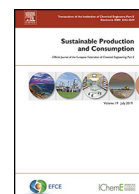Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Sustainable, resilient and responsive mixed supply chain network design under hybrid uncertainty with considering COVID-19 pandemic disruption

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ABSTRACT

The occurrence of the COVID-19 pandemic is a disruption that has adversely affected many supply chains (SCs) around the world and further proved the necessity of combination and interaction of resilience and sustainability. In This paper, a multi-objective mixed-integer linear programming model is developed for responsive, resilient and sustainable mixed open and closed-loop supply chain network design (SCND) problem. The uncertainty of the problem is handled with a hybrid robust-stochastic optimization approach. A Lagrangian relaxation (LR) method and a constructive heuristic (CH) algorithm are developed for overcoming problem complexity and solving large-scale instances. In order to assess the performance of the mathematical model and solution methods, some test instances are generated. The computations showed that the model and the solution methods are efficient and can obtain high-quality solutions in suitable CPU times. Other analyses and computations are done based on a real case study in the tire industry. The results demonstrate that resilient strategies are so effective and can improve economic, environmental and social dimensions substantially. Research findings suggest that the proposed model can be used as an efficient tool for designing sustainable and resilient SCs and the related decision-makings. Also, our findings prove that resilience is necessary for continued SC sustainability. It is concluded that using proposed resilience strategies simultaneously brings the best outcome for SC objectives. Based on the sensitivity analyses, the responsiveness level significantly affects SC objectives, and managers should consider the trade-off between responsiveness and their objectives.

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1. Introduction

Supply chain (SC) networks have been formed as the backbone of economic activities in different countries of the world. The importance of these networks is in the timely and efficient production and delivery of various products such as food, fuel, drugs, clothing, electronic and computer components, etc., and this issue has created interest and motivation to analyze them in researchers and specialists (Nagurney, 2010). The infrastructure and physical structure of the SC are determined by supply chain network design (SCND), which is a part of the planning phase in the SC management (Govindan et al., 2017b).

The goal of mathematical models of SCND is usually to minimize costs or maximize profits. But in recent years, attention to the sustainability topics, including environmental and social dimensions of SCs has increased.

The increasing importance of environmental goals and constraints in today's world has caused decision-makers to pay attention to this issue and to include environmental factors in the decision-making process (Ilgin and Gupta, 2010). Challenges such as rapid population growth and climate change have increased the concerns about environmental issues of industries (Abbas et al., 2021). Industries consume about 50% of the world's energy and are responsible for the emission of more than one-third of carbon dioxide (Ramezanian et al., 2019). Considering environmental issues generalizes the SCND problem taking into account environmental factors and affects items such as facilities, means and modes of transportation, product design, selection of technologies, and so on. There are various methods for modeling the decision-making on environmental factors: life cycle assessment, analytic hierarchy and network process, data envelopment analysis, simulation, etc. In the meantime, the life cycle assessment method is usually used more and is a suitable method for integrating its output with optimization models (Eskandarpour et al., 2015). However, in cases where for some reasons it is not possible to implement methods such as life cycle assessment, the assessment of

Nomenclature

Sets

P	Set of potential locations for production centers, indexed by p
I	Set of suppliers, indexed by i
J	Set of potential locations for distribution centers, indexed by j
C	Set of customers, indexed by c
K	Set of potential locations for collection/ inspection centers, indexed by k
H	Set of potential locations for recycling centers, indexed by h
U	Set of disposal centers, indexed by u
A	Set of fortification levels, indexed by a
W	Set of production technologies, indexed by w
$\bar{W}$	Set of recycling technologies, indexed by $\bar{w}$
E	Set of product types, indexed by e
G	Set of SCs, indexed by g
Q	Set of recycled products, indexed by q
S	Set of scenarios, indexed by s
T	Set of time periods, indexed by t

Parameters

fs_i	Fixed cost of selecting supplier i
fp_{pwa}	Fixed cost of opening production center p with production technology w and fortification level a
fd_j	Fixed cost of opening distribution center j
fc_k	Fixed cost of opening collection/ inspection center k
$fl_{h\bar{w}a}$	Fixed cost of opening recycling center h with recycling technology $\bar{w}$ and fortification level a
tr	Unit transportation cost of raw materials
tc_e	Unit transportation cost of product type e
$\overline{tc}_q$	Unit transportation cost of recycled product type q
da_{ip}	The distance between supplier i and production center p
db_{pj}	The distance between production center p and distribution center j
dc_{jc}	The distance between distribution center j and customer c
de_{ck}	The distance between customer c and collection/ inspection center k
dg_{kh}	The distance between collection/ inspection center k and recycling center h
dh_{ku}	The distance between collection/ inspection center k and disposal center u
dj_{hp}	The distance between recycling center h and production center p
di_{pc}	The distance between production center p and customer c
dk_{hg}	The distance between recycling center h and production centers of SC g
$\widetilde{mc}_{epws}$	Cost of producing one unit product type e in production center p with technology w under scenario s
$\widetilde{ce}_{pews}$	Cost per unit of adding extra production capacity for product type e in production center p with technology w under scenario s
ch_{ep}	Cost of holding one unit of product type e in production center p
cd_j	Cost of distributing one unit of product in distribution center j
cc_k	Cost of collecting and inspecting one unit of product in collection/ inspection center k
$rc_{h\bar{w}}$	Cost of recycling one unit of raw material in recycling center h with technology $\bar{w}$
$\overline{rc}_{qh\bar{w}}$	Cost of producing one unit of recycled product q in recycling center h with technology $\bar{w}$
dp_u	Cost of disposing of one unit of product in disposal center u
$\widetilde{cr}_{is}$	Cost of purchasing one unit of raw material from supplier i under scenario s
ud_{ec}	Cost of not meeting one unit of demand related to product type e for customer c
$\overline{ud}_{qg}$	Cost of not meeting one unit of demand related to recycled product type q for SC g
eo_{paw}	Environmental impact of establishing production center p with fortification level a and manufacturing technology w
eo_j	Environmental impact of establishing distribution center j
eo_k	Environmental impact of establishing collection/inspection center k
$eo_{ha\bar{w}}$	Environmental impact of establishing recycling center h with fortification level a and manufacturing technology $\bar{w}$
ep_{epw}	Environmental impact of producing a unit of product type e in production center p by using manufacturing technology w
ed_j	Environmental impact of handling a unit of product in distribution center j
ec_k	Environmental impact of handling a unit of product in collection/inspection center k
es_e	Environmental impact of disposing a unit of product type e or releasing in environment
$er_{h\bar{w}}$	Environmental impact of recycling a unit of raw material in recycling center h by using manufacturing technology $\bar{w}$
$eq_{qh\bar{w}}$	Environmental impact of producing a unit of recycled product type q in recycling center h by using manufacturing technology $\bar{w}$
et_{ip}	Environmental impact of transporting a unit of product from supplier i to production center p per unit distance
et_{pj}	Environmental impact of transporting a unit of product from production center p to distribution center j per unit distance
et_{jc}	Environmental impact of transporting a unit of product from distribution center j to customer c per unit distance
et_{ck}	Environmental impact of transporting a unit of product from customer c to collection/inspection k per unit distance
et_{kh}	Environmental impact of transporting a unit of product from collection/inspection center k to recycling center h per unit distance
et_{ku}	Environmental impact of transporting a unit of product from collection/inspection center k to disposal center u per unit distance
et_{hp}	Environmental impact of transporting a unit of product from recycling center h to production center p per unit distance
et_{pc}	Environmental impact of transporting a unit of product from production center p to customer c per unit distance
et_{hg}	Environmental impact of transporting a unit of product from recycling center h to production centers of SC g per unit distance

jf_{paw}	Number of fixed job opportunities created by establishing production center p with fortification level a and production technology w
jf_j	Number of fixed job opportunities created by establishing distribution center j
jf_k	Number of fixed job opportunities created by establishing collection/inspection center k
$jf_{ha\bar{w}}$	Number of fixed job opportunities created by establishing recycling center h with fortification level a and recycling technology $\bar{w}$
jv_{pw}	Number of variable job opportunities created through working of production center p with manufacturing technology w
jv'_p	Number of variable job opportunities created through distributing products from production center p
jv_j	Number of variable job opportunities created through working of distribution center j
jv_k	Number of variable job opportunities created through working of collection/inspection center k
$jv_{h\bar{w}}$	Number of variable job opportunities created through working of recycling center h with recycling technology $\bar{w}$
lf_{paw}	Average lost days caused from work's damages during the establishment of production center p with fortification level a and production technology w
lf_j	Average lost days caused from work's damages during the establishment of distribution center j
lf_k	Average lost days caused from work's damages during the establishment of collection/inspection center k
$lf_{ha\bar{w}}$	Average lost days caused from work's damages during the establishment of recycling center h with fortification level a and recycling technology $\bar{w}$
lv_{pw}	The lost days caused from work's damages during the manufacturing of products in production center p with recycling technology w
lv'_p	The lost days caused from work's damages during distributing products from production center p
lv_j	The lost days caused from work's damages during the handling of products in distribution center j
lv_k	The lost days caused from work's damages during the handling of products in collection/inspection center k
$lv_{h\bar{w}}$	The lost days caused from work's damages during the recycling of products in recycling center h with manufacturing technology $\bar{w}$
we_{jo}	Weighting factor of created job opportunities
we_{ld}	Weighting factor of lost days caused from work's damages
rm_e	The percentage of raw material waste in producing one unit of product type e
δ	Quantity of recycled raw materials obtained from recycling one unit of product
β_q	Quantity of recycled product q obtained by recycling one unit of product
d_{cets}	Demand of customer c for product type e in period t, under scenario s
τ_{cs}	Amount of determined value for SC responsiveness level related to the demand of customer c under scenario s
$\bar{\tau}_{gs}$	Amount of determined value for SC responsiveness level related to the demand of SC g under scenario s

dr_{gqts}	Demand of SC g for recycled product q in period t, under scenario s
cps_i	Capacity of supplier i
cpp_{pe}	Capacity of production center p for producing product type e
cep_{pe}	Maximum addable capacity related to production center p for product type e
chp_p	Holding Capacity of production center p
cdp_p	Distribution Capacity of production center p
cpd_j	Capacity of distribution center j
cpc_k	Capacity of collection/ inspection k
cpl_h	Capacity of recycling center h
iv_{ep0}	Initial inventory of product type e at production center p
α_{ce}	Percentage of returned product type e from customer c
γ_e	Percentage of returned product type e sent from collection/ inspection centers to recycling centers
λ_{paes}	Percentage of decrease in production capacity of production center p with fortification level a for producing product type e under scenario s
λ'_{pas}	Percentage of decrease in holding capacity of production center p with fortification level a under scenario s
λ''_{pas}	Percentage of decrease in distribution capacity of production center p with fortification level a under scenario s
η_{is}	Percentage of decrease in capacity of supplier i under scenario s
φ_{js}	Percentage of decrease in capacity of distribution center j under scenario s
μ_{ks}	Percentage of decrease in capacity of collection/ inspection center k under scenario s
θ_{has}	Percentage of decrease in capacity of recycling center h with fortification level a under scenario s
π_s	Probability occurrence of scenario s
M	A large positive number

Variables

qr_{ipts}	Quantity of raw material shipped from supplier i to production center p in period t under scenario s
ma_{epwts}	Quantity of product type e produced at production center p in period t with technology w under scenario s
ac_{pewts}	Quantity of added capacity to production center p for producing product type e with technology w in period t under scenario s
iv_{epts}	Inventory of product type e at production center p in period t under scenario s
v_{epjts}	Quantity of product type e shipped from production center p to distribution center j in period t under scenario s
r_{epcts}	Quantity of product type e shipped from production center p to customer c in period t under scenario s
o_{ejcts}	Quantity of product type e shipped from distribution center j to customer c in period t under scenario s
n_{eckts}	Quantity of product type e shipped from customer c to collection/ inspection center k in period t under scenario s
b_{ekhts}	Quantity of product type e shipped from collection/ inspection center k to recycling center h in period t under scenario s

b'_{ekuts}	Quantity of product type e shipped from collection/inspection center k to disposal center h in period t under scenario s
$f_{h\bar{w}pts}$	Quantity of materials recycled with recycling technology $\bar{w}$ shipped from recycling center h to production center p in period t under scenario s
$f'_{q\bar{w}hgts}$	Quantity of recycled product type q produced with recycling technology $\bar{w}$ shipped from recycling center h to supply chain g in period t under scenario s
fr_{ts}	Quantity of returned products used for recycling raw materials in period t under scenario s
fq_{ts}	Quantity of returned products used for producing recycled products in period t under scenario s
ω_{cets}	Quantity of unmet demand of customer c for product type e in period t under scenario s
ω'_{gqts}	Quantity of unmet demand of SC g for product type q in period t under scenario s
ss_i	A binary variable; 1 if supplier i is selected, 0 otherwise
x_{paw}	A binary variable; 1 if production center p with fortification level a and technology w is established, 0 otherwise.
y_j	A binary variable; 1 if distribution center j is established, 0 otherwise
z_k	A binary variable; 1 if collection/inspection center k is established, 0 otherwise
$rh_{ha\bar{w}}$	A binary variable; 1 if recycling center h with fortification level a and technology $\bar{w}$ is established, 0 otherwise.

a subset of environmental factors can be an appropriate step towards comprehensive attention to environmental concerns. One of the methods of evaluation is to add one or more environmental objectives and constraints to common SCND optimization models. These objective functions and constraints affect network facilities, transportation, and product/process design. Greenhouse gas emissions, waste generation, energy consumption, material recycling, etc., are usually used as performance indicators in these problems (Mota et al., 2018).

Social sustainability, which has received less attention than environmental sustainability, deals with issues such as regional development, social justice and human rights. In general, in SC design research papers that have considered the social dimension of sustainability, three items have been considered: working conditions, social commitments and customer issues. In terms of working conditions, employment is the most important factor. The number of jobs created, the social benefit index (job creation in less developed areas), damage to customer areas and job security measures are some of the factors that have been considered on working conditions in various studies. The field of social commitment includes decisions about improving public health, education, culture, regional development policies, and so on. Customer issues are factors that affect the customer, such as the impact of pollution in hospital environments on patients, the risk of using recycled materials and etc. (Eskandarpour et al., 2015).

