



Designing a resilient and sustainable closed-loop supply chain network in copper industry

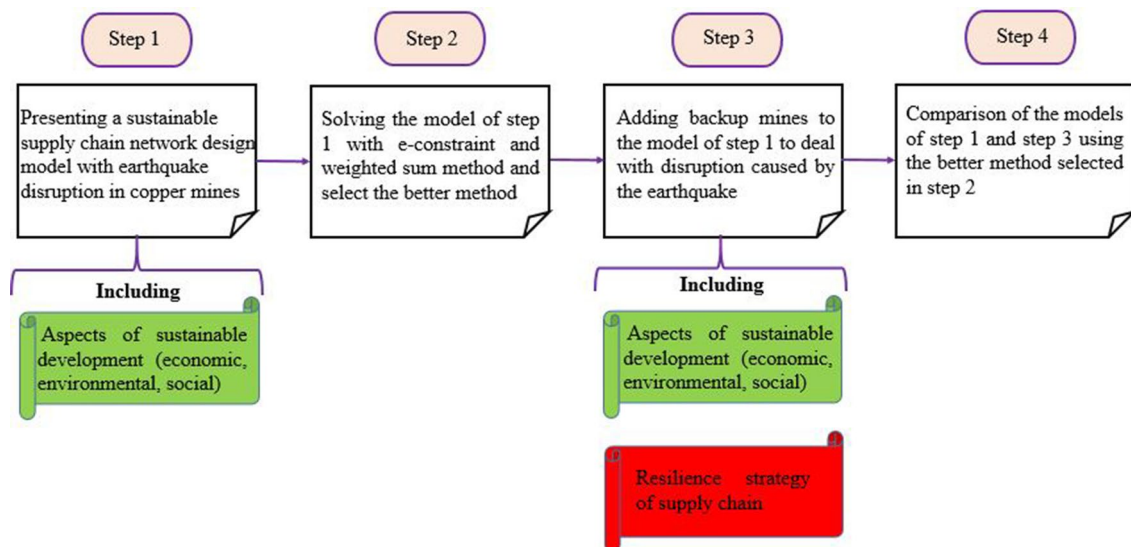
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Abstract

Due to industrialization, copper demand has increased over the last decades. Recycling rate of copper is high and its scrap requires less energy than primary production, so sustainable closed-loop supply chain network design is considered a primary decision. Besides, the uneven distribution of copper has exaggerated the destructive effects of natural disasters such as earthquakes on mines. To the best of the authors' knowledge, there is no research about copper supply chain network design. In this paper, a copper network is designed and backup suppliers are used as a resilience strategy to reduce the effects of earthquakes on mining operations. Without backup model and with backup model are presented as multi-objective and are compared with each other. In each model, the economic objective is to maximize the supply chain profit; the environmental objective is to minimize water consumption and air pollutants; and the social objective is to maximize social desirability by considering security and unemployment rates. The models are formulated using mixed-integer linear programming and they are solved by ϵ -constraint and weighted sum methods. Results show that, with backup model increases the supply chain responsiveness. Also, the model is able to improve the economic and social performances of the supply chain. But in environmental aspect, it performs worse than without backup model. This is because the backup suppliers are added to the supply chain and their exploitation will create negative environmental effects. In addition, using copper scraps saves costs, energy and the consumption of this non-renewable metal.

Graphical Abstract



Keywords Copper industry · Network design · Sustainable development · Resiliency · Mathematical programming

Extended author information available on the last page of the article

Introduction

The ongoing process of global industrialization has turned the attention of industries to supply chain management (Muduli et al. 2013). Supply chain in its classic (forward) form is a combination of processes that meet customer needs. The supply chain includes suppliers, manufacturers, transportations, warehouses, retailers and customers (Peng et al. 2020). Generally, in any industry, researching the supply chain can have an effective role in making right decisions and planning. Network design is one of the most important decisions in managing a supply chain, which determines the configuration of the supply chain, the location of facilities and their communications to each other (Chopra and Meindl 2007). Today, stakeholders' increased awareness has led to the formation of other structures such as reverse logistic (RL) and closed-loop in the supply chain in addition to the classic supply chain network (Mardani et al. 2020). RL is an efficient and cost-effective process from the point of consumption to planning, execution and control of raw materials, inventory, final products and related information processes to re-create value or appropriate product disposal. If both classic and reverse supply chains are considered together to create value throughout the product life cycle, a Closed-Loop Supply Chain (CLSC) will be created (Peng et al. 2020). Every industry can take advantage of these structures according to its condition.

Among different industries, mining industries are very important, because they form the basis of economic development in various countries (Umar et al. 2019). Therefore, deciding on their Supply Chain Network Design (SCND) will be more important. Generally, minerals are divided into four groups according to their main uses: (i) building minerals such as sandstones, which are used in construction; (ii) industrial minerals such as salt and gypsum which are non-metallic and are used for special applications; (iii) energy minerals such as oil, gas, and coal which are used to produce energy; (iv) metals such as iron, aluminum and copper which have different chemical and physical properties and are used for various purposes (Gunn 2014).

Among mineral metals, copper has unique properties (such as high conductivity in electricity and heat (Chen et al. 2019; Fuentes et al. 2021)) that make it widely used (Elshkaki et al. 2016). The copper value chain includes the following stages: first, it is extracted from mines and crushed; afterwards, impurities are separated; later, undergoing various processes, it is changed into usable products for consumers (Gunn 2014). The copper scrap, which remains after the use of copper products, can also be valuable because it has a high recyclability rate (Valenta et al. 2019). In general, recycling mineral metals usually consumes less energy than supplying them with raw materials. Moreover,

it has less environmental impact (Gunn 2014). Thus, it is reasonable to reuse copper scraps and apply the concept of CLSC in copper network design. The copper CLSC allows copper scrap to re-enter the production cycle. Production of copper products from scrap requires 85% less energy than the production from raw material (Moreno-Leiva et al. 2020). Also, production of copper products from scrap creates less pollution than the production from raw material and is an environmentally friendly method (Dong et al. 2020). Therefore, it can be a good example of a closed-loop structure in the supply chain which aids to achieve the environmental goal of sustainable development (SD). As another example of a successful closed-loop supply chain, it can be referred to a research done by Gholipour et al. (2019). They applied a used faucet exchange plan in a faucet forward supply chain and converted it to the faucet closed-loop supply chain. Their proposed plan helped environment and saved costs.

In SD, the needs of the present generation are met, and at the same time, efforts are made so that the future ones can meet their needs without facing any problems (Roostaie et al. 2019). SD consists of economic, environmental and social aspects (Moreno-Camacho et al. 2019), and industries need to pay attention to them in their activities. Copper industry is no exception to this rule because the consumption of large quantities of water and the emission of air pollutants in copper production processes can cause environmental problems (Moreno-Leiva et al. 2020; Fuentes et al. 2021)). Thus, efforts to reduce the industry's destructive effects on the environment will be a key aspect in attaining SD in the copper SCND. Also, promoting SD is the only way to reduce the increasing number of global concerns such as water scarcity, inequality, hunger, poverty, and climate change (Sherafati et al. 2019). Therefore, considering the economic and social aspects of SD will be important to all industries and businesses, including, of course, copper industry. The social aspect entails promoting corporate social responsibility. The international standard for social responsibility (ISO 26000) defines seven main responsibilities as the social facet of the SD: human rights, participation and community development, environment, equitable practices, labor practices, organizational governance, consumer issues (Anvari and Turkey 2017).

Another important issue in SCND is considering uncertainty. Uncertainty refers to a situation that cannot be directly expressed with a certain amount of information (Peng et al. 2020). Risk in the supply chain is anything that interferes with or hinders the delivery of information, materials or products from the main suppliers to the end user (Tordecilla et al. 2021). Risk in supply chain is divided into two categories: Operational risk and Disruption risk (Torabi et al. 2015). Operational risks are related to the inherent uncertainty of supply chain data (e.g. uncertainty

in capacity, demand, and costs), while disruption risks are caused by human-made or natural disasters (e.g. terrorist attacks, floods, and earthquakes) (Haghjoo et al. 2020). Besides, disruption risk has higher importance in mining industries SCND since mineral resources, such as copper, are not equally distributed on the planet. Therefore, the supply chain of mining industries will be more vulnerable to natural disasters such as earthquakes.

The mentioned issues such as unequal distribution of copper resources in different areas of the globe, the resulting risks and the various concerns related to SD in copper's supply and use indicate challenges to copper SCND. A few researches have been conducted on copper in the past. They were mostly concerned with the following: determining earthquake risk in copper supply (Schnebele et al. 2019), recycling scrap copper (Liu et al. 2020), using renewable energy in copper production (Moreno-Leiva et al. 2020) and using solar energy in copper mining (Haas et al. 2020). Some researches have also been conducted in other mining industries areas, some of which are briefly described here:

Pimentel et al. (2013) designed a global mining supply chain network. Despite the uneven distribution of mineral resources on land, they did not take into account the disruption risk of facilities and supply chain resilience practices. Also, there was no attention to the aspects of SD in their research. The steel industry to which Zadeh et al. (2014) designed the network and incorporated some tactical decisions such as inventory management into their proposed model is also a subset of mining industries. However, they did not consider possible network disruptions and resilience strategies. They also did not pay attention to the paradigm of SD and its aspects in their research. Valenta et al. (2019) explained the dispersion of copper resources on Earth and identified the risks of the copper supply chain, but they did not design a copper supply chain network to assess the impact of risks on the structure of the chain. One of the materials that can have a somewhat similar process to copper is iron ore, the network design of it has been studied by Valderrama et al. (2020). They formulated the iron ore CLSC network design as a Mixed-Integer Linear Programming (MILP) model. The objective functions of their model included minimizing both costs and emitting greenhouse gases. However, they did not consider uncertainty and risk. In addition, they did not consider the social aspect of SD. To date, to the best of the authors' knowledge, there is no research about copper SCND in order to consider the issues of SD and disruption risk, although network design can improve the supply chain's performance (Valderrama et al. 2020).

