEc: Others economic aspects except optimization of cost/profit, R: Robust, F: Fuzzy, S: Stochastic.

the sustainable SCND papers and the second column reveals the corresponding social categories. Societal commitment aspect includes some concerns such as increasing regional (Fattahi and Govindan, 2018) and balancing of regional development (Zahiri et al., 2017). Customer satisfaction is second social target, which it was addressed by some scholars such as Zhang et al. (2016) and Feitó-Cespón et al. (2017). As the final social aspect, work conditions is imposed in the social supply chain networks. Some researchers like Arampantzi and Minis (2017) and Govindan et al. (2018) improved employee satisfaction as well as the work environment. Most authors considered creating job opportunities and lost working days caused by damages to the work.

The most important issue in social responsibility dimension is attention to the regional development, which has often been neglected (as Table 1 shows); therefore, in this study, this important research gap has been considered. The proposed model considers some significant criteria beyond those in the previous studies, e.g., potential of regions for growth, their ability to communicate more closely with neighboring countries, etc., to achieve a fair and equitable regional development. Other aspects of social responsibility, such as customer satisfaction and working conditions, are included in the model as well. In fact, the proposed model covers all the seven focal subjects included in "International Guidance Standard on Social Responsibility-ISO 26000" (ISO, 2010).

2.2. Environmental aspects

The second dimension of the TBL is the protection of the environment. Increased public awareness of the environmental concerns has raised the interest in designing an environmentally friendly supply chain network (Pishvaee and Razmi, 2012) and the literature in this area is moving toward "green" supply chain management. Recently, Waltho et al. (2018) reviewed papers on green supply chain network design, carbon emissions, and environmental policies and emphasized the importance of these models. The researchers have considered various environmental aspects in sustainable SCND. For example, Pishgar-Komleh et al. (2017), de Figueiredo et al. (2017), Yadav et al. (2018), Liu et al. (2018a), Liu et al. (2018b), and Liu et al. (2018c) minimized greenhouse gas (GHG) or carbon footprint; Mathioudakis et al. (2017) and Zhang et al. (2017) concerned the water footprint; Mohammed et al. (2017) and Zahiri et al. (2017) considered the carbon policies like cap-and-trade and so on; Arampantzi and Minis (2017) addressed the waste reduction. Some scholars such as Zhalechian et al. (2016) considered other aspects like attention to fuel consumption and energy.

This study takes water footprint and CO_2 footprint into consideration in terms of environmental impact. Eskandarpour et al. (2015), by reviewing the papers in the field of sustainable supply chain network design, concluded that the most common metric to measure environmental impact is the carbon footprint, which is the total amount of GHG emitted by a company's supply chain. Other scholars emphasize this statement. For example, Pandey and Agrawal (2014) presented that being a quantitative indicator of the emission of greenhouse gases, carbon footprint is usefulin identification of environmentally friendly production systems and climate change lessening measures. Tjandra et al. (2016) revealed that among different quantitative indicators, the carbon footprint has gained widespread popularity and application because of its role in assessing environmental quality and management. Waltho et al. (2018) stated that carbon footprint plays a role as important as cost and price in supply chain configuration. Yadav et al. (2018) declared that carbon footprint can provide insights on the environmental impacts. Moreover, attention to this factor has highly been recommended to mitigate the economic, environmental, and social negative impacts by other researchers (e.g., Santibanez-Gonzalez, 2017).

The last decades witnessed a rapid economic development and population growth, which cause water consumption, and also water is an increasingly scarce resource, so water footprint should be considered as an effective sustainability indicator (Zhang et al., 2017). Since water footprint presents decision making support about water resources management (Hoekstra and Chapagain, 2006) and its evaluation is one of the priorities for water sustainability from the perspective of water consumption and pollution

(Čuček et al., 2015), some researchers such as Hoekstra (2003) and Zhang et al. (2017) proposed water footprint as an indicator to evaluate water resources utilization associated to human consumption. This indicator is so important and as it was shown, this should be included in a sustainable supply chain model containing TBL as well as carbon footprint. As Allaoui et al. (2018) presented carbon footprint and water footprint indicators should be considered together, but this is often ignored, and most researchers, as introduced above, impose one of them into their green models. According to their advantages, consideration both impact on the supply chain more efficiently, so in this study both indicators are taken into account.

In this paper, the facilities are evaluated from the environmental viewpoint (carbon footprint and water footprint) every several years. Environmentally friendly facilities can operate in the supply chain network and others have to be repaired. To the best of our knowledge, this study is the first work to take renovation and repair decisions into consideration in designing a sustainable supply chain network.

2.3. Economic aspects

Another dimension of TBL is the economic, which is the most traditional and most popular objective function of the SCND models (Govindan et al., 2015b). The majority of TBL studies consider environmental impacts as a separate objective besides other economy-related objectives, while others apply some mechanism to achieve both goals. Companies incur huge costs transporting their products; on the other hand, the most polluting activity is transportation; therefore, reduction of the amount of transportation can be a significant way to save costs and keep the environment cleaner. Some suggested strategies that reduce transportation activity include economies of scale (Wu et al., 2015; Tsao et al., 2016; Hsu and Li, 2011), shipment consolidation (Rizk et al., 2006; Park et al., 2016), cross-docking operations (Mousavi and Tavakkoli-Moghaddam, 2013; Govindan et al., 2015a), and outsourcing of transportation activities to 3 PL companies (Ghaffari-Nasab et al., 2016).

Full truckload is a preferable mechanism to some of the mentioned strategies. It leads to reducing the number of fleet and, consequently, decreasing the total cost as well as the environmental emissions.

It should be noted that there are a few researches that consider transportation decisions in the sustainable SCND. For example, Ramos et al. (2014) and Govindan et al. (2018) considered a vehicle route planning; Feitó-Cespón et al. (2017), Arampantzi and Minis (2017), and Fattahi and Govindan (2018) addressed transportation mode selection; and Devika et al. (2014) tried to minimize the number of vehicles. The current study deals with the vehicle capacity efficiency. It seeks to reduce the total number of used vehicles and, consequently, decrease cost and environmental impact.

2.4. Tackling with uncertainty

It is clear that modeling of supply chain without considering uncertainty cannot be actual and the need for a model overcoming the drawbacks of using deterministic optimization models has frequently been emphasized (Pishvaee et al., 2012; Yu and Solvang, 2018). Klibi et al. (2010) reviewed SCND problems under uncertainty in the literature and discussed their classification comprehensively. We refer the readers to the study by Daghigh et al. (2017), which includes a review of the literature related to mathematical programming models and solution methods for sustainable SCND in an uncertain environment. The sustainable supply chain network design models containing TBL approach, have handled the uncertain parameters by robust (Ghaderi et al., 2018); fuzzy (Soleimani et al., 2017; Tsao et al., 2018; Babazadeh et al., 2017a); and stochastic (Feitó-Cespón et al., 2017; Rahimi and Ghezavati, 2018; Fattahi and Govindan, 2018), and Rahimi et al., (2019) programming. Klibi et al. (2010) believed that robustness is an essential condition to ensure sustainability. Attention to the suggestions of the above-mentioned papers and the features of the considered problem encouraged us to apply the Bertsimas and Sim (2004) approach to cope with the uncertainty and create a protected solution against uncertainty.