SCs can be divided into three types based on their network configuration, including forward SC, reverse SC, and SC with both forward and reverse flows. The latter can be classified into three categories: closed-loop, open-loop, and mixed open and closed-loop (Van Engeland et al., 2020). In the mixed open and closed-loop SCs (MOCSCs), a portion of the returned and recycled products and materials remains within the network and are utilized, and the other portion enters other SCs (Salema et al., 2007). One

of the issues related to the sustainability of SCs is reverse logistics. While in traditional (forward) SCs the end of life (EOL) products and their adverse effects on the environment are ignored, in SCs with considering reverse logistics the EOL products are collected and reused. The SCs with reverse logistics especially the MOCSCs can enhance the environmental dimension of sustainability in many facets, such as reductions in energy consumption, material consumption and environmental pollutions (Taleizadeh et al., 2019). Besides, with establishing facilities of reverse logistics, the social dimension of sustainability will be promoted due to creating jobs, developing the economy of different areas and etc.

The risks in SCs can be divided into two groups, including disruption and operational risks (Farrokh et al., 2018). Operational risks arise from intrinsic uncertainties in the SC like uncertainty in supply, demand, delivery time and costs. SCs are also exposed to various disruption risks. These risks can have negative effects on goals, performance and natural flows of a SC. Disruptions can be caused by natural disasters (such as floods, earthquakes, and pandemics) or intentional or unintentional human actions (such as staff strikes, wars and terrorist attacks), or by technical factors (such as equipment breakdowns and system failures) (Sabouhi et al., 2018). The sustainability of SCs can also be adversely affected by disruptions. These disruptions have negative economic effects such as lost sales, lack of inventory and increased transportation costs (Dixit et al., 2016). Moreover, disruptions can disturb reverse logistic operations and degrade the environmental dimension of sustainability. The social dimension would also be at stake due to creating problems for employees, losing jobs, facilities shutdown and other challenges due to disruptions.

Recently, the world has been confronted with the COVID-19 pandemic, which is the most destructive disruption of recent decades (Remko, 2020). World health organization (WHO) announced a universal epidemic on 31th January 2020, and then because of the accelerated spread of the virus, it was reported as a pandemic on March 11, 2020 (Mofijur et al., 2021). This widespread disruptive pandemic has adversely affected the SCs around the world (Karmaker et al., 2021). Over the last months, many researchers have investigated the substantial impacts of the COVID-19 on SCs. The productivity, efficiency and responsiveness of SCs have been damaged because of shortage of materials, delay in deliveries, disruption in logistics and transportation systems, reduction in the capacity of facilities and other damages resulting from the occurred disruption. The occurrence of this pandemic led to pay special attention to SC sustainability (Karmaker et al., 2021). Because of different limitations like quarantines and entry bans in order to reduce the spread of disease, many industries substantially decreased their activity which brought different economic, social and environmental results such as losing jobs, business closures, bankruptcies and stopping recycling activities (Mofijur et al., 2021).

For some SCs, the demand has risen dramatically and the supply was unable to keep up (for example, face masks and disinfectants) and for some SCs, demand and supply have plummeted due to reduction or stop in manufacturing (like the automotive industry). All in all, The COVID-19 epidemic has had a massive impact on different aspects of the economy and society; it has assayed the resilience of SCs as well (Ivanov and Dolgui, 2020).

SC resilience is the ability of the SC to deal with the consequences of risk events in order to return to the original state or reach a more desirable state after the occurrence of the disruption (Ganguly et al., 2018). There are several definitions of SC resilience; for example, Ponomarov and Holcomb (2009. P. 131) defined the concept as "The adaptive capability of the SC to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function." With-

out proper planning, recovery of SCs after disruption is associated with a lot of damages and costs, which in most cases are far more than investing in risk management strategies. Most organizations, on the other hand, prepare themselves for high-probability, low impact risks and ignore low-probability, high-impact risks because of their investment costs. (Chopra and Sodhi, 2004). In order to augment resilience in SCs, usually one or more resilience strategies are used. Some of the most important resilience strategies are multiple sourcing, using backup facilities, fortification of facilities, capacity expansion and holding emergency inventory (Sabouhi et al., 2018). The outbreak of the COVID-19 pandemic obviously indicates the need to promote SC resilience in research and application (Ivanov and Dolgui, 2020). Sustainability and resilience attempt to guarantee the survival of the SC. Sustainability which follows optimum utilization of humans and the environment along with the decrease in costs, tries to obtain long-term survival of the SC (Katiyar et al., 2018) and resilience focuses on the survival of the system with regard to disruptions. Thus, resilience and sustainability should be considered in an integrated framework in order to benefit the synergetic effects between them and obtain the best outcome. From another view, the SC should be resilient enough to maintain its sustainability, for disruptions may damage sustainability (Zare Mehrjerdi, and Shafiee, 2021).

As mentioned, the responsiveness of the SC may be declined when disruptions occur. A responsive SC is capable of responding to changes in customer demands and variations in the target market (Gunasekaran et al., 2008). There are different approaches for considering responsiveness in optimization models. One approach is defining some objective functions like minimizing lateness of delivery, maximizing the fill rate of customers' demand, or minimizing the unmet demand. The other approach is defining some constraints in the optimization model, like constraints on the fulfillment rate of customers' demand (Sabouhi et al., 2020).

Our research contributes to the literature by presenting a new multi-objective optimization model for designing a sustainable, resilient and responsive SC under hybrid uncertainty. It is assumed that the network structure is mixed open and closed-loop and the suppliers, production centers, distribution centers, collection/inspection centers and recycling centers are exposed to disruptions. Some resilient strategies, including multiple sourcing, facilities fortification, dual-channel distribution and capacity expansion are utilized in order to enhance SC resilience. Economic, social and environmental aspects of sustainability have been considered. The responsiveness of SC has also been taken into account by imposing constraints on the fulfillment rate of customers' demand. Two-stage stochastic programming and a robust optimization approach are utilized for handling uncertainties. A Lagrangian relaxation (LR) method and a constructive heuristic (CH) are developed to cope with the complexity of the problem. A case study is also presented to show the applicability of the model, extracting the main results and getting closer to real-world situations.

The remainder of the paper is organized as follows. The related literature on resilient SCND, sustainable SCND and sustainable-resilient SCND are briefly reviewed in section 2. Section 3 explains the problem and represents the mathematical model and solution methods. The computational results and analyses and the case study are provided in section 4. Finally, section 5 presents the conclusion and some directions for future research.

2. Literature review

In this section, research papers that are related to the problem studied in this research are reviewed. The research papers of literature are reviewed in three subsections which are sustainable SCND, resilient SCND and sustainable and resilient SCND.

2.1. Sustainable supply chain network design

In a sustainable SC, different objectives related to economic, environmental and social dimensions are usually considered. Many researchers have studied this issue in the last recent years. Studies published up to the end of 2014 have been reviewed by Eskandarpour et al. (2015). Therefore, considering the breadth of literature of this field, in this paper, the researches that have been published since 2015 are reviewed. Also, we concentrate on sustainable SCND papers that have considered reverse logistics.

Some researchers studied the problem of sustainable reverse logistics network design. In the paper of Govindan et al. (2016), the sustainable reverse logistics network design has been studied with considering economic, environmental and social aspects. Based on LCA thinking, Eco-indicator 99 method has been used to quantify and model the environmental issues. Yu and Solvang (2018) studied reverse logistics network design problem with considering flexible capacity. They did not consider the social aspect of sustainability.

Most of the research papers studied sustainable closed-loop SC (CLSC) network design problem. Soleimani et al. (2017) studied the sustainable CLSC network design problem. They considered the maximization of responsiveness as one of the objective functions of their proposed mathematical model. Govindan et al. (2017a) worked on the sustainable CLSC network design and considered the vehicle rooting problem in their paper. Hajiaghaei-Keshteli and Fathollahi Fard (2019) presented a nonlinear programming model for the sustainable CLSC network design problem considering discount supposition in transportation costs. The multi-period sustainable CLSC network design problem was studied in Sahebjamnia et al. (2018). Taleizadeh et al. (2019) investigated pricing and discount decisions in the problem of multi-period sustainable CLSC network design. Pourmehdi et al. (2020) studied sustainable CLSC network design in the steel industry in a stochastic environment. They proposed a scenario-based multi-objective mathematical model for the problem. The same works on sustainable CLSC network design can be found in the papers of Darbari et al. (2017), Mota et al. (2018), Zhen et al. (2019) and Nayeri et al. (2020).

Given that the structure of the proposed SC in our paper is mixed closed and open-loop and this issue has relation with environmental issues, a paper that has been done on mixed open and closed-loop SCND is reviewed. Özceylan (2016) studied the problem of optimizing the mixed open and closed-loop SC network. In fact, the considered SC network in that paper included an open-loop network and a closed-loop network. The closed-loop SC and the forward SC produce different goods which have common components. In the reverse SC, reusable components are divided into two parts. Some of them are delivered to closed-loop SC factories and some are transferred to another SC, which authors named open-loop SC.

2.2. Resilient supply chain network design

Due to the importance of SC disruptions and resilience, the issue of resilient SCND has been considered by researchers in the last decade and a growing research trend is observed. Peng et al. (2011) proposed a mixed integer programming model for the SCND problem and studied the mitigation of the disruption risks and increasing resilience using p-robustness. Azad et al. (2013) studied the SCND problem under random disruptions in facilities and transportation. They applied fortification of facilities and backup transportation modes as resilience strategies. Salehi Sadghiani et al. (2015) worked on retail SCND problem under operational and disruption risks and used backup facilities as a strategy to enhance SC resilience.

Nooraie and Mellat Parast (2016) investigated the trade-off among investments in upgrading SC capabilities and reducing SC risks and minimizing the cost of SC disruptions. They presented a multi-objective stochastic model for their presented problem. Hasani and Khosrojerdi (2016) proposed a mixed-integer non-linear programming model for formulating the robust global SCND problem under disruptions and uncertainty. They used semi-manufactured production, facility dispersion, keeping inventory, multiple sourcing and alternative BOM adaptation as resilience strategies. Jabbarzadeh et al. (2016) studied resilient SCND problem under disruption risks and supply/demand interruptions and utilized facility fortification and backup facilities as strategies to increase resilience. Sabouhi et al. (2018) proposed a hybrid approach based on data envelopment analysis and mathematical programming for resilient SCND problem. Recently, Gholami-Zanjani et al. (2021a) studied resilient food SCND problem under demand uncertainty and epidemic disruptions. They proposed four resilience strategies, including multiple-sourcing, fortification, backup supplier and capacity expansion.

Integrated responsive and resilient SCND problem was studied in the paper of Fattahi et al. (2017). They assumed that the demand of customers is sensitive to delivery lead time. Facility fortification and altering sourcing decisions were proposed as resilience strategies. Sabouhi et al. (2020) also studied responsive and resilient SCND problem. They developed a two-stage stochastic optimization model and used multiple sourcing, backup suppliers, direct shipment and some other resilient strategies in their problem to mitigate the impacts of disruptions in facilities and transportation routes.

Competition is another issue that has been considered in the literature of resilient SCND. Ghavamifar et al. (2018) studied the resilient SCND problem under competition. They used bi-level multi-objective programming approach to formulate the problem. The competitive resilient SCND was also studied by Rezapour et al. (2017).

The reviewed research papers above have studied resilience in forward SCs. Based on the literature, Jabbarzadeh et al. (2018b) worked on CLSC network design under disruption risks in the centers of supply, production, collection and disposal. They considered uncertainties in the parameters of the problem, including demand and costs. The resilience strategy used in this study was lateral transshipment.

2.3. Resilient and sustainable supply chain network design

In recent years, some researchers have studied the resilient and sustainable SCND problem due to the importance of considering resilience and sustainability simultaneously. This is a growing field of research and more steps are needed towards completing and promoting this issue.

Some of the researchers considered environmental aspects of SC along with resilient in SCND problem. In other words, they studied green and resilient SCND. The papers of Mohammed et al. (2019), Yavari and Zaker (2019), Hasani et al. (2021) and Gholami-Zanjani et al. (2021b) have been done in this field.

In the other articles, economic, social and environmental aspects of sustainability is considered alongside resilience. These articles have a direct relation with the problem studied in this paper. Fahimnia and Jabbarzadeh (2016) explored the sustainable–resilient relationship in the SCND problem. They only considered the sustainability of suppliers. Zahiri et al. (2017) proposed a MILP model for integrated sustainable-resilient SCND. Reducing complexity and criticality of nodes, reducing the complexity of flows and multiple sourcing were used as resilience strategies. Jabbarzadeh et al. (2018a) proposed a hybrid approach using the fuzzy clustering method and a stochastic programming

model to design a resilient and sustainable SC. The resilience strategies included multiple sourcing, contracting with backup suppliers, and adding extra production capacity. In their paper, only the sustainability of suppliers was considered. Hosseini-Motlagh et al. (2020) studied sustainable and resilient SCND in the electricity SC. They incorporated resilience in the problem by using an objective function minimizing de-resiliency in the electricity SC network. Addressing resilience in the objective functions is also considered in the paper of Sazvar et al. (2021). They studied sustainable and resilient SCND problem in vaccine SC. They used capacity planning to increase the redundancy and augment the resilience of SC. Maximization of SC resilience in terms of capacity redundancy, lead time and service level was one of the objective functions of their presented model. Sabouhi et al. (2021) studied sustainable and resilient SCND problem with regional considerations. They presented a hybrid methodology using K-means clustering method and a multi-objective mathematical model. Some resilience strategies such as supplier fortification, use of substitutable products and facility dispersion were used for coping with random disruptions. Recently the sustainable and resilient CLSC network design problem has been studied by Zare Mehrjerdi and Shafiee (2021). They used a number of resilient strategies such as Multiple sourcing, contracting the primary and backup suppliers and information sharing.

2.4. Research gap

Table 2 represents the different characteristics of the papers that have a closer relationship with our paper. The abbreviations used in Table 2 are introduced in Table 1. Based on the literature review, there are some research gaps that can be considered. Firstly, despite efforts to ensure both sustainability and resilience in SCND problems, there is still a research gap in this area, especially when reverse logistics is considered and the network structure is closed-loop. As can be seen, based on our research, only the paper of Zare Mehrjerdi and Shafiee (2021) has considered both sustainability and resilience in the CLSC network design problem and there is no work considering sustainability and resilience in mixed open and closed-loop SCND problem. Secondly, given that only the works of Jabbarzadeh et al. (2018b), Yavari and Zaker (2019) and Zare Mehrjerdi and Shafiee (2021) have paid attention to reverse logistics and CLSC in resilient SCND, there is still a lack of regard in this context. Note that there is no research for mixed open and closed-loop SCND considering resilience. Thirdly, only two papers have considered responsiveness besides resilience, and more research should be done for responsive and resilient SCND. Fourthly, only the paper of Gholami-Zanjani et al. (2021a) has studied resilient SCND considering the COVID-19 epidemic. Furthermore, sustainability is not mentioned in this paper. Finally, to the best of our knowledge, no work has been done on integrated sustainable, responsive and resilient SCND problem. Based on the aforementioned points, this paper addresses sustainable, resilient and responsive mixed open and closed-loop SCND problem. The main contributions of this paper are as follows:

- Presenting a new mathematical model for mixed open and closed-loop SCND problem
- Considering sustainability, resilience and responsiveness simultaneously in a mixed open and closed-loop SC
- Considering operational and disruption risks in the design of the mixed SC network and proposing a hybrid robust-stochastic approach and some resilience strategies to deal with risks
- Proposing a novel constructive heuristic to cope with problem complexity
- Presenting a real case study and various test instances in order to evaluate the solution methods and analyze the problem

Table 1
The used abbreviations in Tabel 2.