In this paper, a multi-objective mathematical model is proposed for copper resilient sustainable closed-loop SCND problem for the first time (to the best of the authors' knowledge). In its economic aspect, the aim is maximizing the

total profit of the supply chain, while in its environmental aspect, the aim is minimizing water consumption in various production processes as well as minimizing air pollution in different supply chain activities. The social dimension of the model concerns the fair division of supply chain activities among areas with different levels of unemployment and security. Also, the disruption risk of earthquakes in copper mines (primary suppliers) is considered and backup mines (backup suppliers) are used. In fact, backup suppliers are used (as one of the resilience strategies that are described in "Problem Description" Section) to cope with disruption risk in SCND (Jabbarzadeh et al. 2018). In this paper, firstly, a mathematical model is presented by considering SD aspects without considering backup mines and is solved by using ϵ -constraint method and Weighted Sum Method (WSM), then the better method is selected. Afterwards, without backup (WOB) model and with backup (WB) model are compared in terms of achieving the objective functions (SD aspects) using the better method. Results show that WB model increases the supply chain responsiveness and improves the economic and social performances of the supply chain. But in environmental aspect, it performs worse than WOB model. This is because the backup suppliers are added to in the supply chain and their activities will create negative environmental effects.

Literature review

In the "Introduction" Section, the characteristics of copper industry and the importance of its SCND were identified. In line with the stated content, in this section, the applications of copper, the trend of consumption changes as well as its production processes are briefly expressed. Then, previous researches are reviewed in sustainable and resilient subsections. Finally, the gaps of the previous researches and the innovations of this paper are expressed.

Copper subject to its unique properties can be used in various economic sectors, including plumbing, wiring, transportation, infrastructure, electrical equipment production, etc. (Elshkaki et al. 2016). Such factors as increasing urbanization rates and global welfare, global population growth, and technological development have increased its demand (Northey et al. 2018; Dong et al. 2020) so that demand for copper has more than doubled between 1990 and 2015 (Kuipers et al. 2018). Figure 1 shows the global copper usage trend between 1990 and 2018. Increasing demand and increasing consumption of copper in recent years indicates the need to design a copper supply chain network in accordance with scientific principles.

As mentioned, copper products have many applications in different sectors, but for them, there are two main production processes called pyrometallurgy and hydrometallurgy. They

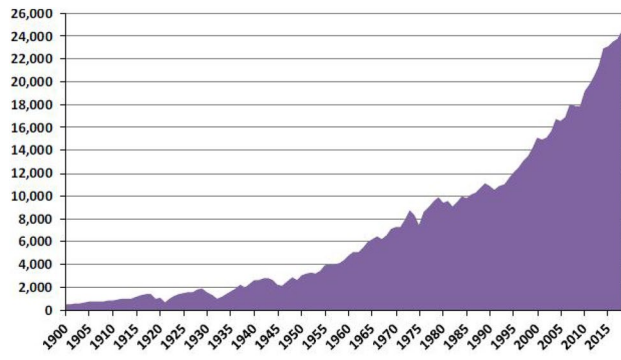


Fig. 1 World Refined Copper Usage, 1900–2018 (Thousand metric tonnes) (ICSG xxxx)

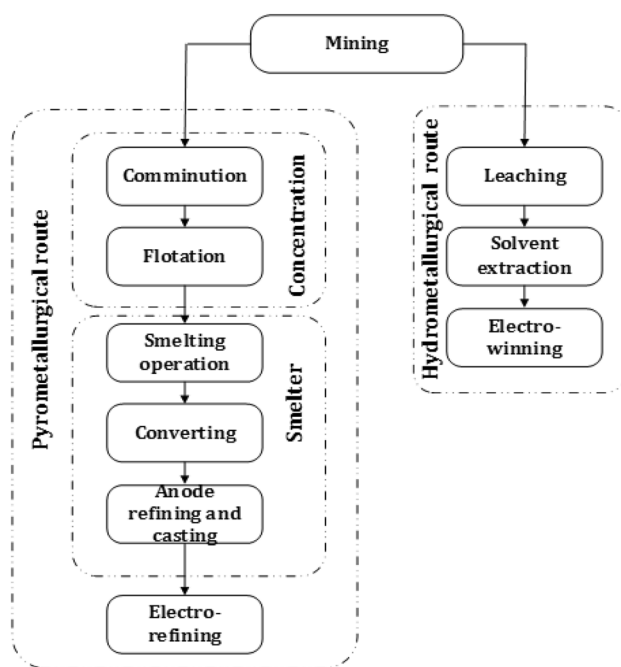


Fig. 2 Copper production processes (Moreno-Leiva et al. 2020)

account for 67% and 16% of global production, respectively, with the remaining 17% representing recycling production. Copper production processes are shown in Fig. 2 (Moreno-Leiva et al. 2020).

After getting acquainted with copper industry and the necessity of its network design, here the literature is categorized into two subsections: literature dealing with the green, sustainable, and sustainable closed-loop supply chains and literature dealing with the resilient supply chain. After reviewing related researches, existing research gaps are described and the contribution of this paper are served to fill the gaps.

Green, sustainable and sustainable closed-loop supply chains

Green and sustainable supply chains pay attention to environmental issues in supply chain management processes, including product design, material sourcing, production and delivery of the product to consumers. In addition, in these supply chains, the end-of-life management of the product is performed after its useful life (Mardani et al. 2020). Due to rising concerns of the stakeholders about social issues as well as the pressures to prevent pollution, researchers have been paying more and more attention to sustainability (Das et al. 2020). The closed-loop structure helps achieve a sustainable supply chain (Peng et al. 2020). A CLSC can create economic and social advantages while reducing undesirable environmental impacts by combining forward and backward chains (Pourmehdi et al. 2020). Here, some of the researches that have been conducted on green, sustainable and sustainable closed-loop supply chains in recent years are reviewed.

Devika et al. (2014) were among the first researchers to consider combining closed-loop and sustainable supply chains. They presented a multi-objective Mixed-Integer Programming (MIP) model and solved it with Meta-Heuristic (MH) algorithms and applied it to the glass industry. Khan et al. (2018) used Generalized Method of Moments (GMM) to find the relationship between green logistics operations and energy demand, economic growth and the need for environmental sustainability. Samadi et al. (2018) studied a Sustainable Closed-Loop Supply Chain (SCLSC) problem. They used innovative heuristics to generate the initial population called Red Deer Algorithm (RDA) and Genetic Algorithm (GA). Soleimani (2018) proposed an SCLSC network design problem for travertine quarries. The problem was formulated as an MILP model. The multi-objective model was designed to maximize profit while minimizing energy consumption. Moreover, the social aspect of SD was entered into the model in the form of service level constraint. He used ϵ -constraint method to solve the model. Pourmehdi et al. (2020) proposed an uncertain model with multiple objectives for the SCLSC network design problem applied to the steel industry. Their model featured the possibility of using combined facilities. To solve it, they used the Fuzzy Goal Programming (FGP) approach. Abdolazimi et al. (2020) designed a CLSC network by formulating the problem as an MILP model. ϵ -constraint method and WSM were used to solve the model and it was finally implemented at a tire company. Pahlevan et al. (2021) presented an SCLSC network design problem for the aluminium industry. They formulated the problem as an MILP model and solved it using an exact method and MH algorithms. Yu and Khan (2021) modelled a three-level supply chain network consisting of factories, distribution centers, and retailers using

stochastic programming theory, Fuzzy Mathematical Programming (FMP), and Monte Carlo simulation. The problem was formulated as an MIP model. The aim of the model was to minimize supply chain costs and carbon emissions. They integrated hierarchical method, ϵ -constraint method and weighted ideal point method to solve the model.

Khan et al. (2021a) evaluated five supply chain strategies, namely risk-based strategy, efficiency-based strategy, resource-based strategy, innovation-based strategy and closed-loop strategy, in order to identify the best strategy for food supply chain. The results showed that closed-loop strategy is the best option. Khan et al. (2021b) reviewed research trends in sustainable supply chain management. They stated that most of the studies were modelled using the Multiple-Criteria Decision Making (MCDM) approach, while more attention needs to be paid to efficient algorithms and advanced economic modelling.

Resilient supply chain

As mentioned, risk in supply chain is divided into two categories: operational risk and disruption risk. Although operational risk is more frequent, disruption risk causes more damage. Many studies have been devoted to studying operational risk, and so the disruption risk in SCND remains an issue requiring further study (Jabbarzadeh et al. 2018).

Here, some researches including operational risk are briefly reviewed.

Romeijn et al. (2007) designed a two-echelon supply chain network. The proposed model incorporated location decisions, location-specific transportation cost and two-echelon inventory cost. Han et al. (2015) considered a closed-loop supply chain. In their model, the yield of the manufacture and the demand of the retailer were considered as random and the objective function of the model was profit maximization. Yin et al. (2015) considered a supply chain consisting of one manufacturer and several suppliers. They determined production quantities, prices, and inventory with uncertain demand. Giri and Bardhan (2015) considered a two-echelon supply chain with one manufacture and one retailer. In the proposed model, the yield of the manufacture and the demand of the customer were considered as random.

Jabbarzadeh et al. (2017) presented a production–distribution planning model in which demand was considered as uncertain.

In terms of disruption risk in mining industries, it should be said that the global concentration of mineral deposits in certain areas increases disruption risk in their supply (Schnebele et al. 2019). For instance, some copper mines have been damaged by earthquakes in the past, losing part of their capacity as a result (Schnebele et al. 2019). Table 1 shows the damage caused by earthquakes in copper mines. This is why it is very important to take into account the possibility of disruption in the SCND of mining industries (including the copper) due to earthquakes.

Generally, uncertainty complicates network design problems and creates risks in the network decisions. In recent years, resiliency has become a trend in the network design literature dealing with these risks. Resiliency can be defined as the ability of a system to return to a stable state after a disruptive event (Tordecilla et al. 2021). Resilience strategies are commonly used in supply chain design to encounter risks (Jabbarzadeh et al. 2018). In recent years, researchers have applied different strategies to induce resiliency in supply chains. Here, some of these researches are reviewed briefly.