According to the review of related studies, it can be concluded that in the models containing three dimensions economy, environment and society, which called the TBL principle, designing of a sustainable supply chain network is a remarkable gap. There is a limited studies considering sustainable development, because of its complexity and there is a need to propose a model addressing TBL aspects and it can estimate and quantify three dimensions. Most supply chain models considering social aspects, try to increase job opportunity in the designed network, while the development is often ignored. However, by regional development, job opportunities can increase as well and it has many advantages that encompass the entire community and have some economic and social benefits. Moreover most sustainable SCND models have one objective function which tries to maximize the profit or minimize the cost and also they consider another objective function as minimization of environmental impact. However, by utilization of some mechanisms such as FTL they can improve both targets, simultaneously. Evaluating the performance of supply chain facilities from an environmental point of view, and in particular, efforts to improve them are the gaps in TBL related studies which can be a remarkable future research opportunity. For example, by incorporating various carbon policies, the environmental impact can be reduced significantly. Furthermore, there are some approaches to handle uncertainty, like robust, fuzzy and stochastic programming. Most TBL problems containing the uncertain parameters have been modeled in the fuzzy or stochastic environments, however the body of the literature is very thin in the robust optimization. According to this fact that robustness is an essential condition to ensure sustainability (Klibi et al., 2010) and emphasis of some scholars such as Talaei et al. (2016), Ghaderi et al. (2018), and Dehghani et al. (2018) modeling of the sustainable SCND using robust programming can be considered by the interested researchers.

A brief review of the related previous studies can be observed in Table 1. According to Table 1, sustainable development with a weighted balanced regional development scheme has been seldom studied in previous related studies. To the best of the authors' knowledge, designing a sustainable supply chain network, which deals with the permitted cap as well as renovation and repair decisions, has not been addressed in the literature yet. Contrary to the previous published works, the proposed model is more general, in line with the real world, and it overcomes many of the existing weaknesses and presented research gaps. The most important, the most useful and the most recommended indicators are selected to design an effective and efficient sustainable supply chain network. For example development, people satisfaction (both customer and employee), carbon footprint, water footprint, FTL strategy, which identified based on a comprehensive literature review, are applied in the proposed TBL methodology.

3. Problem description

Here, first, problem definition and the underlying assumptions are presented and then, the model formulation is illustrated. A bi-objective nonlinear programming model is proposed to design a

Table 2
The sustainability aspects and proposed methodology to design of a sustainable supply chain network.

Bottom line	Indicators	Calculation approach	Considering in the model
Social	Work conditions	AHP	Parameter Sc_i
Social	Consumer issues		
Social, Economical	Societal commitment - Location	TOPSIS (For the beginning of the first period)	Parameter w_i
Social, Economical	Societal commitment - Development growth	Mathematical model (for updating the score at other strategic periods)	Decision variable Dv_{is}
Economical, Environmental	FTL	Mathematical model	Constrains 23 - 26
Environmental	Carbon footprint	Mathematical model	Constrains 19 - 22
Environmental	Water footprint	Mathematical model	

sustainable supply chain network with a weighted balanced regional development scheme. The network contains manufacturers, distribution centers, and customer zones. Products can be shipped from the manufactures to the distribution centers by different vehicles depending on their capacity and the model tries to maximize the vehicle capacity usage. In the proposed model, maximizing the profit is considered in the first objective function while the social responsibility and balanced development of regions are considered in the second objective.

The proposed model consists of three TBL aspects, which are economic, environmental, and social pillars as shown in Table 2. As illustrated, in each pillar, some indicators are identified to design an SCND considering the sustainable development paradigm.

The work conditions indicator is measured by the following criteria: insurance, stable employment, dismissals, rest periods, safety, health, and welfare status of employees. Responsiveness level to customers, their satisfaction, and after-sale services are used as consumer issues criteria. A social score is obtained by the AHP (Analytical Hierarchy Process) approach considering all the aforementioned criteria for each potential manufacturer. If the social score of a candidate does not reach a predetermined minimum social score, it cannot be selected as an opened manufacturer.

To achieve societal community development, two strategies are considered in this study. In the first strategy, new facilities are established in less developed regions at the beginning of planning horizon; thus, growth potential of each region is measured and considered as an input parameter to the proposed mathematical model. Growth potential of the regions is calculated by the TOPSIS (Technique for Order Preferences by Similarity to Ideal Solution) approach considering the following criteria: (1) Export Potential Score (EPS), (2) number of mines, (3) capacity of power plants, (4) agricultural land (% of land area), (5) agricultural irrigated land (% of the total agricultural land), (6) total road network, (7) freight transport volume, (8) number of full-time teaching staff at the universities, (9) population, and (10) unemployment rate. It should be noted that the EPS concept is innovative and it is obtained by the SAW (Simple Additive Weighting) approach considering the distance to neighboring countries. It is assumed that if a region is close to countries with higher GDP (Gross Domestic Product) will potentially have more export. So GDP of the neighboring countries are considered as weights and then distances between the regions to neighboring countries are calculated and after normalizing, EPS is calculated for each region according to equation (1).

$$EPS_i = \sum_{o \in O} NGDP_o \times \frac{\min_i dis_{io}}{dis_{io}} \tag{1}$$

where $NGDP_o$ and dis_{io} are normalized GDP of neighboring country o and distance between region i and neighboring country o, respectively.

Balancing of regional development is the second strategy for the societal community development. During the strategic periods, the model calculates regions development values and tries to make tactical decisions in order to eliminate regional inequality in the level of economic development. Less developed regions are determined in the mathematical model by comparison with a predefined development threshold. It is worth mentioning that the societal commitment is related to social and economic pillars.

Full truckload strategy is utilized to address both economic and environmental pillars of the sustainability.

Furthermore, the environmental impact is another main concern in this study. If the environmental impact (consisting of total CO_2 emission and water consumption) exceeds a permitted cap, the manufacturer has to be repaired and renovated. We refer the readers to Allaoui et al. (2018) for more information about the applied indicators of environmental pillar.

Assumptions

Main assumptions of this study are presented here:

- Two kinds of strategic and tactical time horizons are considered. Each strategic period consists of a few tactical periods (Fattahi et al., 2015; Badri et al., 2013).
- Manufacturing cost consists of purchasing cost of raw material and components from the suppliers as well as other production costs.
- The shortage is considered as a lost sales in the proposed model.
- There is no inventory at the beginning of the planning horizon. It is assumed that the inventory of the last tactical period in each strategic period is transferred to the first tactical period in the next strategic period.
- Developmental level of regions at the beginning of the planning horizon (Dv_{i0}) are predefined parameters.

3.1. Model formulation

Definitions of sets, parameters and decision variables used in the proposed model formulation are provided as follows.