Symbol	Description	Symbol	Description
F	Forward	MHeu	Metaheuristic
CL	Closed-loop	FP	Fuzzy programming
OL	Open-loop	FRO	Fuzzy robust optimization
S	Sustainability	RO	Robust optimization
Rs	Resilience	SP	Stochastic programming
Rp	Responsiveness	LR	Lagrangian relaxation
BD	Benders decomposition	EC	Epsilon-constraint
Heu	Heuristic	WM	Weighted sum method
CHeu	Constructive heuristic	GP	Goal programming
Ec	Economic	Oth	Other
En	Environmental	CS	Commercial optimization software
So	Social	LM	LP-metric
Rv	Reverse		

3. Methods

3.1. Problem statement

This paper addresses the multi-period and multi-echelon mixed open and closed-loop SCND problem, including suppliers, production centers, distribution centers, customers, collection/inspection centers, recycling centers and customers of recycled products (other SCs). The raw materials needed for the manufacturing of products are provided by suppliers. Manufactured products are directly transshipped to customer zones by production centers or sent to distribution centers and then distributed in markets (dual-channel distribution). A part of the distributed products is collected by collection centers. A portion of the collected products is transshipped to recycling centers and the rest is transshipped to disposal centers. In recycling centers, some materials required for manufacturing new products are recycled and sent to production centers and also some recycled products are sold to other SCs. Based on the description of mixed open and closed-loop network, the presented SC is mixed open and closed-loop. The introduced network is schematically depicted in Fig. 1.

3.1.1. Uncertainty

Totally, there are three types of uncertainties in input data, including randomness, epistemic and deep uncertainty (Bairamzadeh et al., 2018). In the randomness uncertainty, the probability distribution can be estimated using sufficient and valid historical data. Stochastic programming can be used for handling this type of uncertainty. Epistemic uncertainty is related to the lack of knowledge in input data. Linguistic attributes or judgmental data are often provided in this type of uncertainty that can be specified using experts' opinions. For modeling the epistemic uncertainty possibilistic programming can be applied. In the deep uncertainty, a lack of information exists about the parameters of the problem. Robust optimization approaches are developed to manage deep uncertainty (Bairamzadeh et al., 2018).

In many cases, there are different types of uncertainties in the parameters of the problem and hybrid uncertainty occurs (Gholizadeh et al., 2020). In the presented problem, there are two types of uncertainties, including randomness and deep uncertainty.

It is assumed that facilities of SC network including suppliers, production centers, distribution centers, collection centers and recycling centers are exposed to disruptions. As mentioned before, the SCs of many countries are now prone to COVID-19 epidemic disruption. In order to augment SC resilience and deal with disruptions, four resilience strategies are applied, including multiple sourcing, facility fortification, capacity expansion and dual-channel distribution. Multiple sourcing is the most well-known strategy for dealing with disruptions (Jabbarzadeh et al., 2018a). This strategy allows facilities to be served by a required number of up-stream facilities. This issue is beneficial when one or more facilities shut down or confronts with the capacity reduction due to disruptions. In facility fortification strategy, a number of fortification levels are defined for facilities to strengthen them against disruptions so that each level has its own cost; i.e., more fortification costs more (Fattahi et al., 2017). The capacity expansion, as its name implies, is adding capacity for times when the capacity of the production center is decreased due to disruptions. The dual-channel distribution strategy was described in the last paragraphs. In order to consider the uncertainty that originated from disruptions, the scenario-based two-stage stochastic programming approach is utilized. Due to the occurrence of disruptions, especially the occurred epidemic disruption and the volatility and lack of awareness of some cost parameters, the parameters related to the manufacturing and purchasing costs, in addition to being scenario-based stochastic, are assumed to have deep uncertainty. In order to manage these uncertainties, Bertsimas and Sim (2004) robust optimization approach is used. Thus, in this paper, randomness and deep uncertainty are handled with a hybrid robust-stochastic approach.

3.1.2. Sustainability

The principles of sustainable development have been considered in many papers of the SC management literature. Researchers mainly have considered sustainability according to the triple bottom line, including economic, environmental and social aspects (Eskandarpour et al., 2015). This approach provides a comprehensive view of the different dimensions of sustainability. On the economic dimension, the proposed mathematical model minimizes the total cost of the SC. The total cost consists of the fixed establishment cost of facilities and variable costs, including purchasing costs, manufacturing costs, transportation costs, handling costs and costs of unmet demands.

For quantifying and assessing the environmental impacts of SC, LCA methodology is used, which is the most valid one for this purpose (Pishvaee et al., 2014). ReCiPe 2008 (Goedkoop et al., 2009), as a standardized and simplified version of LCA, is chosen for obtaining a good approximation of environmental impacts and overcoming some challenges and complexities in the direct use of LCA methodology. This choice was made due to the comprehensiveness of this method and consideration of the mid-point and end-point of the products' life cycle (for more details, interested readers are referred to the paper of Pishvaee et al. (2014)). In the proposed model, environmental impacts of different SC activities and decisions are considered, including establishing facilities, manufacturing and handling of products, transportation of raw materials, main and recycled products and disposing of used products or releasing them into the environment. It is assumed that there are different technologies for manufacturing and recycling. With establishing each production or recycling center, one technology should be

Table 2
Summary of the related research.

| Research	SC characteristics				Network structure				Sustainability aspects			Multi-Period	multi-product		Resilience strategies	Covid-19 epidemic disruption	Uncertainty approach	Solution methods
	S	Rs	Rp	Oth	F	Rv/ OL	CL	Mixed	Ec	En	So		Main products	Recycled products				
Peng et al. (2011)		√			√				√								SP	MHeu, CS
Azad et al. (2013)		√			√				√						√		–	BD, CS
Salehi Sadghiani et al. (2015)		√			√				√						√		RO	CS
Nooraie and Mellat Parast (2016)		√			√				√						√		SP	Heu
Hasani and Khosrojerdi (2016)		√			√				√			√	√		√		RO	MHeu
Jabbarzadeh et al. (2016)		√			√	√			√						√		RO	LR, CS
Govindan et al. (2016)	√					√			√	√	√	√					FP	MHeu, EC
Fahimnia and Jabbarzadeh (2016)	√	√			√				√	√	√		√				SP	GP, CS
Fattahi et al. (2017)		√	√		√				√				√		√		SP	CS
Govindan et al. (2017)	√						√		√	√							FP	CS
Soleimani et al. (2017)	√						√		√	√	√	√	√	√			FP	MHeu, CS
Darbari et al. (2017)	√						√		√	√	√	√	√	√			FP	GP, CS
Rezapour et al. (2017)	√	√		√	√				√						√		SP	CS
Zahiri et al. (2017)		√			√				√	√	√	√	√		√		FP	MHeu
Ghavamifar et al. (2018)		√		√	√				√			√	√		√		SP	BD, Oth
Sabouhi et al (2018)		√			√				√						√		SP	CS
Yu and Solvang (2018)	√					√			√	√		√	√				SP	EC, WM, CS
Mota et al. (2018)	√						√		√	√	√	√	√	√			SP	CS
Sahebjamnia et al. (2018)	√							√	√	√	√		√				–	MHeu
Jabbarzadeh et al. (2018a)	√	√			√				√	√	√				√		SP	CS
Jabbarzadeh et al. (2018b)		√					√		√	√	√	√	√		√		SP	LR, CS
Hajiaghaei-Keshteli and Fathollahi Fard (2019)	√						√		√	√	√						–	MHeu
Mohammed et al. (2019)	√	√			√				√	√							FP	EC, CS
Zhen et al. (2019)	√						√		√	√		√					SP	LR, CS
Taleizadeh et al. (2019)	√						√		√	√	√	√	√				FP	CS, Oth
Yavari and Zaker (2019)	√	√					√		√	√	√	√	√	√	√		SP	LM, CS
Nayeri et al. (2020)	√							√	√	√	√		√	√			FRO	GP, CS
Pourmehdi et al. (2020)	√						√		√	√	√		√				SP	GP, CS
Sabouhi et al. (2020)		√	√		√				√						√		SP	BD, CS, Oth
Hosseini-Motlagh et al. (2020)	√	√			√				√	√	√						FRO	GP, CS
Gholami-Zanjani et al. (2021a)		√			√				√			√			√	√	SP	BD, CS
Gholami-Zanjani et al. (2021b)	√	√			√				√			√	√		√		SP	Oth, CS
Zare Mehrjerdi and Shafiee (2021)	√	√					√		√	√	√	√	√		√		SP	EC, CS
Hasani et al. (2021)	√	√			√				√	√	√	√	√		√		SP, RO	MHeu
Sabouhi et al. (2021)	√	√			√				√	√	√	√	√		√		SP, RO	BD
Sazvar et al. (2021)	√	√			√				√	√	√	√	√		√		FRO	GP, CS
This paper	√	√	√					√	√	√	√	√	√	√	√	√	**SP, RO**	**LR,** CHeu, **CS**
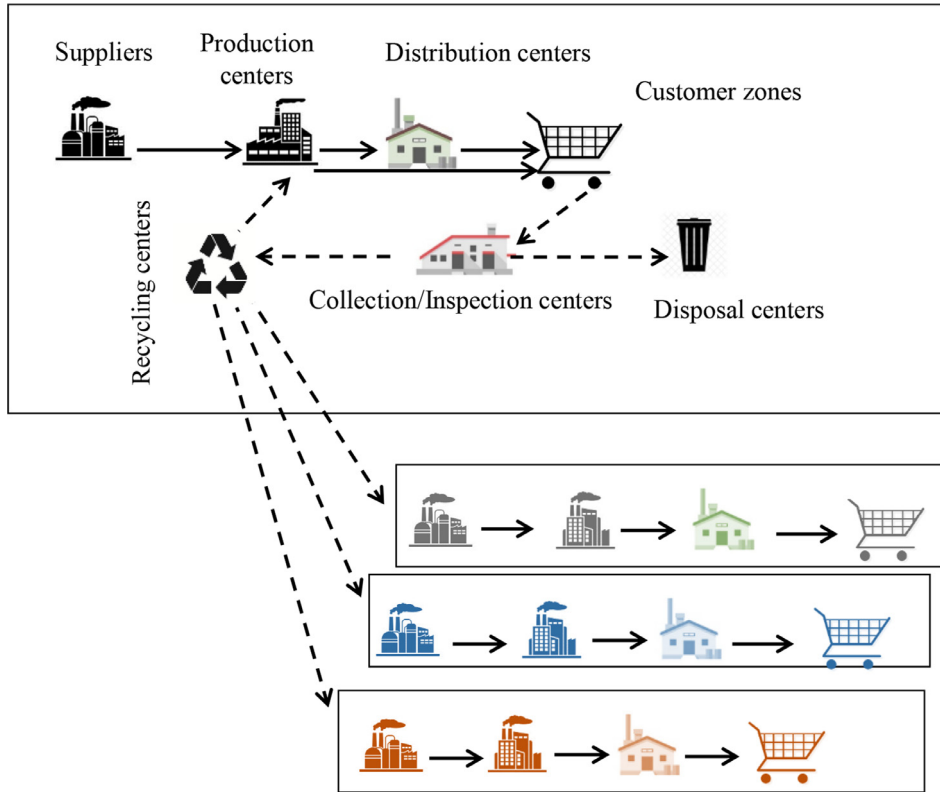
Fig. 1. The graphical representation of the studied supply chain network.

selected. Each technology has its own specific costs, environmental emissions and social impacts.

Different methods and guidelines are utilized by researchers to estimate and quantify the social impact of SC. Here the SA8000 method (SAI, 2008) is applied. In this method, job opportunities and workers' safety are considered. By considering job opportunities, indeed the labor practices and the community development are covered, and by considering the workers' safety, the human rights and fair operating practices are taken into account (Sahebjamnia et al., 2018). In this paper, fixed-job opportunities related to opening facilities and variable job opportunities related to manufacturing and handling the products in different facilities are considered. The work injuries are defined through the lost days due to establishing facilities and also the lost days due to injuries caused by manufacturing, distributing, collecting and recycling the products. The values of the related parameters are determined based on the opinions of related experts and using relevant papers of the literature.

3.1.3. Responsiveness

The explanations about responsiveness were presented in the introduction. As stated before, the responsiveness in the developed model is considered through imposing constraints on the fulfillment rate of the customers' demands for both main and recycled products.