Rezapour et al. (2017) designed a supply chain network for the automotive industry and analyzed the disruption risk of suppliers and the risks of competing with rival suppliers. They used three strategies for building resilience in the proposed supply chain. Strategies consisted of maintaining emergency inventory at the retailers, backup capacity reservation at the suppliers, and multi-sourcing the supply. They formulated the problem as a Mixed-Integer Non-Linear Programming (MINLP) model. Acar and Kaya (2019) designed a supply chain network to provide medical services after earthquakes. They formulated the problem as a two-stage stochastic MILP model. The mobile facilities were used to increase the capacity of the model. Zare Mehrjerdi and Lotfi (2019) considered a resilient sustainable closed-loop network design problem and proposed an MILP model for it. The case study was an automobile assembly company. They utilized facilities with the resilient capacity to deal with disruption. Ahranjani et al. (2020) designed a resilient and sustainable supply chain for bioethanol. They formulated the problem as an MILP model. They investigated the

Table 1 Some damages caused by earthquakes in copper mines

Country	Year	Damages by earthquakes
Ecuador	1996	Mine collapse and disruption in its activities (Schnebele et al. 2019)
Chile	2000	Disruption in mine activities (Schnebele et al. 2019)
China	2008	Increasing demand and price of copper (Search by the authors)
Chile	2014	Temporary closure of the mine (Schnebele et al. 2019)
Chile	2017	Increasing copper price due to concerns about declining copper supply (Search by the authors)

effect of catastrophic droughts on their proposed network. Fattahi et al. (2020) used a new metric to measure supply chain resilience. They used a metric to identify the increase in supply chain costs as a result of disruptive events. Babaeinesami et al. (2021) combined lean and agile approaches to increase the supply chain resilience level in an SCLSC. Adding capacity to the facilities was the resilient strategy to cope with the effects of disruption in the model. They implemented the model in the digital and radio equipment industry. Mehrjerdi and Shafiee (2021) proposed a multi-objective MIP model for a resilient sustainable closed-loop network design problem in tire industry. They used resilience strategies to cope with disruption. The strategies included information sharing, backup suppliers/facilities, and multiple sourcing. They solved the problem via fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and augmented ϵ -constraint methods.

Research gaps and contributions

Moreno-Camacho et al. (2019) reviewed 113 papers published on sustainable SCND models from 2015 to 2018. Their findings showed that in comparison with the environmental aspect of the SD, the social aspect had received less share of attention in studies (Brandenburg and Rebs 2015). In their classification of different sections based on the application of the model, only three papers were dealing with mining. According to Mehrjerdi and Shafiee (2021), a small number of papers have already been published that have considered the concept of resilience in CLSC network design problems. Moreover, due to the lack of attention to the social aspect of SD, the combination of sustainability and resiliency in CLSC still contains a gap.

According to the aforementioned literature review, the number of network design researches on mining industries has been much lower than those on other industries. To the best of the authors' knowledge, despite the rise in demand for copper in recent years, there is no quantitative model on its SCND. What is more, even though the activities of mining industries are related to environmental and social problems, a limited number of researches have addressed all aspects of SD in designing their networks. Another matter of note is that despite the risks of activities in mining industries (such as earthquakes that have been mentioned in this paper), as far as the authors know, no study has so far considered resiliency in designing mining industries network.

According to the gaps in literature and Table 2, which reviews the most relevant literature with the model of this paper, the main contributions of this research are described as follows:

- Designing a copper supply chain network for the first time (to the best of the authors' knowledge),
- Using a closed-loop structure in copper industry, aiming to reuse scraps and reduce energy consumption as well as environmental pollution,
- Taking into account all three aspects of SD in designing the copper supply chain network, including economic: profit maximization; environmental: minimizing water consumption and environmental pollution; social: fair locating of potential facilities in various areas according to the security and unemployment rates,
- Designing and comparing two models (with and WOB suppliers, i.e. mines) to deal with catastrophic earthquakes at different damage levels to reduce the effects of disruption on the supply chain response rate,
- Using resilience strategy to reduce disruption risk in mining industries for the first time (to the best of the authors' knowledge), especially in copper industry,
- Considering simultaneous resiliency and sustainability in the closed-loop structure of the supply chain, which has rarely been addressed in previous studies.

Problem description and model formulation

In this section, problem is described and then mathematical models are formulated.

Problem description

Here, a sustainable closed-loop SCND model is presented for copper industry. As Fig. 3 shows, in the model, raw materials like sulfur and oxide minerals (Moreno-Leiva et al. 2020) are extracted from the copper mines and are transported to factories. Also, copper scraps are entered to the factories for reproduction. After processing, the final products are transported to distribution centers, then they are delivered to customers. The customers can return part of the product to collection centers after use (it is reasonable to assume that not all customers return all used products). In collection centers, the scraps are separated into non-recyclable and recyclable parts. The former is sent to disposal centers, while the latter is returned to the factories. In the proposed model, the location of the factory, the distribution center, and the collection center are considered as potential and must be located.

As stated in "Introduction" and "Literature review" sections, the facilities of the supply chain may suffer from disruptions caused by natural disasters. Usually, in a disaster scenario, the whole capacity of the facility is not lost; rather, only a part of its capacity is affected by the disaster. This

Table 2 Literature review

Authors	Type of SC	Mathematical model	Solution approach	Pillar of sustainability	Resiliency measures	Industry
Devika et al. (2014)	CL	MIP	MH	EC, EN, S	–	Glass
Rezapour et al. (2017)	F	MINLP	E	EC	Holding additional inventory, Adding extra supply/production capacities, Multiple-sourcing	Automotive
Soleimani (2018)	CL	MILP	E	EC, EN, S	–	Travertine quarry
Samadi et al. (2018)	CL	MILP	H, MH	EC, EN, S	–	–
Acar and Kaya (2019)	F	MILP	E	S	Adding extra supply/production capacities	Medical
Zare Mehrjerdi and Lotfi (2019)	CL	MILP	E	EC, EN, S	Adding extra supply/production capacities	Automobile assembly company
Pourmehdi et al. (2020)	CL	MILP	E	EC, EN, S	–	Steel
Abdolazimi et al. (2020)	CL	MILP	E	EC, EN, S	–	Tire
Fattahi et al. (2020)	F	MINLP	E	EC	A new metric by considering supply chain recovery time and its performance loss during recovery	Road maintenance and transportation organization
Ahranjani et al. (2020)	F	MILP	E	EC, EN	–	Bioethanol
Babaeinesami et al. (2021)	CL	MINLP	MH	EC, EN, S	Adding capacity to the facilities	Manufacturers of analog and digital equipment and radio transmitters
Pahlevan et al. (2021)	CL	MILP	E, MH	EC, EN, S	–	Aluminium
Yu and Khan (2021)	F	MIP	H	EC, EN	–	–
Mehrjerdi and Shafiee (2021)	CL	MIP	E	EC, EN, S	Multiple sourcing, Forming Contracts with backup suppliers/facilities, Information Sharing	Tire
This study	CL	MILP	E	EC, EN, S	Backup suppliers	Copper

SC Supply chain, CL Closed-loop, F Forward, MIP Mixed-integer programming, MINLP Mixed-integer non-linear programming, MILP Mixed-integer linear programming, E Exact, H Heuristic, MH Meta-heuristic, EC Economic, EN Environmental, S: Social

is identified as a partial disruption (Haghjoo et al. 2020). To ensure that the disruption does not cause bottlenecks in the supply chain and its response rate does not decrease, resilience strategies can be used to reduce the effects of the disruption. Generally, 8 resilience strategies deal with the effects of disruption in SCND (Jabbarzadeh et al. 2018):

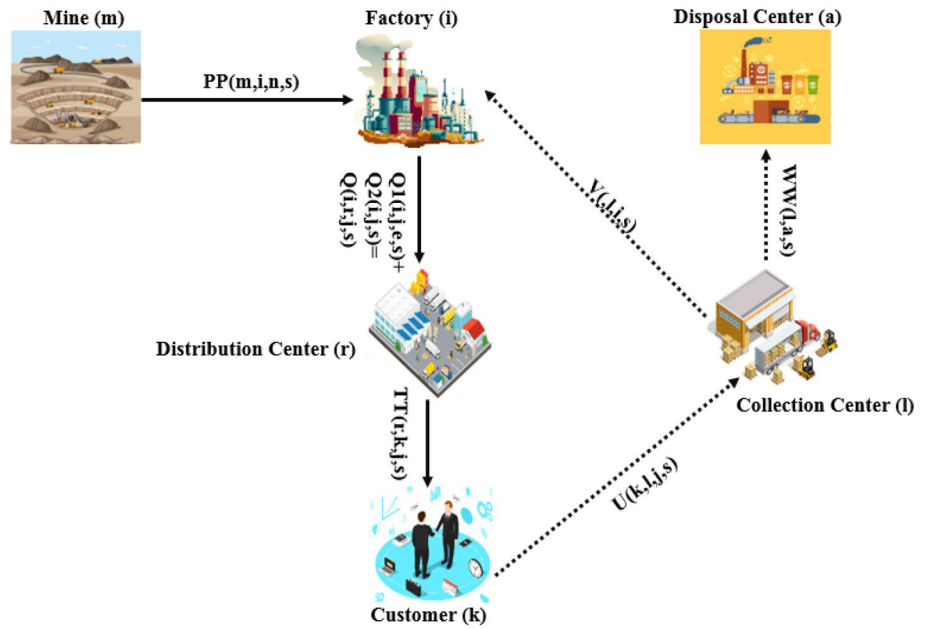
1. Allocating multiple sourcing instead of a single sourcing.
2. Forming contracts with backup suppliers/facilities when primary facilities are not available due to disruption.
3. Enriching suppliers and facilities.
4. Stocking additional inventory to use in case of disruption.

5. Adding extra supply/production capacity to compensate the disrupted capacity.
6. Using business continuity and disaster recovery plans to help organizations.
7. Decreasing flow complexity by minimizing the total number of connections in the network.
8. Managing node complexity by minimizing the total number of active nodes in the network.

In this paper, earthquake disruption is considered in copper mines and the strategy of forming contracts with backup suppliers/facilities is used to reduce the impact of the disruption.