Sets

I	Set of candidate locations for manufacturers, $i \varepsilon I$
J	Set of candidate locations for distribution centers, $j \varepsilon J$
P	Set of products, $p \varepsilon P$
S	Set of strategic periods, $s \varepsilon S$
T	Set of tactical periods, $t \varepsilon T$
V	Set of vehicles, $v \varepsilon V$

Parameters

u_i	Fixed cost for establishing manufacturer *i*.
a_j	Fixed cost for establishing distribution center *j*.
m_{ip}	Manufacturing cost per unit of product *p* at manufacturer *i*.
e_{ip}	Inventory cost per unit of product *p* at manufacturer *i*.
f_{jp}	Inventory cost per unit of product *p* at distribution center *j*.
c_p	Lost sale and lost goodwill cost per unit of product *p* for the network.
g	A penalty cost for each unit exceeding the environmental impact with a permitted cap.
h_i	Cost of renovation and repair for manufacturer *i*.
$CapM_{ip}$	Storage capacity of manufacturer *i* for product *p*.
$CapD_{jp}$	Storage capacity of distribution center *j* for product *p*.
τ_1	Importance of the establishing in the development (the strategic decisions).
τ_2	Importance of the operating in the development (the tactical decisions).
w_i	Growth potential of the corresponding region of manufacturer *i*.
θ	Realization rate of development.
Tr	Expected regional development threshold.
Sc_i	Social score of manufacturer *i*.
Mn	Minimum required social score for opening the manufacturers.
ζ_1	Normalization weight of CO_2 emission generated to produce one unit of a product.
ζ_2	Normalization weight of water consumed to produce one unit of a product.
Po_p	Emission generated to produce per unit of a product *p*.
WS_i	Water stress index for manufacturer *i*.
WP_{pi}	Water consumption to produce one unit of product *p* at manufacturer *i*.
PC	Maximum permitted cap for environmental impact of each manufacturer.
FT^v	Fixed cost for transportation by vehicle *v*.
FT^{Mx}	Fixed cost for transportation by the largest available vehicle.
VT^v	Variable cost for transportation by vehicle *v*.
VT^{Mx}	Variable cost for transportation by the largest available vehicle.
U^v	Maximum capacity of vehicle *v*.
U^{Mx}	Maximum capacity of the largest available vehicle.
L^v	Minimum capacity of vehicle *v*.
BN	A big number.

Integer decision variables

q_{ijpst}	Order quantity of product *p*, which is requested by distribution center *j* from manufacturer *i* in tactical period *t* and strategic period *s*.
n_{ipst}	Quantity of product *p*, which is produced by manufacturer *i* in tactical period *t* and strategic period *s*.
k_{ipst}	Amount of inventory of product *p* in manufacturer *i* in tactical period *t* and strategic period *s*.
l_{jpst}	Amount of inventory of product *p* in distribution center *j* in tactical period *t* and strategic period *s*.
b_{pst}	Amount of lost sales of product *p* in tactical period *t* and strategic period *s*.
D_{pst}	Demand of product *p* in tactical period *t* and strategic period *s*.
μ_{ijst}	Number of the largest vehicle traveling as FTL from manufacturer *i* to distribution center *j* in tactical period *t* and strategic period *s*.
$\lambda^v{}_{ijst}$	Quantity of products transported from manufacturer *i* to distribution center *j* by LTL (Less than truckload) vehicle *v* in tactical period *t* and strategic period *s*.

Continuous decision variables

Pr_{pst}	Price of product *p* in tactical period *t* and strategic period *s*.
TC_{ijst}	Transportation cost from manufacturer *i* to distribution center *j* in tactical period *t* and strategic period *s*.
TE_{is}	Total environmental impact emitted by manufacturer *i* in strategic period *s*.
Ex_{is}	Excessive environmental impact from a permitted cap by manufacturer *i* in strategic period *s*.
Dv_{is}	Developmental level of the corresponding region of manufacturer *i* in strategic period *s*.

Binary decision variables

x_i	1 if manufacturer *i* is established, otherwise 0.
y_j	1 if distribution center *j* is established, otherwise 0.
r_{is}	1 if manufacturer *i* needs to be repaired and renovated in strategic period *s*, otherwise 0.
η_{is}	1 if development level of the corresponding region of manufacturer *i* exceeds a minimum expected regional development threshold in the strategic period *s*, otherwise 0.
δ_{vijst}	1 if vehicle *v* travels from manufacturer *i* to distribution center *j* in tactical period *t* and strategic period *s*, otherwise 0.

Objective functions

$$\max Z_1=\sum_p\sum_s\sum_t(D_{pst}-b_{pst})\times \Pr_{pst}-\sum_i u_i\times x_i-\sum_j a_j\times y_j-\sum_i\sum_p\sum_s\sum_t\tilde{m}_{ip}\times n_{ipst}-\sum_p\sum_s\sum_t c_p\times b_{pst}$$
$$-\sum_i\sum_j\sum_s\sum_t TC_{ijst}-\sum_i\sum_p\sum_s\sum_t e_{ip}\times k_{ipst}-\sum_j\sum_p\sum_s\sum_t f_{jp}\times l_{jpst}-\sum_i\sum_s g\times Ex_{is}-\sum_i\sum_s h_i\times r_{is} \quad (2)$$

Objective function (2) maximizes total profit, which is the difference of total revenue and total cost. The revenue is multiplication of price by demand while demand depends on the price variable. Also, total costs borne comprises opening, manufacturing, lost sale, transportation, inventory, extra environmental impact, and renovation costs.

Objective function (3) is concerned with social responsibility and weighted balanced regional development as follows.

$$\max Z_2=\tau_1\sum_{i\in\bar{I}}w_i\times x_i+\tau_2\sum_i\sum_p\sum_s\sum_t w_i\times\left(n_{ipst}+\sum_j q_{ijpst}\right) \quad (3)$$

where $\bar{I}$ is a set of candidate locations for manufacturers in undeveloped and less developed regions. It is assumed that new manufacturers are established in candidate locations only in less developed regions, while the acquired scores are maximized. The second term of the objective function maximizes the production and transportation operations to improve the development level.

Constraints

Constraints of the proposed model are described as follows:

$$D_{pst}=\alpha_{pst}-\beta_{pst}\Pr_{pst} \quad \forall p,s,t \quad (4)$$

Equation (4) is related to demand with a linear relation to price (Yaghin et al., 2012 and Hong and Lee, 2013).

$$k_{i,p,s,t-1}+n_{ipst}=k_{ipst}+\sum_j q_{ijpst} \quad \forall i,p,s,t\ge 2 \quad (5)$$

$$k_{i,p,s-1,T}+n_{i,p,s,1}=k_{i,p,s,1}+\sum_j q_{i,j,p,s,1} \quad \forall i,p,s\ge 2 \quad (6)$$

$$\sum_j l_{j,p,s,t-1}+\sum_i\sum_j q_{ijpst}+b_{pst}=\sum_j l_{j,p,s,t}+D_{pst} \quad \forall p,s,t\ge 2 \quad (7)$$

$$\sum_j l_{j,p,s-1,T}+\sum_i\sum_j q_{i,j,p,s,1}+b_{p,s,1}=\sum_j l_{j,p,s,1}+D_{p,s,1} \quad \forall p,s\ge 2 \quad (8)$$

Equations (5)–(8) express inventory balance constraints in manufactures and distribution centers (Park et al., 2016).

$$k_{i,p,s,t-1}+n_{ipst}\le CapM_{ip}\times x_i \quad \forall i,p,s,t \quad (9)$$

$$k_{i,p,s-1,T}+n_{i,p,s,1}\le CapM_{ip}\times x_i \quad \forall i,p,s\ge 2 \quad (10)$$

$$l_{j,p,s,t-1}+\sum_i q_{ijpst}\le CapD_{jp}\times y_j \quad \forall j,p,s,t \quad (11)$$

$$l_{j,p,s-1,T}+\sum_i q_{i,j,p,s,1}\le CapD_{jp}\times y_j \quad \forall j,p,s\ge 2 \quad (12)$$