3.2. Mathematical model

The proposed multi-objective mixed-integer linear programming model for responsive, sustainable and resilient SCND problem is as follow:

$$Min\ Z_{Ec} = Z_1^F + Z_1^T + Z_1^V \tag{1}$$

$$Z_1^F = \sum_p \sum_w \sum_a fp_{paw}x_{paw} + \sum_i fs_i ss_i + \sum_j fd_j y_j$$
$$+ \sum_k fc_k z_k + \sum_h \sum_a \sum_{\overline{w}} fl_{h\overline{w}a} rh_{ha\overline{w}} \tag{1-1}$$

$$Z_1^T = \sum_s \pi_s \begin{pmatrix} \sum_i \sum_p \sum_t tr\ qr_{ipts}da_{ip}+ \\ \sum_p \sum_j \sum_e \sum_t tc_e v_{epjts}db_{pj}+ \\ \sum_j \sum_c \sum_e \sum_t tc_e o_{ejcts}dc_{jc}+ \\ \sum_p \sum_c \sum_e \sum_t tc_e r_{epcts}di_{pc}+ \\ \sum_e \sum_c \sum_k \sum_t tc_e n_{eckts}de_{ck}+ \\ \sum_k \sum_h \sum_e \sum_t tc_e b_{ekhts}dg_{kh}+ \\ \sum_k \sum_u \sum_e \sum_t tc_e b'_{ekuts}dh_{ku}+ \\ \sum_h \sum_p \sum_{\overline{w}} \sum_t tr\ f_{h\overline{w}pts}dj_{hp}+ \\ \sum_q \sum_h \sum_g \sum_{\overline{w}} \sum_t \overline{tc}_q f'_{q\overline{w}hgts}dk_{hg} \end{pmatrix} \tag{1-2}$$

$$Z_1^V = \sum_s \pi_s \begin{pmatrix} \sum_i \sum_t \sum_p \widetilde{cr}_{is}qr_{ipts}+ \\ \sum_p \sum_e \sum_w \sum_t \widetilde{mc}_{epws}ma_{epwts}+ \\ \sum_p \sum_e \sum_w \sum_t \widetilde{ce}_{pews}ac_{pewts}+ \\ \sum_e \sum_p \sum_t ch_{ep}iv_{epts}+ \\ \sum_j \sum_e \sum_c \sum_t cd_j o_{ejcts}+ \\ \sum_c \sum_k \sum_e \sum_t cc_k n_{eckts}+ \\ \sum_e \sum_k \sum_u \sum_t dp_u b'_{ekuts}+ \\ \sum_h \sum_{\overline{w}} \sum_p \sum_t rc_{h\overline{w}}f_{h\overline{w}pts}+ \\ \sum_q \sum_{\overline{w}} \sum_g \sum_t \overline{rc}_{qh\overline{w}}f'_{q\overline{w}hgts}+ \\ \sum_c \sum_e \sum_t ud_{ec}\omega_{cets}+ \\ \sum_g \sum_q \sum_t \overline{ud}_{qg}\omega'_{gqts} \end{pmatrix} \tag{1-3}$$

The first objective function (1) of the problem related to the economic dimension of sustainability includes three parts. Eq. (1-1) consists of fixed costs of opening facilities. Eq. (1-2) consists of transportation costs. Eq. (1-3) includes variables costs of manufacturing, distributing, collecting/inspecting, recycling, purchasing and shortage.

$$Min\ Z_{En} = Z_2^F + Z_2^V + Z_2^T \tag{2}$$

$$Z_2^F = \sum_p \sum_a \sum_w eo_{paw}x_{paw} + \sum_j eo_j y_j$$
$$+ \sum_k eo_k z_k + \sum_h \sum_a \sum_{\overline{w}} eo_{ha\overline{w}} rh_{ha\overline{w}} \tag{2-1}$$

$$Z_2^V = \sum_s \pi_s \begin{pmatrix} \sum_e \sum_p \sum_w \sum_t ep_{epw}(ma_{epwts} + ac_{pewts}) + \\ \sum_e \sum_j \sum_c \sum_t ed_j o_{ejcts} + \\ \sum_e \sum_c \sum_k \sum_t ec_k n_{eckts} + \\ \sum_h \sum_{\overline{w}} \sum_p \sum_t er_{h\overline{w}} f_{h\overline{w}pts} + \\ \sum_h \sum_{\overline{w}} \sum_q \sum_g \sum_t eq_{qh\overline{w}} f'_{q\overline{w}hgts} + \\ \sum_e \sum_k \sum_u \sum_t es_e b'_{ekuts} \end{pmatrix} \tag{2-2}$$

$$Z_2^T = \sum_s \pi_s \begin{pmatrix} \sum_i \sum_p \sum_t et_{ip} qr_{ipts} da_{ip} \\ \sum_e \sum_p \sum_j \sum_t et_{pj} v_{epjts} db_{pj} + \\ \sum_e \sum_j \sum_c \sum_t et_{jc} o_{ejcts} dc_{jc} + \\ \sum_e \sum_p \sum_c \sum_t et_{pc} r_{epcts} di_{pc} + \\ \sum_e \sum_c \sum_k \sum_t et_{ck} n_{eckts} de_{ck} + \\ \sum_e \sum_k \sum_h \sum_t et_{kh} b_{ekhts} dg_{kh} + \\ \sum_e \sum_k \sum_u \sum_t et_{ku} b'_{ekuts} dh_{ku} + \\ \sum_h \sum_{\overline{w}} \sum_p \sum_t et_{hp} f_{h\overline{w}pts} dj_{hp} + \\ \sum_q \sum_{\overline{w}} \sum_h \sum_g \sum_t et_{hg} f'_{q\overline{w}hgts} dk_{hg} \end{pmatrix} \tag{2-3}$$

The environmental dimension is optimized via objective function (2). Eq. (2-1) includes the negative environmental impacts of establishing facilities. Eq. (2-2) consists of the variable environmental impacts of manufacturing, distributing, collecting/inspecting, recycling and disposing. The environmental impacts of transportation are given in Eq. (2-3).

$$Max\ Z_{So} = we_{jo}(Z_3^{FJ} + Z_3^{VJ}) - we_{ld}(Z_3^{FL} + Z_3^{VL}) \tag{3}$$

$$Z_3^{FJ} = \sum_p \sum_a \sum_w jf_{paw}x_{paw} + \sum_j jf_j y_j +$$
$$\sum_k jf_k z_k + \sum_h \sum_a \sum_{\overline{w}} jf_{ha\overline{w}} rh_{ha\overline{w}} \tag{3-1}$$

$$Z_3^{VJ} = \sum_s \pi_s \Bigg(\sum_p \sum_w jv_{pw}$$
$$\sum_e \sum_t \frac{ma_{epwts} + ac_{pewts}}{cpp_{pe} + cep_{pe}} +$$
$$\sum_e \sum_p \sum_t \frac{jv'_p \sum_c r_{epcts} + \sum_j v_{epjts}}{cdp_{pe}} +$$
$$\sum_e \sum_j \sum_c \sum_t \frac{jv_j o_{ejcts}}{cpd_j} +$$

$$\sum_e \sum_c \sum_k \sum_t \frac{jv_k n_{eckts}}{cpc_k} +$$
$$\sum_h \sum_{\overline{w}} \sum_t \frac{jv_{h\overline{w}} \sum_p f_{h\overline{w}pts} + \sum_q \sum_g f'_{q\overline{w}hgts}}{cpl_h} \Bigg) \tag{3-2}$$

$$Z_3^{FL} = \sum_p \sum_a \sum_w lf_{paw}x_{paw} + \sum_j lf_j y_j +$$
$$\sum_k lf_k z_k + \sum_h \sum_a \sum_{\overline{w}} lf_{ha\overline{w}} rh_{ha\overline{w}} \tag{3-3}$$

$$Z_3^{VL} = \sum_s \pi_s \Bigg(\sum_p \sum_w lv_{pw}$$
$$\sum_e \sum_t \frac{ma_{epwts} + ac_{pewts}}{cpp_{pe} + cep_{pe}} +$$
$$\sum_e \sum_p \sum_t \frac{lv'_p \sum_c r_{epcts} + \sum_j v_{epjts}}{cdp_{pe}} +$$
$$\sum_e \sum_j \sum_c \sum_t \frac{lv_j o_{ejcts}}{cpd_j} +$$
$$\sum_e \sum_c \sum_k \sum_t \frac{lv_k n_{eckts}}{cpc_k} +$$
$$\sum_h \sum_{\overline{w}} \sum_t \frac{lv_{h\overline{w}} \sum_p f_{h\overline{w}pts} + \sum_q \sum_g f'_{q\overline{w}hgts}}{cpl_h} \Bigg) \tag{3-4}$$

Eq. (3) is the third objective function of the problem and optimizes to the social dimension. Eqs. (3-1) and 3–(2) are related to fixed and variable job opportunities created in SC, respectively. Eqs. (3-3) and 3–(4) includes fixed lost days related to establishing facilities and variable lost days caused by works damage during manufacturing, distributing, collecting/inspecting and recycling.

$$\sum_a \sum_w x_{paw} \leq 1\ \forall p \tag{4}$$

$$\sum_a \sum_{\overline{w}} rh_{ha\overline{w}} \leq 1\ \forall h \tag{5}$$

$$\sum_i qr_{ipts} + \sum_h \sum_{\overline{w}} f_{h\overline{w}pts} = \sum_e (1 - rm_e) \sum_w (ma_{epwts} + ac_{pewts})\ \forall p, t, s \tag{6}$$

$$\sum_w (ma_{epw1s} + ac_{pew1s}) + iv_{ep0} - \sum_c r_{epc1s} = \sum_j v_{epj1s} + iv_{ep1s}\ \forall p, e, s \tag{7}$$

$$\sum_w (ma_{epwts} + ac_{pewts}) + iv_{ep(t-1)s} - \sum_c r_{epcts} = \sum_j v_{epjts}$$
$$+ iv_{epts}\ \forall p, e, t > 1, s \tag{8}$$

$$\sum_p v_{epjts} = \sum_c o_{ejcts}\ \forall j, e, t, s \tag{9}$$

$$\sum_j o_{ejcts} + \sum_p r_{epcts} + \omega_{cets} = d_{cets}\ \forall e, c, t, s \tag{10}$$

$$\sum_k n_{eckts} = \alpha_{ce} \Bigg(\sum_j o_{ejcts} + \sum_p r_{epcts} \Bigg)\ \forall\ e, c, t, s \tag{11}$$

$$\sum_c n_{eckts} = \sum_h b_{ekhts} + \sum_u b'_{ekuts} \ \forall \ e, k, t, s \tag{12}$$

$$\sum_k \sum_h b_{ekhts} = \gamma_e \sum_c \sum_k n_{eckts} \ \forall \ e, t, s \tag{13}$$

$$\sum_k \sum_h \sum_e b_{ekhts} = fr_{ts} + fq_{ts} \ \forall \ t \ , s \tag{14}$$

$$\sum_h \sum_p \sum_{\bar w} f_{h\bar w pts} = \delta \ fr_{ts} \ \forall t, \ s \tag{15}$$

$$\sum_h \sum_g \sum_q \sum_{\bar w} f'_{q\bar w hgts} = fq_{ts} \ \forall t, \ s \tag{16}$$

$$\sum_h \sum_g \sum_{\bar w} f'_{q\bar w hgts} = \beta_q fq_{ts} \ \forall q, \ t, s \tag{17}$$

$$\sum_h \sum_{\bar w} f'_{q\bar w hgts} + \omega'_{gqts} \ = \ dr_{gqts} \ \forall q, g, t, s \tag{18}$$

$$\sum_p qr_{ipts} \le \ cps_i(1 - \eta_{is}) ss_i \ \forall \ i, t, s \tag{19}$$

$$ma_{epwts} \le \ cpp_{pe} \sum_a (1 - \lambda_{paes}) x_{paw} \ \forall \ e, p, w, t, s \tag{20}$$

$$\sum_e iv_{epts} \le chp_p \sum_a \sum_w (1 - \lambda'_{pas}) x_{paw} \ \forall \ p, t, s \tag{21}$$

$$\sum_e \sum_c r_{epcts} + \sum_e \sum_j v_{epjts} \le \ cdp_p \sum_a \sum_w (1 - \lambda''_{pas}) x_{paw} \ \forall \ p, t, s \tag{22}$$

$$ac_{pewts} \le \ cep_{pe} \sum_a x_{paw} \ \forall \ e, p, w, t, s \tag{23}$$

$$\sum_c \sum_e o_{ejcts} \le cpd_j (1 - \varphi_{js}) y_j \ \forall \ j, t, s \tag{24}$$

$$\sum_c \sum_e n_{eckts} \le cpc_k (1 - \mu_{ks}) z_k \ \forall \ k, t, s \tag{25}$$

$$\sum_q \sum_g f'_{q\bar w hgts} + \sum_p f_{h\bar w pts} \le cpl_h \sum_a (1 - \theta_{has}) rh_{ha\bar w} \ \forall \ h, \bar w, t, s \tag{26}$$

$$\frac{\sum_j \sum_e \sum_t o_{ejcts} + \sum_e \sum_p \sum_t r_{epcts}}{\sum_e \sum_t d_{cets}} \ge \tau_{cs} \ \forall \ c, s \tag{27}$$

$$\frac{\sum_q \sum_h \sum_{\bar w} \sum_t f'_{q\bar w hgts}}{\sum_q \sum_t dr_{gqts}} \ge \bar\tau_{gs} \ \forall \ g, s \tag{28}$$

$$qr_{ipts}, ma_{epwts}, ac_{pewts}, r_{epcts}, v_{epjts}, o_{ejcts}, n_{eckts}, \ b_{ekhts}, b'_{ekuts},$$
$$f_{h\bar w pts}, \ iv_{epts}, f'_{qh\bar w gts}, fr_{ts}, fq_{ts}, \omega_{cets}, \omega'_{gqts} \ge 0, \tag{29}$$

$$ss_i, x_{paw}, y_i, z_k, rh_{ha\bar w} \in \{0, 1\}$$

Constraints (4) guarantees that for each production center, at most one fortification level and one production technology should be selected if established. Constraint (5) is the same as constraint (4) and is related to recycling centers. Constraint (6) states that the raw materials required for manufacturing products are supplied by suppliers and recycling centers. Constraints (7)-(10) guarantee the flow balance of products in the forward flow of the SC network.

Constraint (11) states that a fraction of used products is collected by collection centers. The flow balance of products related to the reverse flow of the network is guaranteed by constraints (12–18). Constraints (19)-(26) ensure that the maximum capacity limit of facilities should not be violated. Constraints (27) and (28) ensure the minimum pre-specified responsiveness level for customers of main products and recycled products, respectively. The type of decision variables is determined in constant (29).

Some of the parameters of the presented stochastic model are assumed to have deep uncertainty. In order to deal with these uncertainties and make the model applicable, robust optimization approach developed by Bertsimas and Sim (2004) is applied.