As widely known, disruption is a source of uncertainty in the supply chain. To model uncertainty, in this paper is used

Fig. 3 The structure of the supply chain in WOB mine state

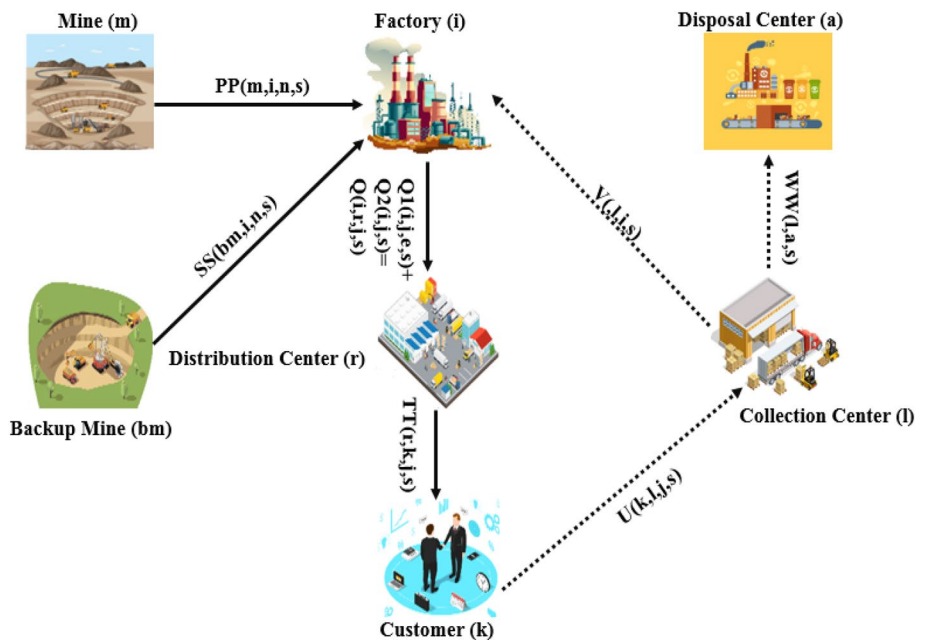


scenario-based two-stage stochastic programming (disruption is usually modeled using scenario-based programming (Vahidi et al. 2018)) that, in a given scenario, allows a mine to either experience a disruption or not. The two-stage stochastic programming used in most network design problems involves the following processes: in the first stage, before the disruption occurs, some decisions, such as potential facilities establishment, are made; in the second stage, after the disruption has occurred, other decisions, such as quantity production, are made according to scenarios, so that second-stage variables will depend on the scenario. Also, the

disruption may cause change to some parameters such as facility capacity utilization rate. Therefore, these parameters are considered as uncertain and scenario-based.

In summary, in this paper, two models are presented and are compared with each other. In the first model, which is depicted in Fig. 3, disruption occurs but backup mines are not used. In the second model, which is depicted in Fig. 4, backup mines are used to reduce the effect of the disruption. The first model is called WOB model and the second model is called WB model. In both models, three objective functions of economic, environmental, and social are taken

Fig. 4 The structure of the supply chain in WB mine state



into account (They were explained in “Introduction” and “Literature review” sections.), and constraints are expressed according to the conditions of the problem. The most important assumptions for clarifying the problem description are as follows:

Assumptions

- In the factory, there are two main production processes (hydrometallurgy and pyrometallurgy) for the transformation of raw materials into the final product but scrap usually can be processed through the pyrometallurgy process. This creates the need for two types of decision variables for production; therefore, the structure of the mathematical model (decision variables and constraints) will be different from other models.
- It is assumed that both types of raw materials (sulfur and oxide minerals) can be produced by both production processes.
- Scrap cannot be converted into raw materials. It saves production costs and is taken into account in modeling.
- The location of suppliers (mines) is always fixed and no decision can be made regarding it.
- The location of the factory, distribution center, and collection center are considered potentially and decisions are made about their location.
- Copper mines are assumed to be open-pit because that is the most common form of copper mine (Moreno-Leiva et al. 2020).
- Primary mines may be affected by earthquake disruptions, but backup mines are not.
- Primary mines damaged by earthquake disruptions lose only part of their capacity.

Table 3 List of sets

Indices	Description
m	Set of suppliers (mines) $m \in \{1, 2, \dots, M\}$
bm	Set of backup suppliers (backup mines) $bm \in \{1, 2, \dots, BM\}$
j	Set of product types $j \in \{1, 2, \dots, J\}$
i	Set of potential factories $i \in \{1, 2, \dots, I\}$
r	Set of potential distribution centers $r \in \{1, 2, \dots, R\}$
k	Set of customer zones $k \in \{1, 2, \dots, K\}$
l	Set of potential collection centers $l \in \{1, 2, \dots, L\}$
s	Set of disruption scenarios $s \in \{1, 2, \dots, S\}$
n	Set of raw material types $n \in \{1, 2, \dots, N\}$
e	Set of production process types $e \in \{1, 2, \dots, E\}$
a	Set of disposal centers $a \in \{1, 2, \dots, A\}$

- Such parameters as the cost of mining raw material, production costs of raw material and scrap, demand, and percentage of facility capacity that is lost due to disruption are considered uncertain and scenario-based.
- Facilities have finite capacities.

Sets, parameters, and decision variables

In this section, the sets, parameters, and decision variables used WOB and WB models are shown. Sets, parameters, and decision variables are listed in Tables 3, 4, and 5, respectively.

Formulation of WOB model

In this section, the WOB model is formulated. Figure 3 shows the structure of the WOB model.

Table 4 List of parameters

Parameter	Description
$t1_j$	Unit selling price of product j
$a1_i$	Opening cost of factory i
b_r	Opening cost of distribution center r
$c3_l$	Opening cost of collection center l
$p1_{mns}$	Unit mining cost of raw material n in mine m in scenario s
$p3_{bmns}$	Unit mining cost of raw material n in backup mine bm in scenario s
d_n	Unit transportation cost of raw material n from a supplier (mine or backup mine) to a factory in one unit of distance
g_j	Unit transportation cost of product j from a factory to a distribution center in one unit of distance
h_j	Unit transportation cost of product j from a distribution center to a customer in one unit of distance
$m1_j$	Unit transportation cost of scrap product j (before separating) from a customer to a collection center in one unit of distance
$b1$	Unit transportation cost of scrap product (after separating) from a collection center to a factory in one unit of distance
o	Unit transportation cost of scrap product (after separating) from a collection center to a disposal center in one unit of distance
f_{jes}	Unit production cost of product j by production process e (from raw material) in scenario s
$c1_{js}$	The unit production cost of product j (from scrap products) in scenario s
$c2_j$	Unit separation cost of scrap product j in a collection center
$q11$	Unit disposition cost of scrap product
$a2_j$	Unit cost-saving in production of product j due to recycling
$e1_{mi}$	Distance between mine m and factory i
$e8_{bmi}$	Distance between backup mine bm and factory i
$e2_{ir}$	Distance between factory i and distribution center r
$e3_{rk}$	Distance between distribution center r and customer k
$e4_{kl}$	Distance between customer k and collection center l
$e5_{li}$	Distance between collection center l and factory i
$e6_{la}$	Distance between collection center l and disposal center a
$d1_{kjs}$	Demand of customer k from product j in scenario s
$e7_j$	Minimum disposal rate of non-recyclable part of scrap product j
$f2_{kjs}$	Amount of scrap product j (before separating) returned from customer k in scenario s
$ca1_{mn}$	Maximum capacity of mine m from raw material n
$ca6_{bmn}$	Maximum capacity of backup mine bm from raw material n
$ca2_{ij}$	Maximum production capacity of factory i from product j
$ca3_{rj}$	Maximum capacity of distribution center r from product j
$ca4_{lj}$	Maximum capacity of collection center l from scrap product j (before separating)
$ca5_a$	Maximum capacity of disposal center a
$m2_{mn}$	Unit polluting gas emission rate from mining in mine m from raw material n
$m9_{bmn}$	Unit polluting gas emission rate from mining in backup mine bm from raw material n
$m3_e$	Unit polluting gas emission rate from production (from raw material) by production process e
$m4$	Unit polluting gas emission rate from production (from scrap product)
$m6$	Unit polluting gas emission rate from separating scrap product (recyclable part from non-recyclable part)
$m7$	Unit polluting gas emission rate from disposing of scrap product (non-recyclable part)
$w1_{mi}$	Unit polluting gas emission rate from transportation from mine m to factory i in one unit of distance
$w7_{bmi}$	Unit polluting gas emission rate due to transportation from backup mine bm to factory i in one unit of distance
$w2_{ir}$	Unit polluting gas emission rate due to transportation from factory i to distribution center r in one unit of distance
$w3_{rk}$	Unit polluting gas emission rate due to transportation from distribution center r to customer k in one unit of distance
$w4_{kl}$	Unit polluting gas emission rate due to transportation from customer k to collection center l in one unit of distance
$w5_{la}$	Unit polluting gas emission rate due to transportation from collection center l to disposal center a in one unit of distance
$w6_{li}$	Unit polluting gas emission rate due to transportation from collection center l to factory i in one unit of distance
$q22_e$	Unit water consumption rate in production (from raw material) by production process e
$g1$	Unit water consumption rate in production (from scrap product)
pan	Population density at the national level
hsl	The highest level of national security

Table 4 (continued)

Parameter	Description
msl	Range of security level in the country (the difference between the level of security of the areas with the highest and the lowest level of security)
$pa1_i$	Population density in the area of factory i
$pa2_r$	Population density in the area of distribution center r
$pa3_l$	Population density in the area of collection center l
$ir1_i$	Unemployment rate in the area of factory i
$ir2_r$	Unemployment rate in the area of distribution center r
$ir3_l$	Unemployment rate in the area of collection center l
$sl1_i$	Security level in the area of the factory i
$sl2_r$	Security level in the area of distribution center r
$sl3_l$	Security level in the area of collection center l
α	Percentage of importance of balance in areas with different population densities
$p2_s$	Probability of scenario s
$v1_s$	1 if disruption happens in scenario s , 0 otherwise
$t2_{ms}$	Percentage of damage in mine m in scenario s due to disruption
$per1$	Percentage of total production that is produced from scrap
$per2$	Conversion coefficient of raw material to product
$per3$	Conversion coefficient of scrap to product