Capacity of manufactures is considered in constraints (9) and (10), and constraints (11) and (12) are the capacity limitations for distribution centers.

$$Sc_i\ge Mn\times x_i \quad \forall i,s \quad (13)$$

Constraint (13) ensures that a manufacturer can be established if its social score has a minimum value.

$$Dv_{is}=Dv_{i,s-1}+\theta\sum_p\sum_t w_i\times\left(n_{ipst}+\sum_j q_{ijpst}\right) \quad \forall i,s \quad (14)$$

$$Tr-Dv_{is}\le(1-\eta_{is})\times BN \quad \forall i,s \quad (15)$$

$$Tr-Dv_{is}>-\eta_{is}\times BN \quad \forall i,s \quad (16)$$

$$\sum_p\sum_t n_{ipst}>-\eta_{is}\times BN \quad \forall i,s \quad (17)$$

$$\sum_p\sum_t n_{ipst}\le(1-\eta_{is})\times BN \quad \forall i,s \quad (18)$$

Restricting of production and transportation decisions are carried out by constraints (14)–(18) to balance the regional development.

Renovation and repair decisions of manufacturers with high carbon footprint and water footprint are determined based on a permitted cap at the end of each strategic period using constraints (19)–(22). It is assumed that the repaired and renovated manufacturer will treat as a new environmentally friendly facility.

$$TE_{i,1}=\sum_p\sum_t n_{i,p,1,t}\times(\zeta_1\times Po_p+\zeta_2\times WS_i\times WP_{pi}) \quad \forall i,s=1 \quad (19)$$

$$TE_{is}=TE_{i,s-1}\times(1-r_{i,s-1})+\sum_p\sum_t n_{i,p,s,t}\times(\zeta_1\times Po_p+\zeta_2\times WS_i\times WP_{pi})\ \forall i,s\ge 2 \quad (20)$$

$$TE_{is}=PC+Ex_{is} \quad \forall i,s \quad (21)$$

$$Ex_{is}\le BN\times r_{is} \quad \forall i,s \quad (22)$$

In the proposed model, the appropriate type of transportation vehicles is determined according to cargo size and vehicles capacity through the FTL strategy. Suppose that the transportation cost depending on the type of vehicle and cargo size follows a piecewise linear function (for example, see Fig. 1).

Constraints (23)–(25) determine the number of the shipments and the mentioned piecewise function is converted into its linear form.

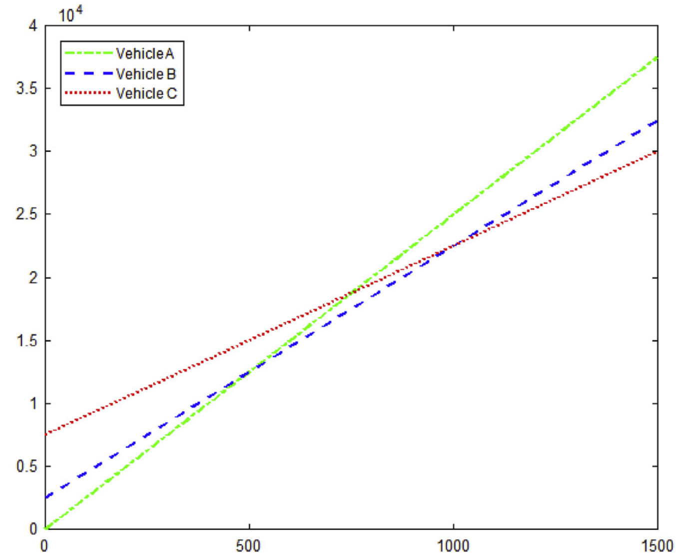

Fig. 1. Transportation cost for three kinds of vehicles.

$$\sum_p q_{ijpst} = U^{Mx} \times \mu_{ijst} + \sum_v \lambda^v_{ijst} \quad \forall i,j,s,t \tag{23}$$

$$L^v \delta^v_{ijst} \le \lambda^v_{ijst} \le U^v \delta^v_{ijst} \quad \forall i,j,s,t,v \tag{24}$$

$$\sum_v \delta^v_{ijst} = 1 \quad \forall i,j,s,t \tag{25}$$

According to the above considerations, transportation cost is determined by equation (26).

$$TC_{ijst} = \left(FT^{Mx} + VT^{Mx} \times U^{Mx}\right) \times \mu_{ijst} + \sum_v FT^v \times \delta^v_{ijst} + \sum_v VT^v \times \lambda^v_{ijst} \, \forall i,j,s,t \tag{26}$$

3.2. Linearization of the model

Despite linearizing the piecewise function in the proposed model, there are still some nonlinear terms. Two continuous decision variables in the first term of the first objective function (2) are multiplied; also, multiplication of a continuous variable and a binary variable is seen in constraint (20).

For linearization of the first term of the profit objective function (2), two new variables are replaced as follows:

$$DP_{pst} = D_{pst} \times \mathrm{Pr}_{pst} \quad \forall p,s,t \tag{27}$$

$$bP_{pst} = b_{pst} \times \mathrm{Pr}_{pst} \quad \forall p,s,t \tag{28}$$

And the mentioned term is converted to. $\sum_p \sum_s \sum_t (DP_{pst} - bP_{pst})$

The following constraints (29)–(36) are added to the model based on McCormick (1976) method in order to perform the linearization:

$$DP_{pst} \ge D^L_{pst} \times \mathrm{Pr}_{pst} + \mathrm{Pr}^L_{pst} \times D_{pst} - D^L_{pst} \times \mathrm{Pr}^L_{pst} \quad \forall p,s,t \tag{29}$$

$$DP_{pst} \ge D^U_{pst} \times \mathrm{Pr}_{pst} + \mathrm{Pr}^U_{pst} \times D_{pst} - D^U_{pst} \times \mathrm{Pr}^U_{pst} \quad \forall p,s,t \tag{30}$$

$$DP_{pst} \le D^U_{pst} \times \mathrm{Pr}_{pst} + \mathrm{Pr}^L_{pst} \times D_{pst} - D^U_{pst} \times \mathrm{Pr}^L_{pst} \quad \forall p,s,t \tag{31}$$

$$DP_{pst} \le D^L_{pst} \times \mathrm{Pr}_{pst} + \mathrm{Pr}^U_{pst} \times D_{pst} - D^L_{pst} \times \mathrm{Pr}^U_{pst} \quad \forall p,s,t \tag{32}$$

$$bP_{pst} \ge b^L_{pst} \times \mathrm{Pr}_{pst} + \mathrm{Pr}^L_{pst} \times b_{pst} - b^L_{pst} \times \mathrm{Pr}^L_{pst} \quad \forall p,s,t \tag{33}$$

$$bP_{pst} \ge b^U_{pst} \times \mathrm{Pr}_{pst} + \mathrm{Pr}^U_{pst} \times b_{pst} - b^U_{pst} \times \mathrm{Pr}^U_{pst} \quad \forall p,s,t \tag{34}$$

$$bP_{pst} \le b^U_{pst} \times \mathrm{Pr}_{pst} + \mathrm{Pr}^L_{pst} \times b_{pst} - b^U_{pst} \times \mathrm{Pr}^L_{pst} \quad \forall p,s,t \tag{35}$$

$$bP_{pst} \le b^L_{pst} \times \mathrm{Pr}_{pst} + \mathrm{Pr}^U_{pst} \times b_{pst} - b^L_{pst} \times \mathrm{Pr}^U_{pst} \quad \forall p,s,t \tag{36}$$

where D^L, Pr^L and b^L are the lower bounds and D^U, Pr^U and b^U are the upper bounds of the related decision variables. In the McCormick (1976) approach for each continuous variable, the upper and lower bounds are considered, which the less the difference between them, the answer is more accurate. This approach is tested by various scholars such as Bonami et al. (2019), Müller et al. (2019), Fischetti and Monaci (2019), Fattahi et al. (2019), Wang et al. (2019), and Niakan and Rahimi (2015) as well.