At first, the mentioned approach is described briefly. Assume that the optimization problem is as follow:

$$\min c' x$$
$$s.t. \sum_j \tilde a_{ij} x_j \le b_i \ \forall \ i, \ \forall \ \tilde a_{ij} \in J_i$$
$$x \in X, \ x_j \ge 0 \ \forall \ j \tag{30}$$

Or equivalently:

$$\min c' x$$
$$s.t. \max_{\tilde a_{ij} \in J_i} \left(\sum_j \tilde a_{ij} x_j \right) \le b_i \ \forall \ i$$
$$x \in X, \ x_j \ge 0 \ \forall \ j \tag{31}$$

$\tilde a_{ij}$ is an uncertain parameter and takes value in $[\bar a_{ij} - \hat a_{ij}, \bar a_{ij} + \hat a_{ij}]$ Where $\bar a_{ij}$ and $\hat a_{ij}$ are the nominal value and the maximum deviation from the nominal value, respectively. J_i is the set of uncertain parameters of constraint i. We have:

$$\eta_{ij} = \frac{\tilde a_{ij} - \bar a_{ij}}{\hat a_{ij}} \tag{32}$$

Where η_{ij} takes value in $[-1, 1]$. Problem (31) can be written as follows:

$$\min c' x$$
$$s.t. \sum_j \bar a_{ij} x_j + \max_{\eta_{ij}} (\hat a_{ij} \eta_{ij} x_j) \le b_i \ \forall \ i$$
$$\sum_j \eta_{ij} \le \ \Gamma_i \ \forall \ i$$
$$0 \le \eta_{ij} \le 1 \ \forall \ j \in J_i$$
$$x_j \ge 0 \ \forall \ j \tag{33}$$

Where Γ_i is the budget of uncertainty using which the decision-maker can adjust the robustness of the method against the conservatism of the solution. Considering problem (33), for the second part of the first constraint we have:

$$\max_{\eta_{ij}} (\hat a_{ij} \eta_{ij} x_j) \le b_i \ \forall \ i$$
$$s.t.$$
$$\sum_j \eta_{ij} \le \ \Gamma_i \ \forall \ i$$
$$0 \le \eta_{ij} \le 1 \ \forall \ j \in J_i$$
$$x_j \ge 0 \ \forall \ j \tag{34}$$

The dual problem of (34) is:

$$\min \Gamma_i z_i + \sum_{j \in J_i} p_{ij} \ s.t. \ \Gamma_i + p_{ij} \ge \ \hat a_{ij} x_j \ \forall \ i, \ j \in J_i \ p_{ij} \ge 0,$$
$$\forall \ i, \forall j \in J_i \ z_i \ge 0, \ \forall i \tag{35}$$

$$x_j \geq 0 \; \forall \; j$$

Then, the robust counterpart of problem (33) can be written as below:

$$\min c'x$$
$$s.t.$$
$$\sum_j \overline{a}_{ij}x_j + \Gamma_i z_i + \sum_{j \in J_i} p_{ij} \leq b_i \; \forall \; i$$
$$\Gamma_i + p_{ij} \geq \hat{a}_{ij}x_j \; \forall \; i, \; j \in J_i$$
$$p_{ij} \geq 0, \; \forall \; i, \forall j \in J_i$$
$$z_i \geq 0, \; \forall i$$
$$x_j \geq 0 \; \forall \; j \tag{36}$$

Three cost parameters are affected by operational risks and have deep uncertainty. $\widetilde{mc}_{epws} \in [\overline{mc}_{epws} - \widehat{mc}_{epws}, \; \overline{mc}_{epws} + \widehat{mc}_{epws}]$, $\widetilde{ce}_{pews} \in [\overline{ce}_{pews} - \widehat{ce}_{pews}, \; \overline{ce}_{pews} + \widehat{ce}_{pews}]$ and $\widetilde{cr}_{is} \in [\overline{cr}_{is} - \widehat{cr}_{is}, \; \overline{cr}_{is} + \widehat{cr}_{is}]$. These parameters are in the third part of the first objective function (1–3). The robust counterpart of Eq. (1-3) based on the formulation of Bertsimas and Sim (2004) approach is as follows:

$$Z_1^V = \sum_s \pi_s \begin{pmatrix} \sum_i \sum_t \sum_p \overline{cr}_{is}qr_{ipts} + \zeta^1 \Gamma' + \sum_i \rho_{is}^1 + \\ \sum_p \sum_e \sum_w \sum_t \overline{mc}_{epws}ma_{epwts} + \zeta^2 \Gamma'' \\ + \sum_e \sum_p \sum_w \rho_{epws}^2 + \\ \sum_p \sum_e \sum_w \sum_t \overline{ce}_{pews}ac_{pewts} + \zeta^3 \Gamma''' \\ + \sum_e \sum_p \sum_w \rho_{epws}^3 + \\ \sum_e \sum_p \sum_t ch_{ep}iv_{epts} + \\ \sum_j \sum_e \sum_c \sum_t cd_j o_{ejcts} + \\ \sum_c \sum_k \sum_e \sum_t cc_k n_{eckts} + \\ \sum_e \sum_k \sum_u \sum_t dp_u b'_{ekuts} + \\ \sum_h \sum_{\overline{w}} \sum_p \sum_t rc_{h\overline{w}}f_{h\overline{w}pts} + \\ \sum_q \sum_{\overline{w}} \sum_g \sum_t \overline{rc}_{qh\overline{w}}f'_{q\overline{w}hgts} + \\ \sum_c \sum_e \sum_t ud_{ec}\omega_{cets} + \\ \sum_g \sum_q \sum_t \overline{ud}_{qg}\omega'_{gqts} \end{pmatrix}$$
$$\tag{37}$$

$$\zeta^1 + \rho_{is}^1 \geq \pi_s \widehat{cr}_{is} \sum_p \sum_t qr_{ipts} \; \forall i, s \tag{38}$$

$$\zeta^2 + \rho_{epws}^2 \geq \pi_s \widehat{mc}_{epws} \sum_t ma_{epwts} \; \forall e, p, w, s \tag{39}$$

$$\zeta^3 + \rho_{epws}^3 \geq \pi_s \widehat{ce}_{pews} \sum_t ac_{pewts} \; \forall e, p, w, s \tag{40}$$

$$\varsigma^1, \varsigma^2, \varsigma^3, \rho_{is}^1, \rho_{epws}^2, \rho_{epws}^3 \geq 0 \tag{41}$$

Where ζ^1, ζ^2, ζ^3, ρ_{is}^1, ρ_{epws}^2 and ρ_{epws}^3 are robust variables. Also, $\Gamma' \in [0, |J'|]$ $(|J'| = |I| \times |s|)$, $\Gamma'' \in [0, |J''|]$ $(|J''| = |P| \times |E| \times |W| \times |S|)$ and $\Gamma''' \in [0, |J'''|]$ $(|J''| = |P| \times |E| \times |W| \times |S|)$.

Based on the above formulation, the multi-objective hybrid robust-stochastic mixed-integer linear programming model is as follows:

$$Min \; Z_{Ec} = Z_1^F + Z_1^T + Z_1^V$$
$$Min \; Z_{En} = Z_2^F + Z_2^V + Z_2^T$$
$$Max \; Z_{So} = we_{jo}(Z_3^{FJ} + Z_3^{VJ}) + we_{ld}(Z_3^{FL} + Z_3^{VL})$$
$$s.t$$

$$(1–1), (1–2), (37)-(41), (2–1)-(2–3), (3–1)-(3–4), (4)-(29).$$

3.3. Solution methods

The presented model is multi-objective, and different approaches can be applied to solve it. One of the most common approaches is converting the multi-objective problem to a single-objective one. By doing so, the single-objective techniques can be utilized (Govindan et al., 2019). The proposed tri-objective problem can be transformed into a single-objective one by using the following equation:

$$Min \; Z = \left(W_{Ec}\left(\frac{Z_{Ec} - Z_{Ec}^*}{Z_{Ec}^*}\right)^p + W_{En}\left(\frac{Z_{En} - Z_{En}^*}{Z_{En}^*}\right)^p + \right.$$
$$\left. W_{So}\left(\frac{Z_{So}^* - Z_{So}}{Z_{So}^*}\right)^p\right)^{\frac{1}{p}} \tag{42}$$

Where Z_{Ec}^*, Z_{En}^* and Z_{So}^* denote the optimal values of economic, environmental and social objective functions. For obtaining the optimal value of each objective function, the model is implemented with only that objective function and without considering other ones. W_{Ec}, W_{En} and W_{So} are weights of these objectives and can be determined by experts or decision-makers. The value of p is set to 1, because greater values lead to non-linearity, which substantially increases complexity.

In terms of complexity, SCND falls into the category of NP-hard problems (Govindan et al., 2016). CLSC design problems having more complexities in comparison with traditional SCND are also among this category of problems (Soleimani and Govindan, 2015). Therefore, the presented problem in this paper is also NP-hard. In this paper, in order to deal with the problem complexity, two solution approaches, including a Lagrangian relaxation method and a constructive heuristic algorithm are proposed.

3.3.1. Lagrangian relaxation method

LR is a powerful way to solve mixed-integer programming problems and has been used successfully to solve SCND problems. The works of Jabbarzadeh et al. (2018b), Fahimnia et al. (2017) and Badri et al. (2013) are among research papers that have used this method in the SCND problem. The process of the LR algorithm is described in the following.

In this method, by following a repetitive procedure and improving the lower bound (in minimization problems), the optimal or near-optimal solution is obtained (Fisher, 2004). Initially, an upper bound and a lower bound are considered for the problem and the Lagrangian dual model is constructed by relaxing some constraints and adding them to the objective function with Lagrangian multipliers. Each time the algorithm is executed, the Lagrangian dual model is solved and the previous lower bound is replaced by the new one if improved. The upper bound can also be improved during algorithm execution. This procedure continues until the stopping criterion is met.

In the proposed model, constraints 20, 26 and 27 are released. Relaxing these constraints greatly reduces the complexity of solving the model (these constraints were selected by performing numerous calculations and experiments). By releasing these constraints, we form the Lagrangian dual model as follows:

$$Min \; Z = W_{ec}\left(\frac{Z_{Ec} - Z_{Ec}^*}{Z_{Ec}^*}\right) + W_{En}\left(\frac{Z_{En} - Z_{En}^*}{Z_{En}^*}\right) +$$
$$W_{So}\left(\frac{Z_{So}^* - Z_{So}}{Z_{So}^*}\right) + \sum_e \sum_p \sum_w \sum_t \sum_s \psi_{epwts}^1$$
$$\left(ma_{epwts} - cpp_{pe} \sum_a \left(1 - \lambda_{paes}\right)x_{paw} + \right.$$
$$\sum_h \sum_t \sum_{\overline{w}} \sum_s \psi_{ht\overline{w}s}^2 \left(\sum_q \sum_g f'_{q\overline{w}hgts} + \sum_p f_{h\overline{w}pts} - \right.$$

$$+ \sum_c \sum_s \psi_{cs}^3 \left(\tau_{cs} - \frac{\sum_j \sum_e \sum_t o_{ejcts} + \sum_e \sum_p \sum_t r_{epcts}}{\sum_e \sum_t d_{cets}} \right) \right) \qquad (43)$$

$$cpl_h \sum_a (1 - \theta_{has}) rh_{ha\overline{w}} \Bigg)$$

s.t.

(1–1), (1–2), (37)-(41), (2–1)-(2–3), (3–1)-(3–4), (4)-(29).

ψ_{epwts}^1, $\psi_{ht\overline{w}s}^2$ and ψ_{cs}^3 are Lagrangian multipliers and non-negative. The optimal solution of the above model is a lower bound for the original problem.

To calculate the upper bound, the presented mathematical model is solved, while the variables x_{paw} and $rh_{ha\overline{w}}$ are fixed and their values are considered equal to the values obtained from solving the Lagrangian dual model.

In each iteration of the LR process, the Lagrangian multipliers and the lower and upper bounds are updated. In this paper, the subgradient method presented by Fisher (2004) is used.

$$\sigma_n^1 = \frac{\Phi(UB^n - LB^n)}{\sum_e \sum_p \sum_w \sum_t \sum_s \left(ma_{epwts} - cpp_{pe} \sum_a (1 - \lambda_{paes}) x_{paw} \right)^2} \qquad (44)$$

$$\sigma_n^2 = \frac{\Phi(UB^n - LB^n)}{\sum_h \sum_t \sum_{\overline{w}} \sum_s \left(\sum_q \sum_g f'_{q\overline{w}hgts} + \sum_p f_{h\overline{w}pts} - cpl_h \sum_a (1 - \theta_{has}) rh_{ha\overline{w}} \right)^2} \qquad (45)$$

$$\sigma_n^3 = \frac{\Phi(UB^n - LB^n)}{\sum_c \sum_s \left(\tau_{cs} - \frac{\sum_j \sum_e \sum_t o_{ejcts} + \sum_e \sum_p \sum_t r_{epcts}}{\sum_e \sum_t d_{cets}} \right)^2} \qquad (46)$$

In Eqs. (44) to (46), n represents the iteration number of the algorithm. UB^n and LB^n show the best found upper and lower bounds up to iteration n. Φ is considered 2 in the first iteration, and if after 5 consecutive repetitions no improvement in the lower bound value is obtained, this value is halved (these values are selected by performing numerous experiments and numerical calculations). Finally, σ_n^1, σ_n^2 and σ_n^3 are step size values. The values for the Lagrangian multipliers are updated in each iteration using Eqs. (47) to (49).

$$\psi_{epwts}^{1,n+1} = \max \left\{ 0, \ \psi_{epwts}^{1,n} + \sigma_n^1 (ma_{epwts} - cpp_{pe} \sum_a (1 - \lambda_{paes}) x_{paw}) \right\} \qquad (47)$$

$$\psi_{ht\overline{w}s}^{2,n+1} = \max \left\{ 0, \ \psi_{ht\overline{w}s}^{2,n} + \sigma_n^2 \left(\sum_q \sum_g f'_{q\overline{w}hgts} + \sum_p f_{h\overline{w}pts} \right.\right.$$
$$\left.\left. - cpl_h \sum_a (1 - \theta_{has}) rh_{ha\overline{w}} \right) \right\} \qquad (48)$$

$$\psi_{cs}^{3,n+1} = \max \left\{ 0, \ \psi_{cs}^{3,n} + \sigma_n^3 \left(\tau_{cs} - \frac{\sum_j \sum_e \sum_t o_{ejcts} + \sum_e \sum_p \sum_t r_{epcts}}{\sum_e \sum_t d_{cets}} \right) \right\} \qquad (49)$$

The algorithm continues until the stopping criterion is met. The stopping criterion can be reaching a certain step size, reaching a predetermined CPU time or a number of iterations, or obtaining the desired percentage difference between the upper and lower bounds. The latter is used as the stopping criterion in this paper ($\frac{UB-LB}{LB} \le \varepsilon$).

3.3.2. Constructive heuristic algorithm

CH consists of two phases. In the first phase, the integer (binary) variables of the problem are randomly generated. After generating the binary variables, they are fixed in the proposed mathematical model and then an LP-relaxed model is solved. In the second phase, the obtained solutions of the first phase are improved. In this phase, for each binary variable, some elements are selected randomly and set to zero. Then, some of the zero elements are randomly chosen and set equal to 1. This procedure is done in an iterative loop with a predetermined number of iterations (*MaxIt*) and after complement, the best solution is reported. The pseudocode of the CH algorithm is presented in Fig. 2.

4. Results and discussion

In this section, computational results and analyses are presented. The MILP model and LR method were coded in GAMS version 24.1.3. CH was coded in MATLAB version R2015a and the link between GAMS and MATLAB was used for solving the LP-relaxed model and transferring data between two softwares. The mathematical model and solution methods were performed on a computer with 16 GB of RAM and an Intel (R) Core (TM) i73720QM, 2.6 GHz CPU, running on Windows 10 (64-bit).

4.1. Generating numerical instances

Twelve test problems were randomly generated to assess the performance of the solution methods. The data generation was done using the collected data of the case study presented in Section 4.3. The sizes of the test problems were determined based on the related papers of the literature (such as Devika et al., 2014 and Sahebjamnia et al., 2018), authors and experts opinion. The unit of parameters related to costs is Iranian currency (Toman) and are expressed in million Tomans. The unit of parameters related to the demand and capacity parameters is Ton. The ranges of parameters and details of the test problems are reported in Table 3 and Table 4, respectively.