Table 5 List of decision variables

Decision variable	Description
X_i	1 if factory i is opened, 0 otherwise
Y_r	1 if distribution center r is opened, 0 otherwise
ZZ_l	1 if collection center l is opened, 0 otherwise
$PP_{min s}$	Quantity of raw material n that is transported from mine m to factory i in scenario s
$SS_{bmin s}$	Quantity of raw material n that is transported from backup mine bm to factory i in scenario s
$Q1_{ijes}$	Quantity of product j that is produced in factory i by production process e (from raw material) in scenario s
$Q2_{ijs}$	Quantity of product j that is produced in factory i (from scrap products) in scenario s
Q_{irjs}	Quantity of product j (total products that are produced from raw material and scrap products) that is transported from factory i to distribution center r in scenario s
TT_{rkjs}	Quantity of product j that is transported from distribution r to customer k in scenario s
U_{kljs}	Quantity of scrap product j (before separating) that is transported from customer k to collection center l in scenario s
V_{lis}	Quantity of scrap product (the recyclable part after separating) that is transported from collection center l to factory i in scenario s
WW_{las}	Quantity of scrap product (the non-recyclable part after separating) that is transported from collection center l to disposal center a in scenario s

Objective functions

$$\begin{aligned}
\text{Max } Z_1 = & \sum_s p2_s \times ((\sum_r \sum_k \sum_j (t1_j - (h_j \times e3_{rk})) \times \text{TT}_{rkjs}) \\
& - (\sum_m \sum_i \sum_n (p1_{mns} + d_n \times e1_{mi}) \times \text{PP}_{min s}) \\
& + \sum_i \sum_j \sum_e f_{jes} \times Q1_{ijes} + \sum_i \sum_j (c1_{js} - a2_j) \times Q2_{ijs} \\
& + \sum_i \sum_r \sum_j g_j \times e2_{ir} \times Q_{irjs} + \sum_k \sum_l \sum_j (m1_j \times e4_{kl} + c2_j) \times U_{kljs} \\
& + \sum_l \sum_a (q11 + o \times e6_{la}) \times \text{WW}_{las} + \sum_l \sum_i b1 \times e5_{li} \times V_{lis}) \\
& - \sum_i a1_i \times X_i - \sum_r b_r \times Y_r - \sum_l c3_l \times \text{ZZ}_l
\end{aligned} \tag{1}$$

$$\begin{aligned}
\text{Min } Z_2 = & \sum_s p2_s \times (\sum_m \sum_i \sum_n (m2_{mn} + w1_{mi} \times e1_{mi}) \times \text{PP}_{min s}) \\
& + \sum_i \sum_j \sum_e m3_e \times Q1_{ijes} + \sum_i \sum_j m4 \times Q2_{ijs} \\
& + \sum_i \sum_r \sum_j w2_{ir} \times e2_{ir} \times Q_{irjs} + \sum_r \sum_k \sum_j w3_{rk} \times e3_{rk} \times \text{TT}_{rkjs} \\
& + \sum_k \sum_l \sum_j (m6 + w4_{kl} \times e4_{kl}) \times U_{kljs} \\
& + \sum_l \sum_a (m7 + w5_{la} \times e6_{la}) \times \text{WW}_{las} \\
& + \sum_l \sum_i w6_{li} \times e5_{li} \times V_{lis} + \sum_i \sum_j \sum_e q22_e \times Q1_{ijes} + \sum_i \sum_j g1 \times Q2_{ijs})
\end{aligned} \tag{2}$$

$$\begin{aligned}
\text{Max } Z_3 = & \alpha \times (\sum_i ((ir1_i \times pa1_i) / \text{pan}) \times X_i \\
& + \sum_r ((ir2_r \times pa2_r) / \text{pan}) \times Y_r \\
& + \sum_l ((ir3_l \times pa3_l) / \text{pan}) \times \text{ZZ}_l \\
& + \sum_r ((hsl - sl2_r) / \text{msl}) \times Y_r \\
& + \sum_l ((hsl - sl3_l) / \text{msl}) \times \text{ZZ}_l)
\end{aligned} \tag{3}$$

Constraints

$$\sum_e Q1_{ijes} + Q2_{ijs} = \sum_r Q_{irjs} \quad \forall i, j, s \quad (4)$$

$$\text{per1} \times \sum_r \sum_j Q_{irjs} = \sum_j Q2_{ijs} \quad \forall i, s \quad (5)$$

$$\text{per2} \times \sum_m \sum_n \text{PP}_{\min s} = \sum_j \sum_e Q1_{ijes} \quad \forall i, s \quad (6)$$

$$\text{per3} \times \sum_l V_{lis} = \sum_j Q2_{ijs} \quad \forall i, s \quad (7)$$

$$\sum_i Q_{irjs} = \sum_k \text{TT}_{rkjs} \quad \forall r, j, s \quad (8)$$

$$\sum_r \text{TT}_{rkjs} \leq D1_{kjs} \quad \forall k, j, s \quad (9)$$

$$\sum_r \text{TT}_{rkjs} \geq \sum_l U_{kljs} \quad \forall k, j, s \quad (10)$$

$$\sum_l U_{kljs} = f2_{kjs} \quad \forall k, j, s \quad (11)$$

$$e7_j \times \sum_k U_{kljs} \leq \sum_a \text{WW}_{las} \quad \forall l, j, s \quad (12)$$

$$\sum_k \sum_j U_{kljs} = \sum_i V_{lis} + \sum_a \text{WW}_{las} \quad \forall l, s \quad (13)$$

$$\sum_r \sum_j Q_{irjs} \leq \sum_j X_i \times \text{ca}2_{ij} \quad \forall i, s \quad (14)$$

$$\sum_i \sum_n \text{PP}_{\min s} \leq \sum_n \text{ca}1_{mn} \quad \forall m, s \text{ if } v1_s = 0 \quad (15)$$

$$\sum_i \sum_n \text{PP}_{\min s} \leq (1 - t2_{ms}) \times \sum_n \text{ca}1_{mn} \quad \forall m, s \text{ if } v1_s = 1 \quad (16)$$

$$\sum_i \sum_j Q_{irjs} \leq \sum_j Y_r \times \text{ca}3_{rj} \quad \forall r, s \quad (17)$$

$$\sum_k \sum_j U_{kljs} \leq \sum_j \text{ZZ}_l \times \text{ca}4_{lj} \quad \forall l, s \quad (18)$$

$$\sum_l \text{WW}_{las} \leq \text{ca}5_a \quad \forall a, s \quad (19)$$

$$X_i, Y_r, \text{ZZ}_l \in \begin{cases} 1 \\ 0 \end{cases} \quad (20)$$

$$\text{PP}_{\min s}, \text{SS}_{b \min s}, Q1_{ijes}, Q2_{ijs}, Q_{irjs}, \text{TT}_{rkjs}, U_{kljs}, V_{lis}, \text{WW}_{las} \geq 0$$

Equation (1) shows the first objective function (the economic aspect of SD) in which the profit of the entire supply chain is maximized. In this equation, profit equals the difference between sales revenue and total costs. Costs include mining, production, transportation, separation, disposition, and the establishment of potential facilities. Equation (2) shows the second objective function (the environmental aspect of SD) in which the amount of water consumption in production processes and the amount of air pollutant emissions in the supply chain activities are minimized. Equation (3) shows the third objective function (the social aspect of SD) in which attention is paid to maximize the social utility in the establishment of potential facilities (for more information, see Anvari and Turkay 2017). Constraint (4) shows that the total output is equal to the total production of copper from raw materials and scrap in each factory. Constraint (5) indicates that a part of the total production in each factory is generated from scrap. In constraint (6), inputted raw materials from the mines are converted into products using a coefficient for each factory; during the production process, impurities are separated from the raw materials to

prepare the final product. In constraint (7), the incoming scraps are converted into products by a coefficient for each factory (the removal of impurities). The input and output balance at each distribution center is shown in constraint (8). Constraint (9) is related to satisfying customer demand. Constraint (10) indicates that each customer can deliver his used products (scrap) to collection centers. The amount of returned scrap products by customers is shown in constraint (11). Constraint (12) demonstrates a lower bound for the non-recyclable part of the scrap. Constraint (13) indicates that in each collection center, used products returned from customers are divided into recyclable and non-recyclable parts. The production capacity constraint for each factory is shown in constraint (14). Constraints (15)—(16) present the mining capacity constraint for each mine without and with disturbance situations, respectively. The capacity constraints of the distribution center, collection center, and disposal center are demonstrated in constraints (17)—(19), respectively. Constraint (20) shows the domain of decision variables.

Formulation of WB model

In this section, the WB model is formulated. Figure 4 shows the structure of the WB model.

Objective functions

$$\begin{aligned}
 \text{Max } Z_1 = & \sum_s p2_s \times ((\sum_r \sum_k \sum_j (t1_j - (h_j \times e3_{rk})) \times \text{TT}_{rkjs}) \\
 & - (\sum_m \sum_i \sum_n (p1_{mns} + d_n \times e1_{mi}) \times \text{PP}_{min s} \\
 & + \sum_{bm} \sum_i \sum_n (p3_{bmns} + d_n \times e8_{bmi}) \times \text{SS}_{b \min s} \\
 & + \sum_i \sum_j \sum_e f_{jes} \times Q1_{ijes} + \sum_i \sum_j (c1_{js} - a2_j) \times Q2_{ijs} \\
 & + \sum_i \sum_r \sum_j g_j \times e2_{ir} \times Q_{irjs} + \sum_k \sum_l \sum_j (m1_j \times e4_{kl} + c2_j) \times U_{kljs} \\
 & + \sum_l \sum_a (q11 + o \times e6_{la}) \times \text{WW}_{las} + \sum_l \sum_i b1 \times e5_{li} \times V_{lis}) \\
 & - \sum_i a1_i \times X_i - \sum_r b_r \times Y_r - \sum_l c3_l \times \text{ZZ}_l
 \end{aligned} \tag{21}$$

$$\begin{aligned}
 \text{Min } Z_2 = & \sum_s p2_s \times (\sum_m \sum_i \sum_n (m2_{mn} + w1_{mi} \times e1_{mi}) \times \text{PP}_{min s} \\
 & + \sum_{bm} \sum_i \sum_n (m9_{bmn} + w7_{bmi} \times e8_{bmi}) \times \text{SS}_{b \min s} \\
 & + \sum_i \sum_j \sum_e m3_e \times Q1_{ijes} + \sum_i \sum_j m4 \times Q2_{ijs} \\
 & + \sum_i \sum_r \sum_j w2_{ir} \times e2_{ir} \times Q_{irjs} + \sum_r \sum_k \sum_j w3_{rk} \times e3_{rk} \times \text{TT}_{rkjs} \\
 & + \sum_k \sum_l \sum_j (m6 + w4_{kl} \times e4_{kl}) \times U_{kljs} \\
 & + \sum_l \sum_a (m7 + w5_{la} \times e6_{la}) \times \text{WW}_{las} \\
 & + \sum_l \sum_i w6_{li} \times e5_{li} \times V_{lis} + \sum_i \sum_j \sum_e q22_e \times Q1_{ijes} + \sum_i \sum_j g1 \times Q2_{ijs})
 \end{aligned} \tag{22}$$

$$\begin{aligned}
 \text{Max } Z_3 = & \alpha \times (\sum_i ((ir1_i \times pa1_i) / \text{pan}) \times X_i \\
 & + \sum_r ((ir2_r \times pa2_r) / \text{pan}) \times Y_r \\
 & + \sum_l ((ir3_l \times pa3_l) / \text{pan}) \times \text{ZZ}_l) (1 - \alpha) \times (\sum_i ((hsl - sl1_i) / \text{msl}) \times X_i \\
 & + \sum_r ((hsl - sl2_r) / \text{msl}) \times Y_r \\
 & + \sum_l ((hsl - sl3_l) / \text{msl}) \times \text{ZZ}_l)
 \end{aligned} \tag{3}$$