Conversion of the non-linear term in Constra int (20) into its linear form, is achieved using equations 37–39.

$$TEr_{is} \le BN \times (1 - r_{is}) \quad \forall s,i \tag{37}$$

$$TEr_{is} \le TE_{is} \quad \forall s,i \tag{38}$$

$$TEr_{is} + BN \times r_{is} \ge TE_{is} \quad \forall s,i \tag{39}$$

Finally, the type of variables is defined by following constraints (40)–(42).

$$Pr_{pst},\ TC_{ijst},\ TE_{is},\ Dv_{is},\ Ex_{is},\ DP_{pst},\ bP_{pst},\ TEr_{is} \ge 0 \quad \forall i,j,s,t,p \tag{40}$$

$$q_{ijpst}, n_{ipst}, k_{ipst}, l_{jpst}, b_{pst}, D_{pst}, \lambda^v_{ijst}, \mu_{ijst}, \ge 0 \ \mathit{and\ Integer} \quad \forall i,j,s,t,p,v \tag{41}$$

$$x_i, y_j, r_{is}, \eta_{is}, \delta^v_{ijst} \in \{0,1\} \quad \forall i,j,s,t,v \tag{42}$$

3.3. Robust counterpart of the model

The complicated and dynamic nature of the supply chain inflicts a high level of uncertainty on the supply chain decisions, and it is never possible to make decision certainly about the supply chain plans. One of the main approaches to dealing with uncertainty is stochastic programming, which suffers from some weaknesses such as unavailability of sufficient historical data to fit the uncertain parameters distribution function and the lack of exact expression of stochastic variables due to the large number of scenarios that reduce the computational ability. Consequently, in many cases, the use of stochastic programming is not successful. One of the other approaches to dealing with data uncertainty is the robust optimization approach, which does not have the above-mentioned weaknesses. In this study, the interval uncertainty of data is considered and the cardinality-constrained uncertainty set approach, presented by Bertsimas and Sim (2004), is utilized to capture the uncertainty of the supply chain environment. Another advantage of this approach over other methods is that it is not nonlinear and it has less complexity. In the following, a robust compact objective function is presented briefly:

$$\max \Pr D - cy - \tilde{t}x \tag{43}$$

where Pr, c and $\tilde{t}$ are price, deterministic cost, and uncertain cost parameters, respectively, and D, y, and x are decision variables that are multiplied by the corresponding parameters. The uncertain parameter $\tilde{t}$ obeys a symmetric and bounded random variable in the interval $[t - \hat{t}, t + \hat{t}]$, in which t and $\hat{t}$ define the nominal value of uncertain parameters and maximum deviation from the nominal value (perturbation amplitude), respectively.

Now, equation (43) can be converted to the following robust counterpart:

$$\begin{aligned} &\max \quad \sigma \\ &s.t. \quad \sigma \le \Pr D - cy - tx - \rho - \gamma\pi \\ &\qquad \pi + \rho \ge \hat{t}|x| \end{aligned} \tag{44}$$

where γ is budget of uncertainty, which controls the conservatism level of solution (it is determined by the decision maker), and π and ρ are two common decision variables that come from the dual model.

Therefore, the proposed robust bi-objective linear programming model to design of a sustainable supply chain network is reformulated as follows:

$$\max \sigma$$

$$\max \tau 1 \sum_{i \in \bar{I}} w_i \times x_i + \tau 2 \sum_i \sum_p \sum_s \sum_t w_i \times \left(n_{ipst} + \sum_j q_{ijpst} \right)$$

s.t.

$$\begin{aligned} \sigma \le &\sum_p \sum_s \sum_t (DP_{pst} - bP_{pst}) - \sum_i u_i \times x_i - \sum_j a_j \times y_j \\ &- \sum_i \sum_p \sum_s \sum_t m_{ip} \times n_{ipst} - (\gamma\pi + \sum_i \sum_p \rho_{ip}) \\ &- \sum_p \sum_s \sum_t c_p \times b_{pst} - \sum_i \sum_j \sum_s \sum_t TC_{ijst} - \sum_i \sum_p \sum_s \sum_t e_{ip} \times k_{ipst} \\ &- \sum_j \sum_p \sum_s \sum_t f_{jp} \times l_{jpst} - \sum_i \sum_s g \times Ex_{is} - \sum_i \sum_s h_i \times r_{is} \end{aligned}$$

$$\pi + \rho_{ip} \ge \widehat{m}_{ip} \sum_s \sum_t n_{ipst} \qquad p, i$$

Constraints (4)–(26).
Constraints (29)–(42)

$$\pi, \rho_{ip} \ge 0$$

where $\widehat{m}$ is a constant deviation of manufacturing cost.

3.4. Solving the multi-objective model

There are three methods to solve multi-objectives problems based on the timing of the expression of priorities by the decision maker: priori, interactive and a posteriori (or generation) methods. Although the posteriori method is difficult and time consuming, it has many advantages comparing two others. This method can prepare an appropriate picture of whole Pareto optimal set to decision maker and then he/she can choice the most preferred solution. It means that none of the solutions remain undiscovered and ultimately, the decision maker can select the final solution confidently according to having at hand all the possible alternatives based on comprehensive available information (Mavrotas, 2009).

The ε-constraint method is one of the most widely used and well-organized posteriori methods (Zarbakhshnia et al., 2019) in which the Pareto optimal set is obtained through varying the ε-vectors of objectives considered as constraints and optimizing their corresponding single objective problems (Babazadeh et al., 2017a). The advantages of this approach encouraged us to apply this method to solve the proposed multi-objective model, for example non-extreme efficient solutions can be generated (Balaman et al., 2018), no need scaling of the objective functions (Rezvani et al., 2015), and by effectively tuning some of grid points in the range of each objective function, some controlled efficient solutions can be generated (Norouzi et al., 2014). It should be noted that most sustainable supply chain network design employ the ε-constraint approach (Arampantzi and Minis, 2017).

In this paper, according to the description given above, to handle two objective functions, the ε-constraint approach proposed by Allaoui et al. (2018) is utilized to acquire non dominated solutions. To optimize several objectives with different criteria simultaneously, a sufficiently large number of solutions should be generated, identified and filtered. Creating all the solutions and comparing them is prohibitive in terms of resources and time. However, the proposed approach generates a set of Pareto- optimal solutions to aid users in making decisions and highlights the trade-off conditions (Allaoui et al., 2018). Thus, the developed approach can be more useful than others for the proposed model.