The number of fortification levels and the number of production and recycling technologies is 4 and 3, respectively in all test problems.

4.2. Assaying and comparing solution methods

The test problems presented in the previous section are solved using proposed solution methods. The mathematical model has been solved via CPLEX solver and has been compared with LR and CH. The values of three objective functions for each solution method are represented in Table 5. The values of the integrated objective function and the relative percentage deviation (RPD) are shown in Table 6. The RPD can be calculated as follows:

$$\%RPD = \frac{|Method_{sol} - Best_{sol}|}{Best_{sol}} \times 100 \qquad (56)$$

Where $Method_{sol}$ is the solution obtained from the method used for the problem and $Best_{sol}$ is the best found solution to that problem.

The CPU time limit for all solution methods was considered 43200 seconds. "NA" means that the solution method could not obtain any solution before reaching the CPU time limit. In these computations, W_{Ec}, W_{En} and W_{So} are 0.4, 0.3 and 0.3, respectively. Also, the values of we_{jo} and we_{ld} is selected 0.6 and 0.4. These weights are suggested by industry experts according to supply chain policies.

As mentioned before, the problem under study has high complexity, and optimal solutions may not be found at reasonable CPU

Input: sets and parameters of the problem
output: The best found solution
Begin
  for it=1:$MaxIt$ **do**
    Phase 1. (generating initial solution)
    while LP-relaxed model is **infeasible**
      generate the vacant matrices/vectors for integer variables of the problem
      Let X denote the integer variables ($s_i, x_{paw}, y_i, z_k, rh_{ha\bar{w}}$)
      randomly generate X
      solve LP-relaxed mathematical model
    end
    set *obj(it)* =the objective function value of LP-relaxed model
    $X(it) = X$
    if it=1
      $X^* = X(it)$
      $obj^* = obj(it)$
    end
    Phase 2.1 (Improving the solution)
    Let v be the set of binary variables $iv = 1, ... 5$
    while LP-relaxed model is **infeasible**
      for $i = 1:v$ **do**
        set d_v number (random number) of variables which are 1 equal to 0
        select d'_v number (random number, $d'_v \le d_v$) of zero variables randomly and set them equal to 1
        Save new variables ($X'(it)$)
      end
    end
    solve LP-relaxed mathematical model
    set *obj₂* =the objective function value of LP-relaxed model
    if *obj₂*< *obj**
      $X^* = X'(it)$ and $X(it) = X'(it)$
      $obj^* = obj_2$ and *obj(it)= obj₂*
    end
  end
report obj^*

Fig. 2. Pseudo-code of constructive heuristic algorithm.

Table 3
Ranges of the parameters.

| Parameter	Range/ Value	Parameter	Range/ Value
fs_i	[60, 120]	jf_j, jf_k	[10, 40]
fp_{paw}	[200,000, 800,000]	$jf_{h\bar{w}}$	[20, 80]
fd_j, fc_k	[2000, 4000]	$jva_{paw}, jv_j, jv_k, jf_{h\bar{w}}$	[1, 4]
$fl_{ha\bar{w}}$	[50,000, 150,000]	$lf_{paw}, lf_j, lf_k, lf_{ha\bar{w}}$	[1, 100]
$tr, tc_e, \overline{tc}_q$	[0.004, 0.008]	$lv_{paw}, lv_j, lv_k, lv_{ha\bar{w}}$	[1, 3]
distance parameters	[100, 2000] (km)	rm_e	[0, 0.15]
$\overline{mc}_{epws}$	[30, 40]	δ	[0.4, 0.6]
$\widehat{mc}_{epws}$	[5, 10]	β_q	[0.1, 0.85]
$\overline{ce}_{pews}$	[40, 45]	d_{ces}	[1000, 5000]
$\widehat{ce}_{pews}$	[5, 10]	dr_{glqs}	[500, 2000]
ch_{ep}, cc_k, cd_j	[0.004, 0.006]	cps_i	[60,000, 100,000]
$rc_{h\bar{w}}$	[0.3, 0.6]	$\tau_{cs}, \bar{\tau}_{qs}$	[0.4, 0.9]
$\overline{rc}_{qh\bar{w}}$	[0.05, 0.1]	cpp_{pe}	[3000, 20,000]
dp_u	[0.0004, 0.0006]	cep_{pe}	[600, 2000]
$\overline{cr}_{is}$	[10, 13]	cpd_j, cpc_k	[50,000, 100,000]
$\widehat{cr}_{is}$	[3, 5]	cpl_h	[10,000, 60,000]
ud_{ec}	[15, 25]	cdp_{pe}	[20,000, 40,000]
$\overline{ud}_{qg}$	[0.5, 1]	$\lambda_{paes}, \lambda'_{pas}, \eta_{is},$	
$\varphi_{js}, \mu_{ks}, \theta_{haes}$	[0, 1]		
$eo_{maw}, eo_j, eo_k, eo_{ma\bar{w}}$	[1, 10]	γ_e	[0.25, 0.95]
$ep_{epw}, ed_j, ec_k, es_e,$			
$er_{h\bar{w}}, eq_{qh\bar{w}}$	[0.01, 0.1]	α_{ce}	[0.25, 0.95]
jf_{pw}	[50, 200]	$et_{\alpha\beta}$	
($\alpha, \beta \in i, p, j, c, k, h, u$)	[0.0001, 0.1]		
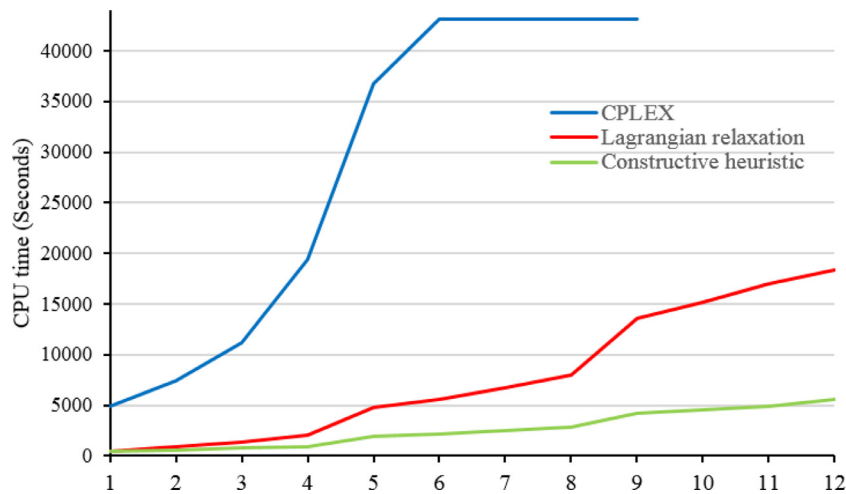
Fig. 3. Comparison of solution methods in term of the CPU time.

Table 4
Generated test problems.

Problem number	Problem size ($|I|, |P|, |J|, |C|, |K|, |H|, |U|, |E|, |G|, |Q|, |S|, |T|$)
1	(2, 1, 2, 4, 3, 1, 2, 2, 1, 2, 3, 2)
2	(4, 2, 3, 7, 4, 2, 4, 2, 2, 2, 3, 2)
3	(6, 3, 5, 10, 5, 3, 6, 2, 3, 2, 3, 2)
4	(8, 4, 6, 13, 6, 4, 8, 2, 4, 2, 3, 2)
5	(10, 5, 7, 16, 7, 5, 10, 3, 5, 3, 4, 3)
6	(12, 6, 8, 19, 8, 6, 12, 3, 6, 3, 4, 3)
7	(14, 7, 9, 22, 9, 7,14, 3, 7, 3, 4, 3)
8	(16, 8, 10, 24, 10, 8, 16, 3, 8, 3, 4, 3)
9	(18, 10, 12, 28, 12, 10, 16, 5, 10, 4, 5, 4)
10	(20, 12, 16, 32, 16, 12, 20, 5, 12, 4, 5, 4)
11	(22, 14, 18, 36, 18, 14, 22, 5, 14, 4, 5, 4)
12	(24,16, 20, 40, 20, 16, 24, 5, 16, 4, 5, 4)

times. Here, in order to obtain solutions by GAMS, even with a distance from the optimal solutions, and for a better comparison between three solution methods, the *optcr* option of GAMS software (see Rosenthal, 2013 for more details) has been used which is the relative distance between the best solution (feasible current solution obtained) to the best estimated solution (which is a bound for the optimal solution). GAMS stops as soon as it reaches a relative distance less than *optcr*.%Gap shows the obtained relative distance. The value of *optcr* was set to 1% in the first 6 problems and for problems 7, 8 and 9 it was set to 3%, 6% and 11%, respectively. These values were selected based on experiments and trial and error so that the problem is solved in the determined CPU time limit and the%GAP is as small as possible. As can be observed from Table 5, GAMS was able to find the optimal solution in the first five test problems (%Gap=0) and was not able to find any solution in three instances with large sizes, including problems number 10, 11 and 12. In instances 1, 2 and 3, LR and CH have also found optimal solutions and they have shown good performance in other problems. Based on Table 6, CH outperforms LR, while the values of RPD are less in this algorithm, such that the average RPD for this solution method is about 0.9%.

Fig. 3 depicts the CPU time of CPLEX, LR and CH for test problems. It indicates that as the size of the problems grows, the CPU time of CPLEX increases exponentially, while the CPU times of LR and CH increase linearly. Due to the results of Table 6 and Fig. 3, LR and CH are suitable for solving large-sized problems. Especially CH is the best solution method comparing with two other methods, for it can find high-quality solution in very suitable times.

The convergence of LR and CH for problem number 2 is shown in Fig. 4.

4.3. Case study

In this section, a tire SC in Iran is presented as a case study in order to further analyze the problem and study it in more depth. In the mentioned SC network, there are four potential suppliers, one manufacturing center, two distribution centers and seven main customer zones. The company produces four types of tires. For developing the SC network, two and three locations are considered for establishing new production centers and distribution centers, respectively. The motivation of the company for redesign and development is increasing resilience to deal with disruptions, maintaining and enhancing SC sustainability, and increasing responsiveness considering the demand of the market and disruptions. In order to upgrade the environmental and social aspects, the company desires to develop reverse logistics and exploit a mixed open and closed-loop SC network. Accordingly, there are two potential locations for collection centers and two potential locations for recycling centers. Six SCs have also been identified as the customers of three types of recycled products which will be produced in recycling centers of the company. A number of industry experts (14 people) were utilized to present the case study better and help in specifying some of the parameters of the problem. The characteristics of consulting experts based on their specialization and average work experience are shown in Fig. 5. Experts' fields of work included logistics and supply chain engineering, risk management, health, safety and environment (HSE), production management, human resource management and financial analysis.

According to the experts, in order to consider the disruptions, especially the disruption caused by COVID-19 disease, three scenarios have been considered, which show optimistic, probable and pessimistic states. These scenarios show different situations caused by the occurrence of disruptions and govern all stochastic parameters of the problem. The intensity of these disruptions, which are shown by scenarios, has been determined based on available data and the experts' opinions. The number of planning periods is three. The collected data on ranges and values of other parameters were presented in Table 3. The problem was solved via proposed solution methods. The mathematical model and two other solution methods obtained the same solutions. The results are reported in Table 7. The locations of existing and potential facilities and also selected locations for establishing facilities are depicted in Fig. 6.

Table 5

The values of objective functions obtained by solution methods.

Test problems	GAMS (CPLEX)				LR			CH		
	Z_{Ec}	Z_{En}	Z_{So}	%Gap	Z_{Ec}	Z_{En}	Z_{So}	Z_{Ec}	Z_{En}	Z_{So}
1	545,700.92	273,249.89	124.18	0.00%	545,700.92	273,249.89	124.18	545,700.92	273,249.89	124.18
2	893,567.28	162,855.52	252.02	0.00%	893,567.28	162,855.52	252.02	893,567.28	162,855.52	252.02
3	942,137.83	313,902.99	382.09	0.00%	942,137.83	313,902.99	382.09	942,137.83	313,902.99	382.09
4	1,078,044.98	335,900.69	426.71	0.00%	1,083,096.03	336,995.17	425.82	1,078,044.98	335,900.69	426.71
5	1,327,130.32	370,267.36	644.77	0.00%	1,342,515.70	373,480.30	640.80	1,330,003.61	370,882.44	643.92
6	930,957.70	627,237.99	677.56	0.45%	937,455.43	630,830.36	675.60	934,716.70	629,319.97	676.41
7	1,041,884.73	522,596.43	636.67	2.32%	1,048,081.28	524,978.37	634.95	1,045,656.95	524,049.03	635.61
8	1,121,790.25	517,650.05	681.01	5.98%	1,139,631.68	523,454.56	676.11	1,137,062.10	522,626.28	676.78
9	1,632,471.12	792,320.88	752.34	10.23%	1,663,239.38	805,851.70	744.86	1,645,777.88	798,194.32	748.91
10	NA				1,725,229.10	892,155.63	879.32	1,718,429.56	889,290.95	881.28
11	NA				1,796,412.11	900,560.15	911.56	1,792,311.93	899,064.44	912.77
12	NA				1,921,486.12	986,131.11	1005.18	1,911,429.05	981,449.75	1007.95

Table 6

Comparing the solution methods based on the values of integrated objective function.

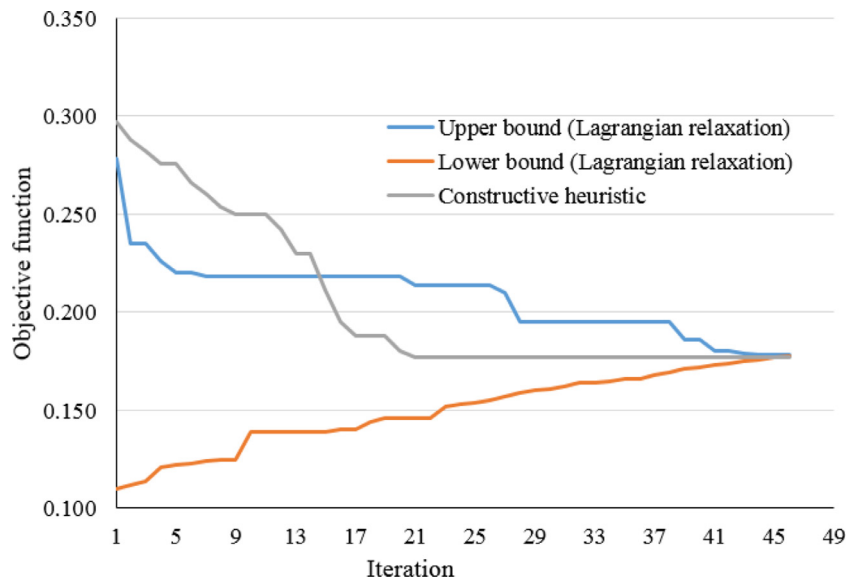|	GAMS (CPLEX)		LR		CH	
	Z	RPD	Z	RPD	Z	RPD
1	0.132	0.00%	0.132	0.00%	0.132	0.00%
2	0.254	0.00%	0.254	0.00%	0.254	0.00%
3	0.178	0.00%	0.178	0.00%	0.178	0.00%
4	0.298	0.00%	0.302	1.32%	0.298	0.00%
5	0.235	0.00%	0.246	4.47%	0.237	0.84%
6	0.380	0.00%	0.387	1.81%	0.384	1.04%
7	0.230	0.00%	0.235	2.13%	0.233	1.29%
8	0.248	0.00%	0.262	5.34%	0.260	4.62%
9	0.276	0.00%	0.296	6.76%	0.285	3.16%
10	NA		0.211	1.90%	0.207	0.00%
11	NA		0.149	1.34%	0.147	0.00%
12	NA		0.242	2.07%	0.237	0.00%

Fig. 4. Convergence of developed Lagrangian relaxation (LR) and constructive heuristic (CH).