Constraints

$$\sum_e Q1_{ijes} + Q2_{ijs} = \sum_r Q_{irjs} \quad \forall i, j, s \quad (4)$$

$$\text{per1} \times \sum_r \sum_j Q_{irjs} = \sum_j Q2_{ijs} \quad \forall i, s \quad (5)$$

$$\text{per3} \times \sum_l V_{lis} = \sum_j Q2_{ijs} \quad \forall i, s \quad (7)$$

$$\sum_i Q_{irjs} = \sum_k TT_{rkjs} \quad \forall r, j, s \quad (8)$$

$$\sum_r TT_{rkjs} \leq D1_{kjs} \quad \forall k, j, s \quad (9)$$

$$\sum_r TT_{rkjs} \geq \sum_l U_{kljs} \quad \forall k, j, s \quad (10)$$

$$\sum_l U_{kljs} = f2_{kjs} \quad \forall k, j, s \quad (11)$$

$$e7_j \times \sum_k U_{kljs} \leq \sum_a WW_{las} \quad \forall l, j, s \quad (12)$$

$$\sum_k \sum_j U_{kljs} = \sum_i V_{lis} + \sum_a WW_{las} \quad \forall l, s \quad (13)$$

$$\sum_r \sum_j Q_{irjs} \leq \sum_j X_i \times ca2_{ij} \quad \forall i, s \quad (14)$$

$$\sum_i \sum_n PP_{min.s} \leq \sum_n ca1_{mn} \quad \forall m, s \text{ if } v1_s = 0 \quad (15)$$

$$\sum_i \sum_n PP_{min.s} \leq (1 - t2_{ms}) \times \sum_n ca1_{mn} \quad \forall m, s \text{ if } v1_s = 1 \quad (16)$$

$$\sum_i \sum_j Q_{irjs} \leq \sum_j Y_r \times ca3_{rj} \quad \forall r, s \quad (17)$$

$$\sum_k \sum_j U_{kljs} \leq \sum_j ZZ_l \times ca4_{lj} \quad \forall l, s \quad (18)$$

$$\sum_l WW_{las} \leq ca5_a \quad \forall a, s \quad (19)$$

$$\text{per2} \times \sum_m \sum_n PP_{min.s} = \sum_j \sum_e Q1_{ijes} \quad \forall i, s \text{ if } v1_s = 0 \quad (23)$$

$$\text{per2} \times (\sum_m \sum_n PP_{min.s} + \sum_{bm} \sum_n SS_{b.min.s}) = \sum_j \sum_e Q1_{ijes} \quad \forall i, s \text{ if } v1_s = 1 \quad (24)$$

$$\sum_i \sum_n SS_{b.min.s} \leq \sum_n ca6_{bmn} \quad \forall bm, s \text{ if } v1_s = 1 \quad (25)$$

$$X_i, Y_r, ZZ_l \in \begin{cases} 1 \\ 0 \end{cases} \quad (26)$$

$$PP_{min.s}, SS_{b.min.s}, Q1_{ijes}, Q2_{ijs}, Q_{irjs}, TT_{rkjs}, U_{kljs}, V_{lis}, WW_{las} \geq 0$$

Equation (21) represents the economic objective function for the WB model. This equation is the same as Eq. (1) to which mining and transportation costs from backup mines have been added. Equation (22) shows the environmental objective function for the WB model. This equation is the same Eq. (2) to which the emission of pollutants from mining and transportation from backup mines have been added. Equation (3) (social objective function) and constraints (4), (5), and (7) to (19) enter the WB model without change. Constraints (23) and (24) on the WB model have the same function as the constraint (6) the WOB model. Constraint (23) shows that if there is no disruption in the scenario, in each factory, the input raw materials from the primary mines are converted into products using a coefficient. Constraint (24) shows that if there is a disruption in the scenario, the input raw materials from the primary and backup mines are converted into products using a coefficient for each factory. The domain of the decision variables is shown in constraint

(26). This constraint is similar to the constraint (20), but it also presents the domain of the amount of extraction from the backup mines.

Results and discussion

In this section, two methods used to solve the models are described. Then, the WOB model is solved using both methods and the better solution method is selected. In the next step, the WOB model and the WB model are compared using the solution method selected in the previous step. Then, sensitivity analysis and validation are performed. Figure 5 shows the flowchart of the research steps.

Based on Fig. 5, the literature is reviewed in the first step, then the gaps of the previous researches and the contribution of this research are presented. The output of this step is the decision to design a resilient sustainable CLSC network for

copper industry. In the second step, the structure of the copper supply chain is investigated; data are collected, and modelling of the problem is performed considering the aspects of SD and the effect of earthquake disruption risk on copper mines. The output of this step is designing multi-objective models (in order to take into account, the economic, environmental, and social aspects of SD) WOB mine and WB mine (as a resilience strategy) in a closed-loop structure (for reuse of copper scrap). In the third step, appropriate solution methods are identified according to the literature. The output of this step is the selection of WSM and ϵ -constraint method to solve the models. In the fourth step, the model solving process is continued. At this step, first, the WOB model is solved in 12 examples produced using the methods of WSM and ϵ -constraint in GAMS software. According to the results, WSM is selected as the better method. Then, WOB and WB models are compared with each other using WSM, which was selected as the better solution method in

the previous step. Generally, in the fourth step, it is determined that WSM is a better method to solve the models of this paper. In addition, the resilient model (WB mine) in this paper has better performance in economic and social aspects of SD than the model WOB mine. In the fifth step, the results of this research are discussed. Gaps extracted in the previous research are responded. In the sixth step, sensitivity analysis and validation of the results are performed. Results are described in [sensitivity analysis](#) and [validation](#) subsections. In the seventh step, the results of this research are presented, and also some developing opportunities of this research are presented in [conclusions](#) section.

Explaining the solution methods

Multi-objective programming is a subset of mathematical programming in which decision variables are optimized in a feasible space created by problem constraints so that they

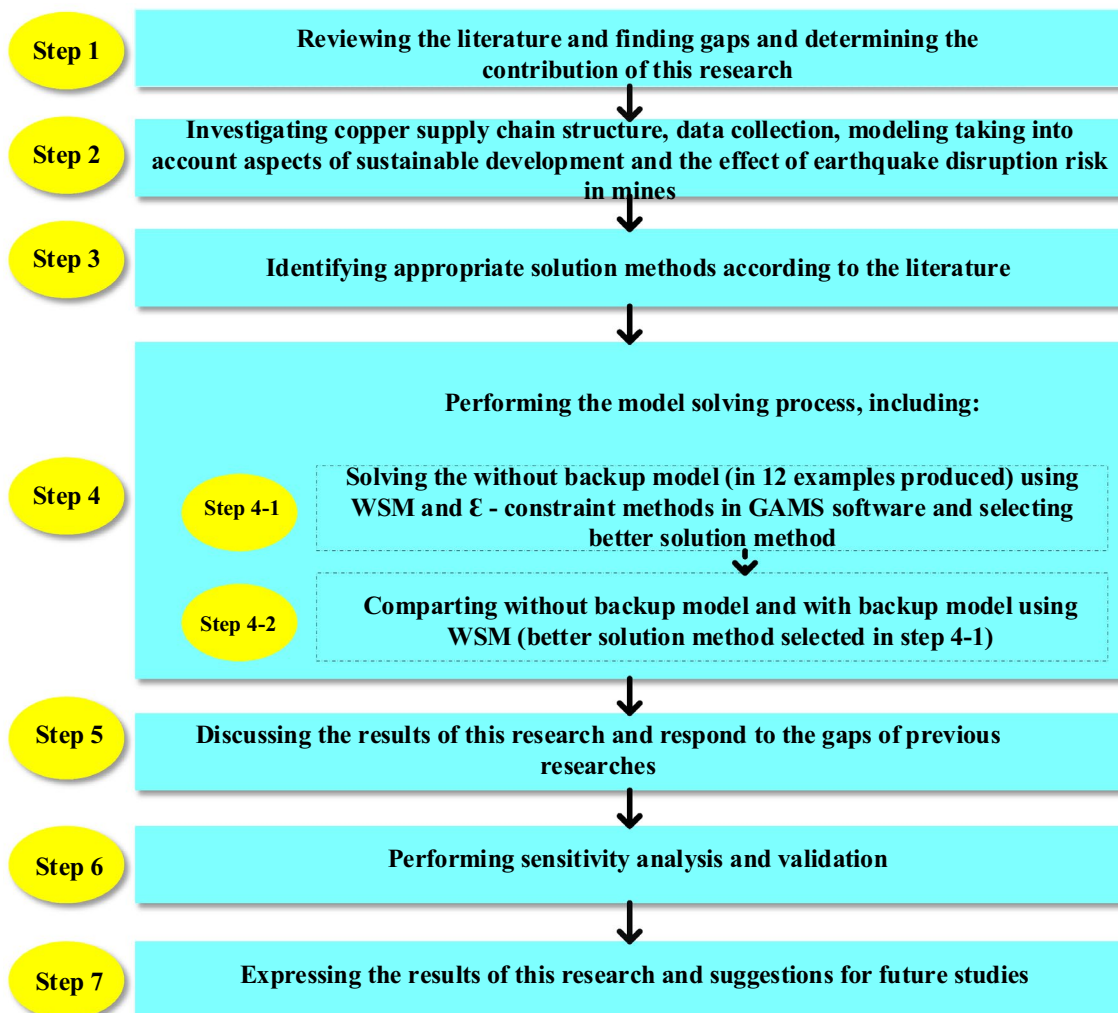


Fig. 5 flowchart of research steps

can simultaneously bring different objective functions to their desired value (Diabat et al. 2019). It is a well-known fact that in real-world problems of engineering, decision variables are usually optimized under a feasible space subject to several different objective functions.