4. Numerical examples

In this section, usefulness of the proposed model is investigated and a comprehensive sensitivity analysis is carried out for a set of randomly generated instances. The proposed MILP model is optimized by a commercial software, namely GAMS 24.1. An Intel Core i7-640 M CPU (2.8 GHz) personal computer with 4.00 GB of RAM has been used in all implementations.

Here, some numerical examples with different dimensions are generated from small to relatively large sizes as it can be seen in Table 3. The values of parameters are simulated using the uniform distributions reported in Table 4. Also, parameters g, PC, Tr, and $\widehat{m}$ are set to 2, 12000, 100, and 0.1, respectively.

The Pareto frontier is obtained for the first instance allowing the visualization of the trade-off between two different objective functions utilizing the approach of Allaoui et al. (2018) as in Fig. 2.

In the following, some sensitivity analyses are conducted to illustrate the significance and applicability of the proposed model and the robust optimization. Reasonable behavior of the proposed model in changing some parameters like those related to demand function α and β confirms the validity of the proposed model. The more interesting results of the sensitivity analysis based on three pillars of sustainability as well as robustness performance are discussed in the following, highlighting the main contributions of this study.

4.1. Environmental dimension analysis

The comparison of total environmental impacts of both scenarios with/without considering repair decisions at different instances can be observed in Table 5.

Table 3
Different numerical instances and their sizes.

Instances	Instance1	Instance2	Instance3	Instance4	Instance5
Problem size |I|*|J|*|T|*|S|*|P|*|V|	2*2*8*2*2*3	4*4*8*2*4*4	6*8*8*2*8*5	8*16*8*2*8*6	16*16*8*2*16*8

Table 4
Values of some parameters.

Parameters	h_i	u_i	m_{ip}	e_{ip}	$CapM_{ip}$	a_j	f_{jp}	$CapD_{jp}$
Values	U(2000,3000)	U(10000,12000)	U(60,80)	U(0.4,0.6)	U(4000,5000)	U(700,800)	U(0.4,0.6)	U(4000,5000)

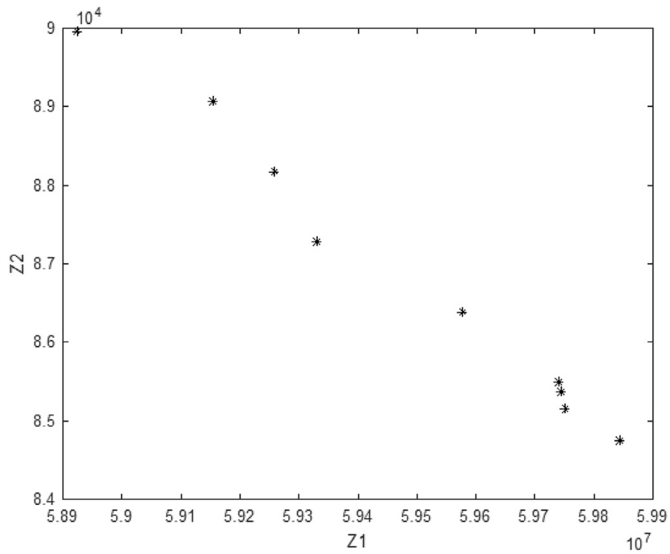

Fig. 2. Pareto front constructed by non-dominated solutions of two objective functions.

Table 5
Total environmental impact values for different numerical instances with/without the repair decision.

Instances	Total environmental impact with the repair decision	Total environmental impact without the repair decision
Instance1	488604	817008
Instance2	1649794	2711578
Instance3	5483863	9221689
Instance4	19904033	33240893
Instance5	44337603	164316300

For different examples (as seen in Table 5), the proposed model is more environmentally friendly than the model in which the repair decisions are ignored.

By increasing the permitted cap for environmental impact as far as the manufacturers are allowed for further water consumption and carbon emissions, accumulated footprints increase. If the total environmental impact (TE), i.e., sum of total CO_2 emission and water consumption, exceeds the permitted value, the manufacturer should be repaired to lower the environmental impact, as Fig. 3 illustrates. Here, Manufacturer 1 should be renovated in the second and fourth strategic periods and Manufacturer 2 does not require the renovation and repair.

4.2. Economic and environmental dimensions analysis

In this section, the effectiveness of the proposed model is evaluated. As reported in Table 6, by using the FTL strategy, the

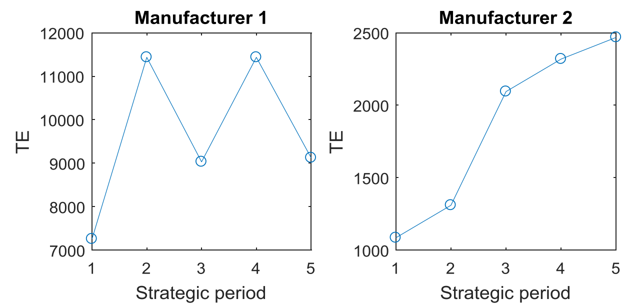

Fig. 3. Total environmental impact emitted during strategic periods by manufacturers 1 and 2.

proposed model utilizes the best arrangement of vehicles for transportation; thus, it will face lower transportation cost and lower environmental impact compared to scenarios in which only one type of vehicle is used. Moreover, as illustrated in Table 7, the proposed model is more efficient for cases with high number of available vehicles. As a result, the proposed model is an advisable option to reduce the imposed costs and bring less damages to the environment.

4.3. Social dimension analysis

The total development levels are compared in the numerical instances with respect to the devised development scheme in Table 8. The results reveal that the model is capable to improve the development level and can provide more useful managerial insights.

4.4. Uncertainty analysis

In order to investigate the effect of uncertainty on the performance of the supply chain network, $\widehat{m}$ is set to different values from 0 to 100 percentage of the parameter m. Moreover, γ is set to different values from 0 to 3. The results are presented in Fig. 4. As illustrated in the figure, by increasing γ, there is more conservatism during the decision making, so the total cost increases. The higher budget of uncertainty results in a higher protection and, consequently, a higher total cost. Furthermore, the greater the interval of the uncertainty, the higher the cost and the lower the profit. The profit value with $\gamma = 0$ is the most profitable one among all, but it has the lowest level of protection against uncertainty. Also, by a more accurate evaluation of the manufacturing cost parameter, the uncertainty range can be reduced and, as a result, the cost decreased. Fig. 4 illustrates that when the uncertainty budget and perturbation amplitude are set to zero, the result is the same as the deterministic state, which this validates the proposed model in the uncertain environment.

Table 6
Comparison of the proposed model and three scenarios based on transportation cost and environmental impact.

	Proposed model	Classic scenario by Vehicle *A*	Classic scenario by Vehicle *B*	Classic scenario by Vehicle *C*
Transportation cost	1530865	4371272	3497018	2622762
Environmental impact	275761	501128	439703	366723

Table 7
Analysis of number of available vehicles for the effectiveness of the proposed model.

Number of vehicles	Proposed model		Classic model	
	Transportation cost	Environmental impact	Transportation cost	Environmental impact
3	1530865	275761	3497018	439703
4	1348506	175751	3130871	190482
5	874254	87337	2495161	112076
6	699403	69150	2005640	102884
7	524553	52346	1843737	93294

Table 8
Total development level for different numerical instances with/without the proposed development scheme.