Table 7

The values of objective functions in case study.

Z_{Ec}	Z_{En}	Z_{So}
401,115.72	225,072.62	296.12

As mentioned before, in this paper sustainability and resilience in SC are studied. Fig. 7. represent the effect of resilience strategies on sustainability aspects, including economic, environmental and social dimensions. Six different cases are considered. In the first case, no resilience strategy is applied (NR). In the last case, all resilience strategies are utilized (R) and in other cases, one of the introduced resilience strategies, including multiple sourcing (MS), facility fortification (FF), capacity expansion (CE) and dual-channel distribution (DD) is applied.

According to the diagrams, resilience strategies have a significant impact on the dimensions of sustainability. On the economic dimension, capacity expansion by 35%, multiple sourcing by 31% and facility fortification and dual-channel distribution by 27% re-
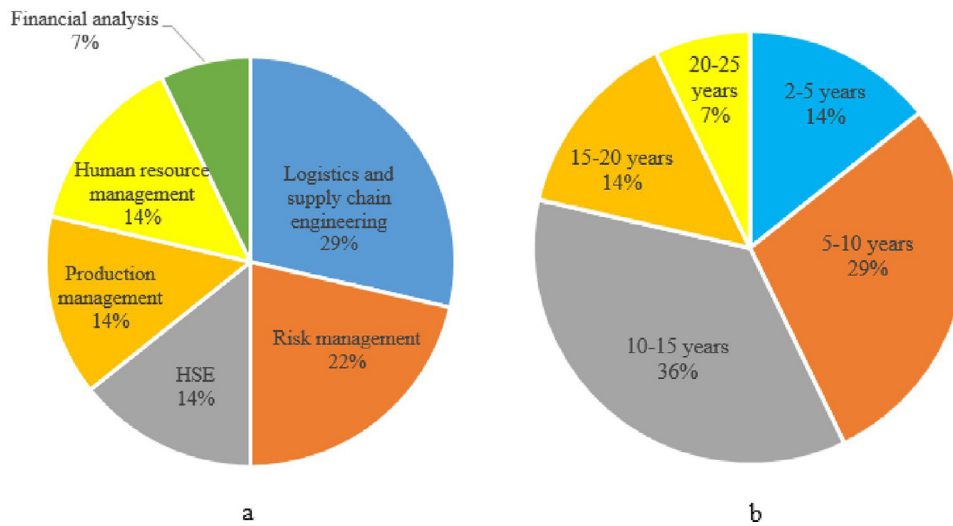
Fig. 5. Classification of experts based on expertise (a) and work experience (b)

Fig. 6. Location of facilities and other components of the supply chain network in the case study.

duce the cost of the entire SC compared to the case where resilience strategies are not used. Besides, using all strategies reduces the SC cost by about 41% compared with the non-resilient mode. On the environmental and social dimensions, using resilient strategies improves these aspects by about 36% and 88%, respectively, compared to the case that no resilient strategy is used. Hence, resilience has a substantial effect on sustainability. Lack of attention to resilience makes the SC unable to meet customers' demands. For

example, with a disaster such as the COVID-19 pandemic and reduction in suppliers' production capacity, if a company only supplies raw materials from one or two specific suppliers facing with disruption, it will run into problems and production will be reduced or stopped. Consequently, SC costs increase due to increasing shortage costs. Also, with decreasing the company's reputation and increasing customers' dissatisfaction the survival of company will be endangered. By using strategies such as multiple
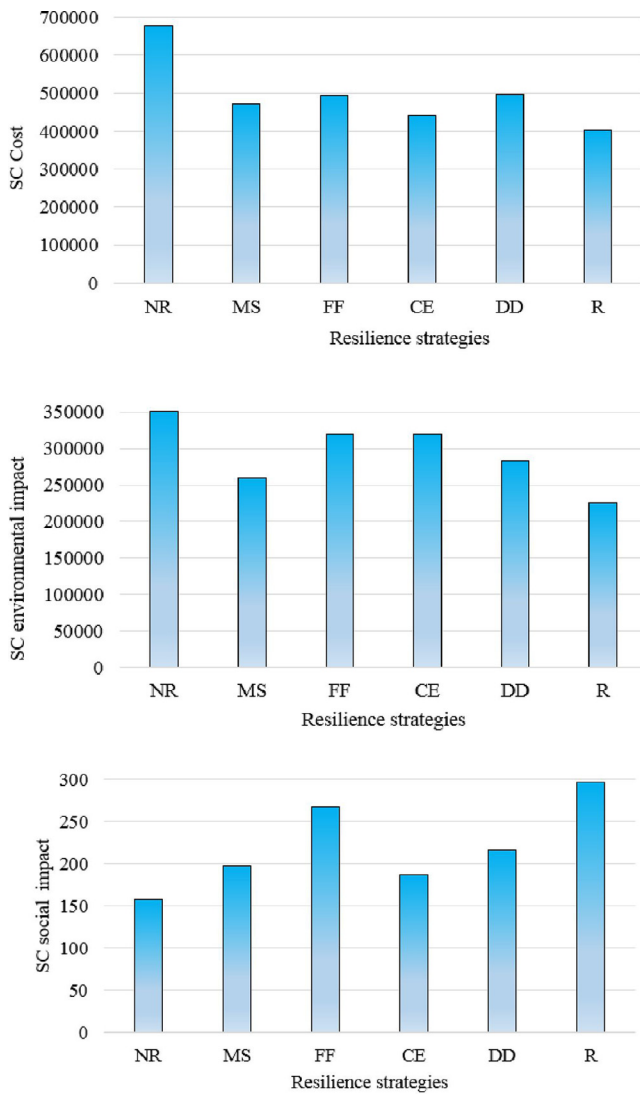
Fig. 7. Evaluation of the effectiveness of resilience strategies on the objective functions (NR: no resilience, MS: multiple sourcing, FF: facility fortification, CE: capacity expansion, DD: dual-channel distribution, R: resilient)

sourcing and dual-channel distribution, costs will be reduced since more efficient allocations are made and the effects of disruptions are neutralized as much as possible. Also, the facility fortification strategy leads to the reduction of negative impacts on the facility in case of disruption occurrence. Aside from economic issues, as shown in the diagrams, attention to resilience has a substantial impact on the social dimension. With the occurrence of disruptions and reduction of activities, many jobs are lost and workers become unemployed, and the social dimension degrades. On the environmental dimension, more special attention is needed. On the one hand, the lack of resilience in the SC network increases the negative environmental impacts due to inefficient allocations. For example, by reducing the capacity of facilities, the amount of transportation increases and the adverse environmental effects will increase. On the other hand, due to the need to open more facilities, the negative effects become more and more. On the other hand, if the network is not resilient, reverse logistics activities may be disrupted or even stopped. Therefore, less recycled raw materials are recycled and there would be a need to supply more raw materials from suppliers, which in turn challenges the environmental dimension and sustainable production and consumption due to increased

use of materials and natural resources. Also, more EOL products remain in the environment and cause pollutions.

In Fig. 8 the values of recycled materials (considering variable $f_{h\bar{w}pts}$) and used raw materials (considering variable qr_{ipts}) for manufacturing products and the values of disposed or released EOL products (considering variable b'_{ekuts}) in resilient and non-resilient modes are compared (based on case study). The reported values are the expected values of the relevant variables, which are calculated based on the probabilities of the scenarios (i.e. used raw materials $= \sum_s \sum_i \sum_p \sum_t p_s qr_{ipts}$). As can be observed, in non-resilient mode, more values of raw materials are used, and also more EOL products are released in the environment

As a result, and in summary, based on the analysis performed and the points mentioned, the SC network should be resilient enough to maintain its sustainability.

Figs. 9 and 10 show the breakdown of SC total cost in resilient and non-resilient modes, respectively. According to the charts, all components of total costs increase in non-resilient mode, except recycling cost. These figures indicate that significant savings can be made in purchasing costs by spending a relatively small amount of cost on recycling.

The SC structure addressed in this paper is mixed open and closed-loop. Table 8 presents the comparison of closed-loop SC and mixed open and closed-loop SC in terms of objective functions and some variables. Note that the mathematical model of the closed loop SC can be easily obtained by omitting the relevant parameters, variables and constraints (for obtaining closed-loop SC model, constraint (11)–(18) and constraints (25), (26) and (28) should be removed. Also variables fq_{ts} and $f'_{q\bar{w}hgts}$ should be omitted from the model.)

According to the results reported in Table 8, in the considered case study, the performance of mixed open and closed loop SC is better in comparison with closed-loop SC. The recycled products sold to other supply chains is specific to mixed open and closed-loop SC model and shows the connection of the main SC to other SCs. In the mixed SC, the revenues increase by selling recycled products to other SCs. Also, more fixed and variable jobs are created in order to produce and deliver recycled products to other SCs. As can be seen from the table, the mixed structure has outperformed closed-loop structure in environmental objective as well.

Based on the results, in the mixed SC, more raw materials are bought from suppliers and less recycled materials are used for producing products, for in this SC a portion of returned product is utilized to produce recycled products and transship them to other SCs. Note that variables $f'_{q\bar{w}hgts}$ and ω'_{gqts} are specific to mixed open and closed-loop SC.

Figs. 11 and 12 depict the effects of different conservatism degrees on supply chain economic objective. Since the parameters having deep uncertainty (production cost and purchasing cost) are only in the economic objective function, this objective is chosen for analysis. For each experiment the normal deviation of the objective function value is calculated. Let Z^0 and Z^{Rb} denote the objective values related to nominal mode and robust mode. In the nominal mode all uncertainty budgets (Γ', Γ'' and Γ''') are 0. The objective function of robust mode is obtained using the presented hybrid robust-stochastic formulation (section 3.2). The normal deviation is computed using $(Z^{Rb} - Z^0)/Z^0$.

The diagrams of Figs. 11 and 12 are depicted using different variations in the data related to purchasing cost and production cost, respectively. The variations are made using the maximum deviation of uncertain parameters ($\hat{cr}_{is}$, $\hat{mc}_{epws}$ and $\hat{ce}_{pews}$), Let $\tilde{a}$ denote the parameters with deep uncertainty (production costs and purchasing cost). Then,%data variability$= (\hat{a}/\bar{a}) * 100$ where $\hat{a}$ and $\bar{a}$ represent the nominal value and the maximum deviation from the nominal value related to $\tilde{a}$. For example, In Fig. 11, when%data
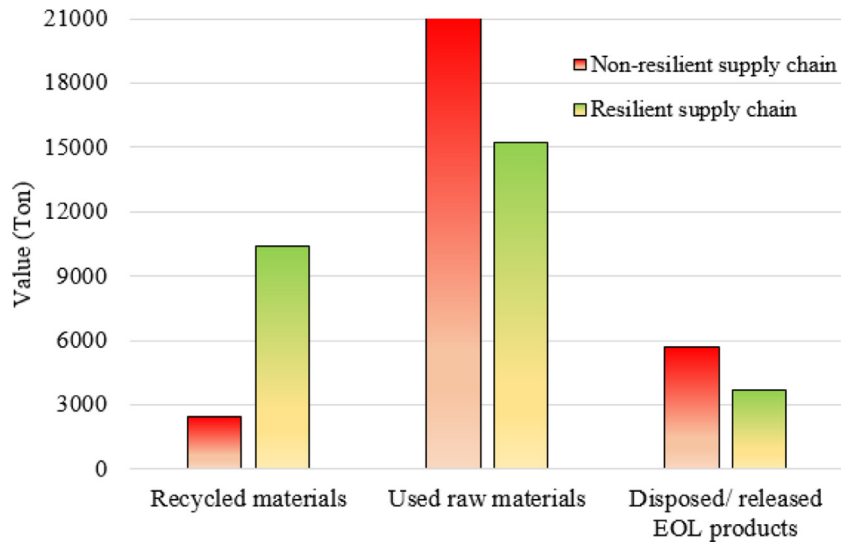
Fig. 8. Recycled materials, used raw materials and released end of life products in resilient and non-resilient modes.
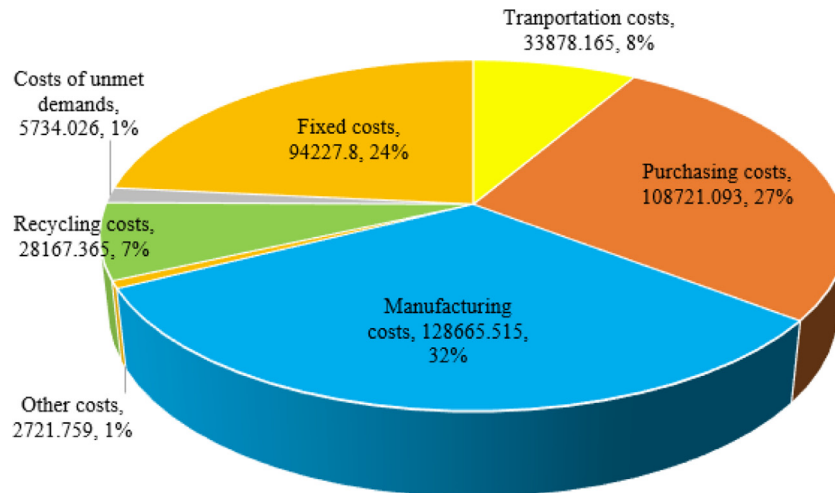

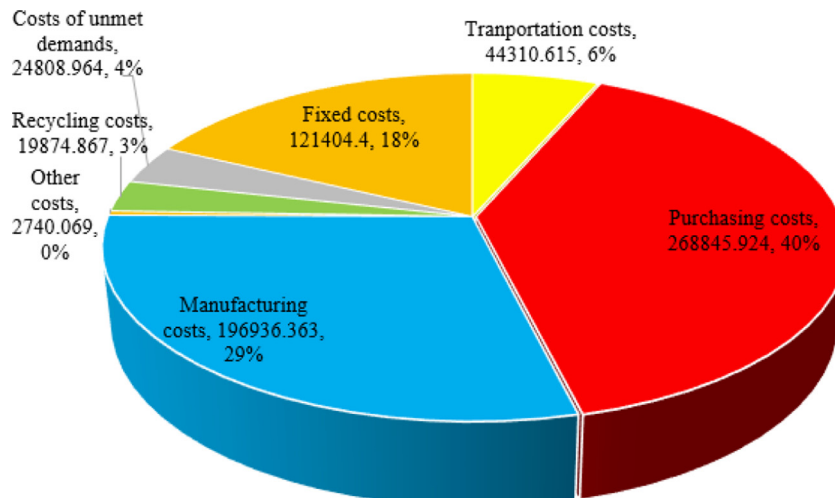**Fig. 9.** Components of supply chain total cost in resilient mode.