In general, the solution methods of the multi-objective programming can be classified into five main categories: scalar, interactive, fuzzy, meta-heuristic, and decision-aided methods (Mohamadi and Yaghoubi 2017; Diabat et al. 2019). Also, the most common methods used to solve multi-objective problems include ϵ - constraint method, weighted sum, weighted metric, goal programming and lexicographic (Mohamadi and Yaghoubi 2017; Diabat et al. 2019).

The reason for choosing ϵ - constraint method and WSM in this paper, is that they are widely used in network design researches. Some of the researches reviewed in the literature review section and Table 2 have also used these methods. Here, some of them are summarized: Soleimani (2018) used ϵ - constraint method to solve the proposed closed-loop model in his research. Abdolazimi et al. (2020) used WSM and ϵ - constraint method to solve the proposed sustainable closed-loop model in their research. Mehrjerdi and Shafiee (2021) used ϵ - constraint method to solve the proposed resilient model in their research.

ϵ -constraint method and WSM are described below.

ϵ - constraint method

ϵ - constraint method has advantages that have led to its use in many multi-objective programming models. These benefits include the following (Mohamadi and Yaghoubi 2017):

- 1- It does not enter the additional variables to the model; So, it will be simple and fast computationally.
- 2- The number of efficient solutions produced are controlled in it by correctly adjusting the number of grid points in the range of each of the objective functions.
- 3- There is no need to same scale different objective functions in it. So, each objective function can be represented on its own scale.
- 4- It can produce efficient non-extreme solutions that help to better understand the results and analyze them.

In this section, ϵ -constraint method (based on Esmaili et al. 2011) is described briefly. It is assumed that there is a mathematical problem with p objective functions. Each objective function is shown as $f_i(x)$ where $i = 1, 2, \dots, p$. S is a feasible space that can be created by constraints and in which the decision variables are located. x is the decision variables vector. In ϵ -constraint method, one objective function is considered as the main objective function and others are added

to the constraints (in this paper, the first objective function is considered as the main objective function). Without losing focus on the general perspective, it is assumed that all objective functions are maximized. The general state of the problem formulation is described as follows:

$$\begin{aligned} &\max f_1(x) \\ &\text{subject to:} \\ &f_2(x) \geq e_2 \\ &f_3(x) \geq e_3 \\ &\vdots \\ &f_p(x) \geq e_p \\ &x \in S \end{aligned} \tag{27}$$

The constraints in Eq. (27) are added to the main constraints of the problem. To determine the range of the objective functions that are in the constraints (e_2, e_3, \dots, e_p), it is needed to find the grid points. The most common method is to calculate the minimum and maximum values of each objective function (f_i^{\min} and f_i^{\max}) subject to the payoff table. As a result, the range of the i^{th} objective function is determined using Eq. (28).

$$r_i = f_i^{\max} - f_i^{\min} \tag{28}$$

The range of the i^{th} objective function is divided to q_i (grid point) equal intervals and e_i is calculated as demonstrated in Eq. (29):

$$e_i^k = f_i^{\max} - \frac{r_i}{q_i} \times k \quad k = 0, 1, \dots, q_i \tag{29}$$

k is the grid point number. In this method, the multi-objective problem is converted to $\prod_{i=2}^p (q_i + 1)$ single objective sub-problems each of which is restricted by its constraint in Eq. (27). These sub-problems can present Pareto optimal solutions for the multi-objective problem.

Weighted sum method

Here, WSM (based on Abdolazimi et al. 2020) is described briefly. In this method, a multi-objective problem is converted to a single objective problem. Each of the objective functions is weighted and normalized before being all summed up into an integrated objective function called $F(x)$. In $F(x)$ the weights of the objective functions can be determined according to the decision-makers' preferences. In this paper, the weights are generated uniformly in the range of $[0, 1]$, which $w_i > 0$, and $\sum_{i=1}^3 w_i = 1$. The formulation of the multi-objective problem using WSM is shown in Eq. (30):

$$\begin{aligned} \min F(x) &= \sum_{i=1}^n w_i \times f_i(x) \\ \text{subject to:} & \quad j = 1, 2, \dots, J \\ g_i(x) &\geq 0 \end{aligned} \tag{30}$$

where w_i is the weight of i^{th} objective function.

Solving the problem and selecting the better method

In this section, the WOB model is solved in 12 different examples using ϵ -constraint method and WSM and afterwards the better method is selected. Model data are generated uniformly in a logical range according to the study of documents. Moreover, the scenarios (They are shown in Table 6.) are inspired by Acar and Kaya (2019) research. The range of some of the parameters is shown in Table 7. In Table 7, supply chain profit and costs are expressed according to dollar, distances to kilometer and others to percent. All calculations in this paper are performed on a personal computer with Intel Core i7-2670QM CPU (2.20 GHz), with 8.00 GB of RAM. Also, the GAMS 24.8.2. software is used to solve both models. The solver in all examples of the two models is CPLEX. The CPLEX solver is a proper tool to solve the linear problems (Mehrjerdi and Shafiee 2021); regarding that, the CPLEX solver of GAMS software is used to solve the proposed models. The solutions of the WOB model with ϵ -constraint method and WSM are shown in Table 8. The results shown in this table show that in all the examples and all the objective functions, WSM performs

better. But regarding CPU-time, ϵ -constraint method has a better performance in the first 6 examples. Since CPU-times are not overly long, this advantage is negligible. Overall, from Table 8, it could be concluded that in WOB model, WSM performs better than ϵ -constraint method. In Tables 8 and 9, supply chain profit is expressed according to million dollars, water consumption and emissions of pollutants are expressed according to million tons (1 cubic meter of water equals 1000 L of water. 1000 L of water equals 1 ton (unit weight) of water. Therefore, in the environmental objective function, the expression of water consumption according to cubic meters is equivalent to its consumption according to ton. Emissions of air pollutants are expressed according to ton.) And the distribution of supply chain activities among areas with different rates of security and unemployment is expressed according to Satisfaction of Stakeholders (SoS). Also, CPU times are expressed according to second.

Comparison of WOB and WB models and discussion of their performances

In pervious section, it was concluded that WSM has a better performance in the proposed model. Now, the WOB and WB models are compared using WSM. The comparison results are shown in Table 9. Table 9 shows the performance of the WB model in each of the objective functions as follows: the first objective function: in 8 out of 12 test problems (i.e., 66%), backup mines have increased the profit of the supply chain. It is known that using backup mines during disruption increases the responsiveness of the supply chain. In addition to this advantage, the results of the proposed model show that the supply chain profit also has increased in most cases compared to the WOB model. Therefore, it can be concluded that the use of backup mines in the proposed model brings an economic advantage. The second objective function: in 9 out of 12 test problems (i.e., 75%), the performance of the WB model in the environmental objective function has gotten worse than the WOB model. This is logical because backup mines are added to the supply chain as an additional

Table 6 Disruption scenarios

Scenario	Magnitude	Probability	Damage
1	Less than 4	0.25	Not damaged
2	4–7	0.5	Moderately—Heavy
3	More than 7	0.25	Very heavy

Table 7 The range of some parameters

Parameter	Amount	Unit
$t1_j$	5500–7500	Dollar per ton of product
$p1_{mns}$	0.36–0.4	Dollar per ton of raw material extracted from mine
f_{jes}	1500–2000	Dollar per ton of product produced from raw material
g_j	0.02–0.03	Dollar per ton of product transported per kilometer
$per1$	0.15	Percent (15% of all products are produced from scrap)
$per2$	0.005	Percent (0.5% tons of product can be obtained from each ton of raw material)
$per3$	0.9	Percent (90% tons of product can be obtained from each ton of scrap)
$e1_{mi}$	10–200	Kilometer
$e2_{ir}$	100–300	Kilometer
$e3_{rk}$	200–600	Kilometer

Table 8 WOB model solutions with ϵ -constraint method and WSM

Number of Test problem	Problem Size	m,j,i,r,k,l,s,n,e,a	Z1 (ECM) (MillionDollars)	Z1 (WSM) (Million Dol-lars)	Z2 (ECM) (Million Ton)	Z2 (WSM) (Million Ton)	Z3 (ECM) (SoS)	Z3 (WSM) (SoS)	CPU time (ECM) (Sec-ond)	CPU time (WSM) (Sec-ond)
BM										
1	Small	2,2,2,2,3,2,3,2,2,2	7.956	37.541	0.342	0.302	80.197	184.791	12.716	34.575
BM			WSM		WSM		WSM		ECM	
2		2,2,2,2,4,2,3,2,2,2	11.894	52.667	0.534	0.478	79.079	222.480	10.463	45.199
BM			WSM		WSM		WSM		ECM	
3		2,3,3,3,5,3,3,2,2,3	26.880	103.301	0.802	0.712	122.800	317.009	19.377	66.139
BM			WSM		WSM		WSM		ECM	
4		2,3,3,3,6,3,3,2,2,3	32.408	122.472	1.127	0.998	69.427	436.028	11.035	36.730
BM			WSM		WSM		WSM		ECM	
5	Medium	3,4,4,4,8,4,3,2,2,4	63.209	228.973	1.735	1.542	150.219	601.789	35.102	71.964
BM			WSM		WSM		WSM		ECM	
6		3,4,4,4,9,4,3,2,2,4	70.783	257.565	2.101	1.878	246.209	541.611	41.325	75.447
BM			WSM		WSM		WSM		ECM	
7		3,5,5,5,10,5,3,2,2,5	98.782	359.781	3.223	2.893	162.339	763.236	108.645	103.153
BM			WSM		WSM		WSM		WSM	
8		3,5,5,5,11,5,3,2,2,5	111.273	392.540	3.158	2.727	191.139	829.743	135.665	110.947
BM			WSM		WSM		WSM		WSM	
9	Large	4,6,6,6,13,6,3,2,2,6	152.689	543.063	3.954	3.470	221.095	790.128	477.232	339.141
BM			WSM		WSM		WSM		WSM	
10		4,6,6,6,14,6,3,2,2,6	158.607	582.355	6.676	6.044	168.973	604.448	458.244	331.048
BM			WSM		WSM		WSM		WSM	
11		4,7,7,7,15,7,3,2,2,7	202.574	685.845	7.816	7.129	188.117	802.079	1138.741	627.557
BM			WSM		WSM		WSM		WSM	
12		4,7,7,7,16,7,3,2,2,7	215.153	656.961	6.799	6.188	225.108	864.160	1068.525	806.380
BM			WSM		WSM		WSM		WSM	