Instances	Total development level with the proposed development scheme	Total development level without the proposed development scheme
Instance1	282	99
Instance2	309	199
Instance3	799	421
Instance4	959	669
Instance5	1399	884

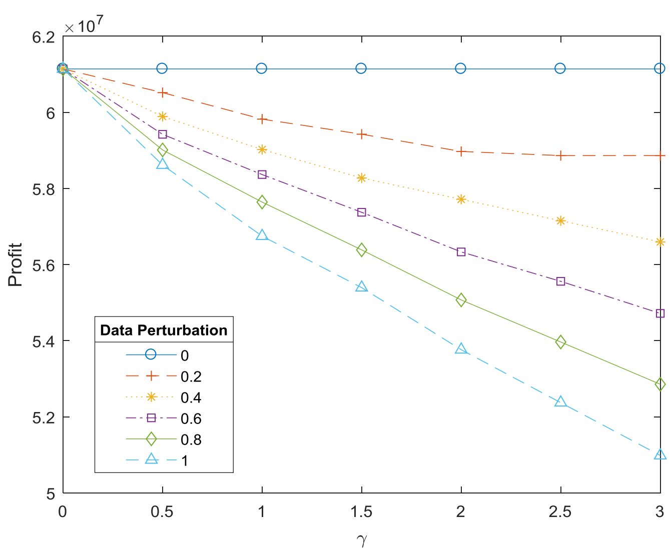

Fig. 4. Sensitivity analysis on the robust parameters values.

To consider the necessity of robust design of network, deterministic and robust models are compared based on the solutions obtained under ten random realizations. The standard deviation of objective function values under random realizations can be considered as a performance measure to validate the robust model (Pishvaee et al., 2012; Mohseni et al., 2016). For a constant γ, the standard deviations of these ten objective function values are calculated and compared for two models. The proposed robust model outperforms the deterministic model in terms of the standard deviation measure. The lower the standard deviation, the greater the reliability and vice versa, so the robust model is more reliable. The differences between two deterministic and robust standard deviation measures for three various values of γ are shown in Fig. 5. It can be concluded that the higher the value of γ, the greater the difference.

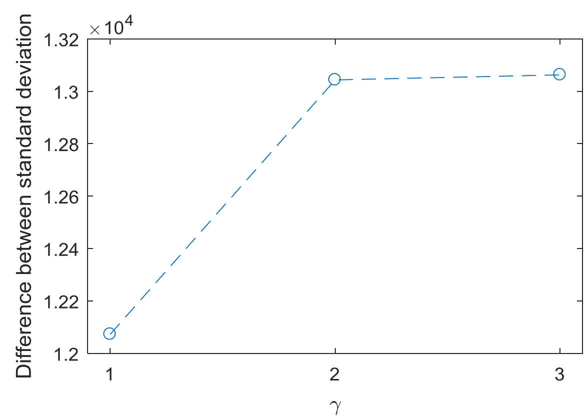

Fig. 5. Difference between standard deviations of two models for various values of γ

It is evident from the above discussions that the proposed model has a more efficient performance compared to other previous models from a different point of view. For example, since the facilities are environmentally controlled and repaired every few times, they have less environmental impact which will lead to less damage to the environment in contrast to other models which ignore the repair decisions. Table 5 reports this discussion and shows the effectiveness of the proposed model in various numerical examples in terms of the environmental impacts. Clearly, the benefits of reducing environmental impact, in addition to supply chain stakeholders, also have beneficial effects on the society. Moreover, after comparing the proposed model in various examples, that do not include FTL strategy, it can be concluded that the proposed model has a more appropriate performance in both economic and environmental terms, as it is shown in Tables 6 and 7. The reason for this is a reduction in the number of transportation activities that have the greatest environmental impact and a huge cost. According to the proposed FTL strategy, the mode with the lowest transportation activity is selected and the vehicle capacity usage is maximized. Therefore, it helps to save environment as well as cost. Furthermore, since a weighted balanced regional development scheme is devised and some significant and effective social criteria such as customer satisfaction, employee satisfaction, and potential capabilities of regions are considered, the TBL approach can be as an appropriate option for societies that are concerned about social problems and want to develop. Table 8 illustrates superiority of the proposed model compared to the classic models that have not addressed the social aspect. Finally, it should be noted that as illustrated in Figs. 4 and 5, the proposed robust model can create more protected and the more reliable results and it is closer to the real-world situations.

5. Case study and managerial implications

"Case studies play a crucial role in the mutual learning process between academics and practitioners in the field of sustainable development" (Steiner and Posch, 2006; Arampantzi and Minis, 2017). Here, the result of analysis by the proposed model for a real case of cable supply chain in Iran is presented to show the performance of the proposed methodology and prove the practical value of this research. Finally, the significance of the case study as managerial implications and suggestions are provided as well.

Specially, about the cable case study it should be noted that the main source of this product is copper and copper price is always fluctuating and uncertain; thus, we face an uncertain production cost. Because of the features of the problem as well as benefits of the robust optimization approach, in this study we consider it to deal with the uncertainty.

In the analyzed case study there are 32 and 18 candidates for distribution centers and manufacturers, respectively among undeveloped and less developed provinces. Based on work conditions, consumer issues assessment and social score, 15 provinces are selected to choose the best location from the sustainable point of view for the cable manufacturer.

Five 4-years strategic periods are considered. It is assumed that each tactical period includes 10 days. To calculate the growth potential for each province, a TOPSIS approach and the mentioned criteria derived from the Statistical Center of Iran[1] are applied. It should be noted that for the second criterion, the number of copper mines and for the seventh criterion, the road freight transport volume are considered.

As a general result, we can claim that investing in and designing a supply chain network using our proposed model would be beneficial to all three pillars of sustainability. The reasons for this claim as well as the further analysis and more detailed results are presented as follows:

(1) To demonstrate the performance of the model in the regions development, the provinces selected for the construction of the cable manufacturer are analyzed over time. Fig. 6 illustrates the provincial development level at the end of each strategic period. It can be concluded that the less developed provinces with higher growth potential have grown more than other provinces. As the developmental level of the less developed provinces grows higher, the developmental level of the more developed provinces increases with a more moderate slope, so the entire community is balanced and improved. Notably, most provinces reach the expected regional development threshold (i.e., 50) and when a province reaches this value before end of the time horizon, e.g., Province 3, its growth stops (socially beneficial).

(2) In addition to the regional balance, the proposed model will improve the country's developmental level. Fig. 7 illustrates an increasing of total development level at the end of strategic periods. As Fig. 7 shows, using the proposed TBL approach, the total development level grows to 5,700.

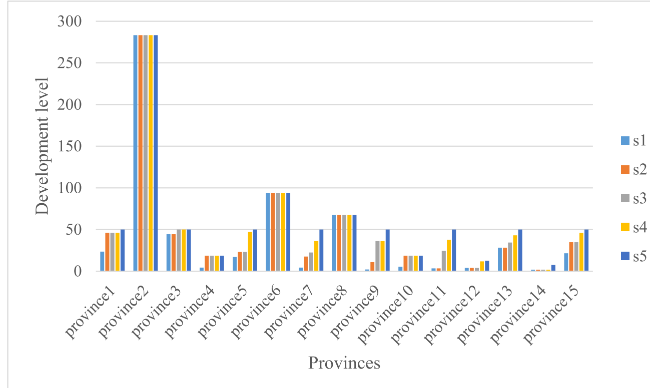

Fig. 6. Development level of provinces in strategic periods of s1 to s5.