Fig. 10. Components of supply chain total cost in non-resilient mode.

Table 8
Comparing closed loop supply chain and mixed open and closed loop supply chain.

|	Closed loop supply chain	Mixed open and closed loop supply chain
Economic objective	515,970.21	401,115.72
Environmental objective	238,805.05	225,072.62
Social objective	241.29	296.12
Bought raw material from suppliers (based cn expected value of qr_{ipts})	46,065.25	48,635.37
Recycled materials (based cn expected value of $f_{h\overline{w}pts}$)	24,750.00	22,179.88
Recycled products sold to other SCs (based cn expected value of $f'_{q\overline{w}hgts}$)	–	1856.71
Quantity of unmet demand of other SCs (based cn expected value of ω'_{gqts})	–	285.57
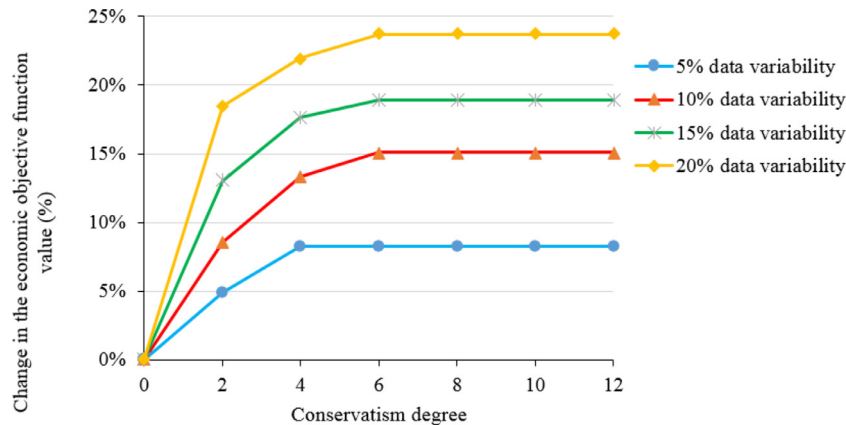
Fig. 11. Effects of different conservatism degrees related to purchasing cost on supply chain economic objective.
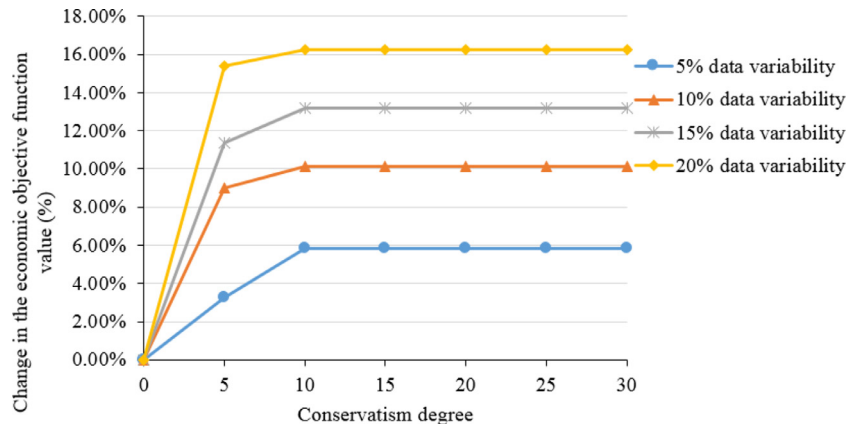

Fig. 12. Effects of different conservatism degrees related to production cost on supply chain economic objective.

variability=5%, then $(\widehat{cr}_{is}/\overline{cr}_{is}) * 100 = 5\%$, $(\widehat{mc}_{epws}/\overline{mc}_{epws})*100 = 5\%$ and in Fig. 12, $(\widehat{ce}_{pews}/\overline{ce}_{pews})*100 = 5\%$.

Figs. 11 and 12 show that the higher the level of conservatism, the greater the changes in the objective function. As can be observed, the worst value of the objective function is obtained when the conservatism degrees are not in their highest level. Also, it was found that, here the impacts of variations in purchasing cost is more than the impacts of variations in production cost. The calculations showed that the environmental and social objective function did not change significantly with the given changes.

One method for determining conservatism degrees is to implement the model with different values and doing a sensitivity analysis and then choosing the values which best fit with a specific situation. The other method is considering the violation probability of constraints based on different conservatism degrees (Zokaee et al., 2017). The latter is not applicable here, for the related uncertainties

managed with robust optimization are in the objective functions and not in constraints. The first approach is considered here. Indeed, analyses like Figs. 11 and 12 are useful for helping decision-makers, including industrial managers to choose values that are suitable for their industrial conditions.

Given that different decisions may be made for the weights of the objective functions based on the opinion of experts, different scenarios for the weight values are considered and the case study problem was solved based on them. Fig. 13. show the different values of the objective functions for the different weight values. The output shown exactly corresponds to what we expected. In more detail, as the weight of an objective function increases, the value of that objective improves, and this indicates the correct performance of the model. Based on the resulting outputs, decision-makers can select their desired weight values according to industry conditions and disruptions. It should be noted that, here by selecting the
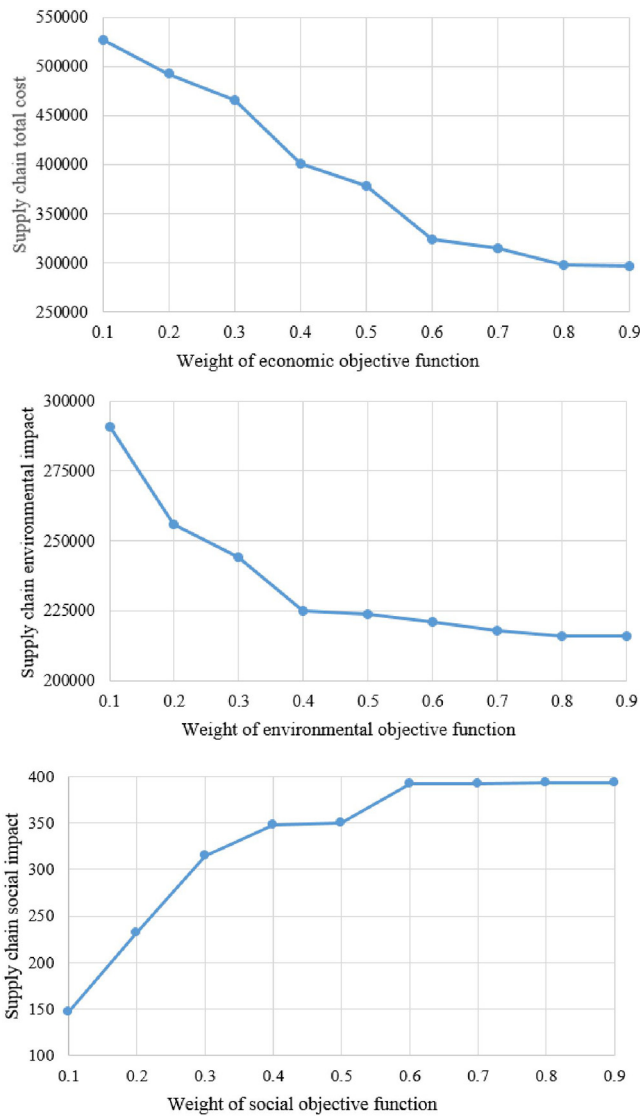
Fig. 13. Changes in the objective functions values for different weights
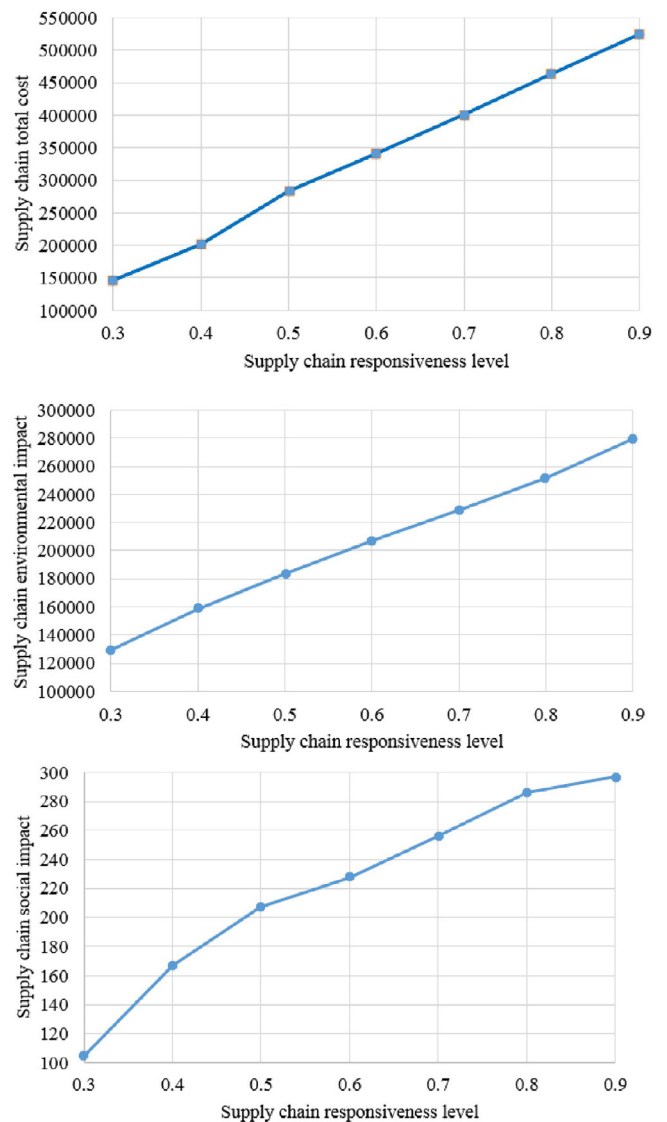

Fig. 14. Changes in the objective functions values for different SC responsiveness levels

weight for one objective function, the amount of remaining value is evenly divided between the other two objectives (note that the sum of the weights of three objective functions is 1).

At the end of this section, a sensitivity analysis is done on the SC responsiveness level. Fig. 14.represent the values of objective functions for different values of responsiveness level (that was defined as the rate of fulfilled demand). The results correspond to our expectations. With increasing the responsiveness level, more demands should be met and consequently, SC costs increase. With increasing the activities of SC (manufacturing, shipment, etc.), the adverse environmental impacts of SC increases. Finally, the social impact of SC grows due to created jobs.

4.4. Managerial insights

The findings of the article show that the proposed mathematical model can be an efficient tool for decision-making of managers and industrial engineers and be the basis for executive decisions. Managers can get insight from the addressed problem to pay attention to the disruption and operational risks of their company and the related industry. They can utilize the proposed resilience strategies to deal with disruptions and can apply the presented hybrid robust-stochastic optimization model to handle the uncertainty of the parameters. The proposed mathematical model can help managers and engineers in decision-making on the location of facilities, selecting suppliers, and the flow of materials and products. They can improve the resilience and sustainability of their intended SCs using the methods and results of this paper. Furthermore, Managers can utilize the results of the analyses on weights of objective functions and choose a setting that is suitable based on the guidelines and policies of their companies. In terms of solution methods, managers can investigate CPU time and the quality of solutions corresponding to each method based on the presented results and select their desired one to obtain the solutions. Also, the analyses on conservatism degrees give the opportunity to managers and responsible engineers to choose their appropriate conservatism degrees based on the situation of their company. Overall, the proposed mathematical model and solution methods in addition to the tire industry can be used in other industries with slight modifications.

5. Conclusion

SCs are exposed to different risks and these risks can adversely affect SC activities and objectives. Since the beginning of 2020 the

world has been under the influence of the COVID-19 epidemic. This epidemic is a disruption that has adversely affected the activities of many SCs. Today, attention to sustainability is very important and has attracted the attention of many industry and university experts. The sustainability objectives including economic, environmental and social dimensions would be degraded by the occurrence of disruptions such as epidemic diseases. Hence, the SC network resilience must be improved to deal with disruptions and mitigate their effects. In this paper, the problem of resilient and sustainable mixed open and closed-loop SCND was studied. Also, SC responsiveness, which has a special role in customer satisfaction and SC survival, was considered. A novel multi-objective MILP model was proposed to formulate the problem.

The two main types of uncertainty including randomness and deep uncertainty were considered. Two-stage stochastic programming approach and a robust optimization approach were applied to handle these uncertainties. In order to cope with problem complexity and solve large-sized problems, a Lagrangian relaxation method and a constructive heuristic algorithm were developed. The computations showed that the proposed solution methods have a good performance and can obtain high-quality solutions in suitable CPU times. A case study was also presented and various analyses were done based on it. The computational results demonstrated that resilience strategies are so effective and can substantially mitigate the impacts of disruptions. We concluded that resilience can guarantee the existence of sustainability and without resilience, sustainability would be damaged. At the end of the last section, the correct performance of the mathematical model was demonstrated through some sensitivity analyses.

Despite our efforts to define and model a problem taking into account real-world conditions, this research is not without limitations. For example in order to consider other types of uncertainty, suitable approaches should be used and the mathematical model should be altered. Other tactical or operational decisions like pricing and routing are not considered in our paper and this issue is a limitation of our research. According to the conditions and configuration of SC there may be other facilities in the network, and the model should be adapted. Sometimes collecting data on different parameters of SC (demand, supply, etc.) would be difficult, especially when they have uncertainty.

Some research directions are offered for extending the presented problem and theories. Adding other operational and tactical decisions is suggested for future research. Also, developing other solution methods such as exact methods or metaheuristics and investigating their performance for solving more complex problems may be interesting for many researchers. Finally, considering uncertainty in other parameters of the SC and applying appropriate uncertainty approaches can be a valuable suggestion for future research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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