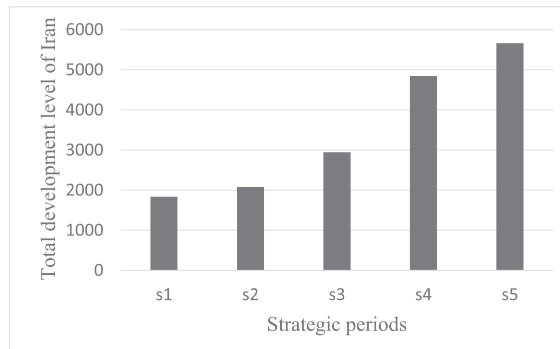

Fig. 7. Total development level in different strategic periods.

Without applying the proposed model, the level of development will remain below the 1800 (if optimistic) and will not grow. It is also socially beneficial since more job opportunities are created and hope, motivation, and accordingly, the general welfare level are improved using the proposed model. It stimulates the economy of the provinces where they are implemented, thus the return on the investment of the involved companies will be seen. Therefore, a virtuous circle is created (Mota et al., 2018). The proposed model would be especially profitable for the developing countries (economically and socially beneficial).

(3) Another advantage of the proposed TBL approach is to control the carbon footprint and water footprint that occurs without imposing huge costs. Costs such as overhaul and repair of worn-out devices are lower costs than other costs and damages to the health of the people and the environment. If the repairs did not happen, high environmental impact would result in environmental problems, damages, and diseases. The proposed model is along the Iran Vision 2025 ,[2], which tries to decrease 90% of industrial environmental impact (Zohal and Soleimani, 2016). The differences between two scenarios (regarding or disregarding the renovation and repair activities) are presented in Fig. 8 (environmentally beneficial).

(4) If vehicles travel in a classic and LTL form, the profit is 99120751 and if they consider the FTL transportation strategy, the profit is 151160336, so by utilizing the proposed FTL

[1] https://www.amar.org.ir/english?portalid=1.

[2] http://www.vision1404.ir.

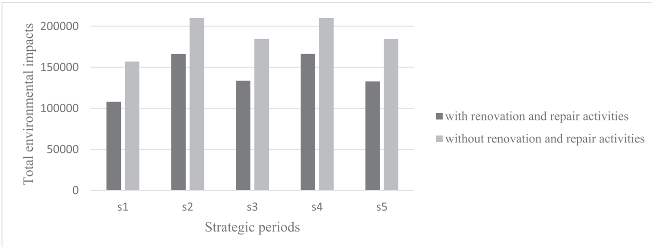

Fig. 8. Total environmental impacts with and without renovation and repair activities.

model, the profit increases by 52.6% (=100 × (151160336 - 99120751/99120751)). It is achieved because of the maximum vehicle capacity usage as well as minimum number of used vehicles. It is clear that without using the proposed FTL model and shipping of vehicles in LTL form, more total cost will incur, so the price will rise with demand reduction as a final result. In addition, it increases the amount of environmental impact and consequently, the physical and mental illnesses resulting from environmental impact (environmentally, economically and socially beneficial).

(5) Based on the analysis, it is observed that by ignoring the optimal designed network such as selecting non-optimal candidate points for locating some facilities, less total profit incurred. As an instance, it is observed that by selecting non optimal locations the total network will face to 151160336 profit, however the optimal profit is 124153583, so 21.8% of total profit will be lost (=100 × (151160336 - 124153583/124153583)). The cost is increased, the price goes up, demand decreases, customers are lost, and so on (economically beneficial). By comparing the other specifications of the proposed model with those of the non-optimal supply chain design, the significance and superiority of the model are shown, as validated above in conclusions (1), (2), (3), and (4). Therefore, the comparison is ignored to avoid repetition.

The managerial insights of this study are discussed and the related findings in theory and practice are provided here.

First, the important research gap in achieving sustainable development of supply chain and studying the impact of the problem on the profit of the whole supply chain, providing the basis for strategic and tactical decisions, is filled. This allows the manufacturers to adjust their profit, development level, people welfare, workers' satisfaction, environmental impact, renovation and repair decisions, attention to water, and FTL strategy, and ultimately design the optimal configuration of a sustainable supply chain.

Second, the proposed approach is an appropriate starting point for a standardized methodology to calculate the sustainable measurement with respect to various important indicators.

Third, imposing renovation and repair decisions based on carbon emitted and water consumed extends the traditional SCND model into a comprehensive sustainable one. This paper shows that the total cost and emissions from both sides can be decreased and more consumers can be attracted. The manufacturers also do not need to bear too much cost to achieve economic and environmental targets.

Fourth, to design a realistic network, a novel multi-product and multi-period SCND problem considering FTL strategy is proposed. It can be an advisable tool to save cost and emissions. As a general result, we can claim that investing in and designing a supply chain network using the proposed model would be environmentally and economically beneficial.

Fifth, it is tried to express the relationship between demand and price in a market area. It can help firm managers who aim to maximize the profit of their supply chain network.

Finally, this study provides guidance on socially friendly behavior of facilities to improve the attractiveness of stores for the consumers and it is a reference for the government in designing a network to achieve an appropriate and equitable regional development level and improve the well-being of people.

As the suggestions for the supply chain members, the cable manufacturers association can sign a contract to be approved by the government, which all cable manufacturers are be obliged to act the provisions of this contract. The permitted cap for facilities and development threshold are determined which are updated every few years. Since the natural conditions and features such as population, unemployment rate and etc. Of provinces may change over the time, the growth potential of each region should also be updated every few years.

6. Conclusions

Sustainability of supply chains has recently become more essential due to the increase in concerns about the social and environmental impacts of business processes. Governmental requirements and expectations of the people intensify the need for sustainability in today's business environment. Optimization of a sustainable SCND model considering significant aspects of sustainable development in an uncertain environment has seldom been studied and it is recommended frequently. To move forward the literature in this area, we attempted to deal with some environmental and social issues existing in the design of a supply chain network and established a balance between economic growth, the care for the environment and improved quality of social life. In the proposed model, corporate social responsibility is addressed from several viewpoints, e.g., a social objective encompasses societal community development and prioritizing less developed regions. To enhance the environmental image of the network, a full truckload transportation is advisable, since higher use of the transportation capacity, decreases environmental damage and yields lower cost. Also, the facilities damaging environment as well as time of renovation and repair of them are determined. The model is regarded as robust programming under an interval uncertainty for the problem to approximate real situations. Solving the numerical examples and conducting some sensitivity analysis further show that the proposed supply chain is more cost-effective, could significantly reduce the environmental impact and could promote the sustainable development. Moreover, the numerical results show superiority of the robust model over the deterministic one. Through conducting a case study, it is demonstrated that the proposed model can be implemented successfully for the case study in cable industry. The proposed TBL methodology to design a sustainable network design can be applied in other cases which try to improve all the three pillars of sustainable development, such as plastic, battery, gold, medical, and pharmaceutical industries. Some extensions of this study can be addressed for future research. For example imposing reverse logistics and closed-loop supply chain network design can be a significant issues. Further research may try to accomplish a model considering other challenges such as facility disruptions. The proposed sustainable supply chain network design model is to be pursued and may be improved in operational time horizon decisions along with strategic and tactical ones. Considering different types of uncertainty for parameters can be another interesting topic for the future research.

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