WSM Weighted sum method, ECM ϵ -Constraint method, BM Better method, SoS Satisfaction of stakeholders

Table 9 Comparison of WOB and WB models using WSM

Number of test problem	Z1 (WOBM) (Million dollars)	Z1 (WBM) (Million dollars)	Z2 (WOBM) (Million ton)	Z2 (WBM) (Million ton)	Z3 (WOBM) (SoS)	Z3 (WBM) (SoS)
1	37.541	39.771	0.302	0.369	184.791	222.480
BM	WBM		WOBM		WBM	
2	52.667	51.883	0.478	0.514	222.480	120.013
BM	WOBM		WOBM		WOBM	
3	103.301	106.120	0.712	0.727	317.009	436.152
BM	WBM		WOBM		WBM	
4	122.472	126.141	0.998	0.895	436.028	357.736
BM	WBM		WBM		WOBM	
5	228.973	226.573	1.542	1.573	601.789	516.052
BM	WOBM		WOBM		WOBM	
6	257.565	258.908	1.878	1.895	541.611	662.455
BM	WBM		WOBM		WBM	
7	359.781	351.499	2.893	2.641	763.236	887.172
BM	WOBM		WBM		WBM	
8	392.540	384.014	2.727	2.826	829.743	542.828
BM	WOBM		WOBM		WOBM	
9	543.063	544.788	3.470	5.544	790.128	806.776
BM	WBM		WOBM		WBM	
10	582.355	592.181	6.044	4.346	604.448	663.204
BM	WBM		WBM		WBM	
11	685.845	738.547	7.129	7.361	802.079	755.467
BM	WBM		WOBM		WOBM	
12	656.961	798.01	6.188	6.232	864.160	932.636
BM	WBM		WOBM		WBM	

WOBM Without backup model, WBM: With backup model, BM: Better model, SoS Satisfaction of stakeholders

level and the mining and the transportation related to them cause environmental pollution. Also, in factories, production from raw materials that have come from backup mine consumes water, and air pollutants caused by production processes are released into the atmosphere. Therefore, a worse environmental performance from the WB model in most test problems is reasonable. The third objective function: in 7 out of 12 test problems (i.e., 58%), the WB model has a better social performance than the WOB model. This expresses the social advantage of using the WB model in the proposed supply chain network design.

In this paper, job and security indicators have been used to maximize social desirability as an aspect of SD in the field of social responsibility. In addition to reducing the effect of the earthquake disturbance, the results of this paper show that the resilient model (which uses backup mines) has a better performance in the social aspect of SD than the WOB model. In general, in this paper, the combination of resiliency and sustainability in the CLSC created more values. This result is in line with the response to the gap expressed in the literature review section; that due to the lack

of attention to the social aspect of SD, the combination of sustainability and resiliency in the CLSC is a gap.

Another gap mentioned in the literature review section was, despite the risks in mining industries, previous researches did not address the issue of resiliency. But in this paper, backup mines are used to increase the resiliency of the copper supply chain against earthquake disturbance. In this paper, first, it is considered a base model that is not resilient. Next, a resilience strategy is used so that the copper supply chain can maintain its responsiveness rate in earthquake conditions. This is an important difference between this paper and previous researches because in mining industries such as copper, the suppliers are in fixed places. Being in fixed locations increases the vulnerability of the supplier against disruptive events. However, in previous researches in mining industries, resilience strategies were not used to reduce the effect of disruption.

The basis of this paper is the comparison of non-resilient and resilient models in copper industry (although aspects of SD are also considered in the models). As stated earlier, mining industries have certain characteristics that distinguish them from other industries (for example, the fixed location

of mines and the inability scrap to convert into raw material, etc.). Due to the special characteristics of mining industries and also subject to the best of the authors' knowledge that there was no model about resiliency in mining industries in the past, so it will be difficult to compare the results of this paper with previous researches. But Akbari-Kasgari et al. (2020) designed a certain, single-objective, and closed-loop model for the copper supply chain network, with the aim of profit maximization. Although the structure of their model is slightly different from the models of this paper, generally, the average result of the models can be compared.

The average profit of the certain model presented by Akbari-Kasgari et al. (2020) was equal to 348.524 million dollars. The average profit of the proposed non-resilient model in this paper using ϵ -constraint method is 96.017 million dollars. The average profit of the proposed non-resilient model in this paper using WSM is 335.255 million dollars and the average profit of the proposed resilient model in this paper is 351.536 million dollars. Comparison of the results shows when environmental and social aspects and disruption risk are added to the certain model (also the structure of the uncertain model is slightly different from the structure of the certain model.) the supply chain profit is reduced on average. This result is not unexpected because the environmental and social aspects of SD and disruption risk act as deterrents to achieve maximum profit. In fact, they are in conflict with supply chain profit maximization. Pourmehdi et al. (2020) confirmed this result in their research. They researched on the steel industry. Their model considered aspects of SD but did not take into account disruption risk and resiliency. They stated that lack of consideration in the environmental and social aspects creates better value in the economic aspect of SD.

Comparing the average profit of the resilience model of this paper with the average profit of the certain model presented by Akbari-Kasgari et al. (2020) shows that the use of resilience strategy has increased the profit of the supply chain. In fact, using a resilience strategy increases the responsiveness of the supply chain. This means that more demand is satisfied and consequently the profit of the supply chain increases potentially.

Generally, supply chain managers can take into account their preferences and the importance of each of the three aspects of SD when making their own decisions on whether or not to use backup mines based on the models of this paper. They need to tradeoff between the advantages and disadvantages of using backup mines to achieve SD goals.

Sensitivity analysis

In this section, the sensitivity of objective functions to changing model parameters are analyzed. Sensitivity analysis is performed on the parameters of test problem number

12 of the WB model using WSM. To perform the sensitivity analysis, all the parameters of the model are changed by 70% and 130% of their value in test problem number 12. This sensitivity analysis approach is inspired by the research of Abdolazimi et al. (2020). Their effect on each of the objective functions is as follows:

The first objective function: The parameters $t1_j, a1_i, b_r, c3_l, p1_{mns}, p3_{bmns}, d_n, g_j, m1_j, e1_{mi}, e2_{ir}, e3_{rk}, e4_{kl}, e5_{li}, e6_{la}, e8_{bmi}, f_{jes}, c1_{js}, c2_j, a2_j, d1_{kjs}, e7_j, f2_{kjs}, ca1_{mn}, t2_{ms}$ have impact on the first objective function and the other parameters are removed. Figure 6 shows the change in the value of the economic objective function versus the 70% change in these parameters relative to their nominal value in test problem number 12. Figure 6A demonstrates the effect of $t1_j, f_{jes}, d1_{kjs}$ (product selling price, production cost, and customer demand) parameters. These three parameters have the greatest impact on the economic objective function. Figure 6B demonstrates the effect of $a1_i, b_r, c3_l, p1_{mns}, p3_{bmns}, d_n, g_j, m1_j, e1_{mi}, e2_{ir}, e3_{rk}, e4_{kl}, e5_{li}, e6_{la}, e8_{bmi}, c1_{js}, c2_j, a2_j, e7_j, f2_{kjs}, ca1_{mn}, t2_{ms}$ parameters. These parameters have less impact on the economic objective function. As an example of the explanation of Fig. 6, it should be said, when $t1_j$ is changed as much as 70% of its nominal value in test problem number 12, the economic objective function changes as much as 318.477 million dollars. Figure 7 is similar to Fig. 6, but Fig. 7 shows changes in the economic objective function versus a 130% change in the parameters from their nominal value in test problem number 12.

The second objective function: The parameters $e1_{mi}, e2_{ir}, e3_{rk}, e4_{kl}, e5_{li}, e6_{la}, d1_{kjs}, e7_j, f2_{kjs}, ca1_{mn}, m2_{mn}, m3_e, w1_{mi}, w2_{ir}, w3_{rk}, w4_{kl}, w5_{la}, w6_{li}, q22_e, t2_{ms}$ have impact on the second objective function and the other parameters are removed. Figure 8 shows the change in the value of the environmental objective function versus the 70% change in these parameters relative to their nominal value in test problem number 12. Figure 8A demonstrates the effect of $q22_e, f2_{kjs}, d1_{kjs}$ (Amount of water required for production from raw material, amount of scrap product returned by customer, and customer demand) parameters. These three parameters have the greatest impact on the environmental objective function. Figure 8B demonstrates the effect of $e1_{mi}, e2_{ir}, e3_{rk}, e4_{kl}, e5_{li}, e6_{la}, e7_j, ca1_{mn}, m2_{mn}, m3_e, w1_{mi}, w2_{ir}, w3_{rk}, w4_{kl}, w5_{la}, w6_{li}, t2_{ms}$ parameters. These parameters have less impact on the environmental objective function. As an example of the explanation of Fig. 8, it should be said, when $q22_e$ is changed as much as 70% of its nominal value in test problem number 12, the environmental objective function changes as much as 1722.934 kilotons. Figure 9 is similar to Fig. 8, but Fig. 9 shows changes in the environmental objective function versus a 130% change in the parameters from their nominal value in test problem number 12.

The third objective function: The parameters $pa1_i, pa2_r, pa3_l, ir1_i, ir2_r, ir3_l, sl1_i, sl2_r, sl3_l$ have impact on the third

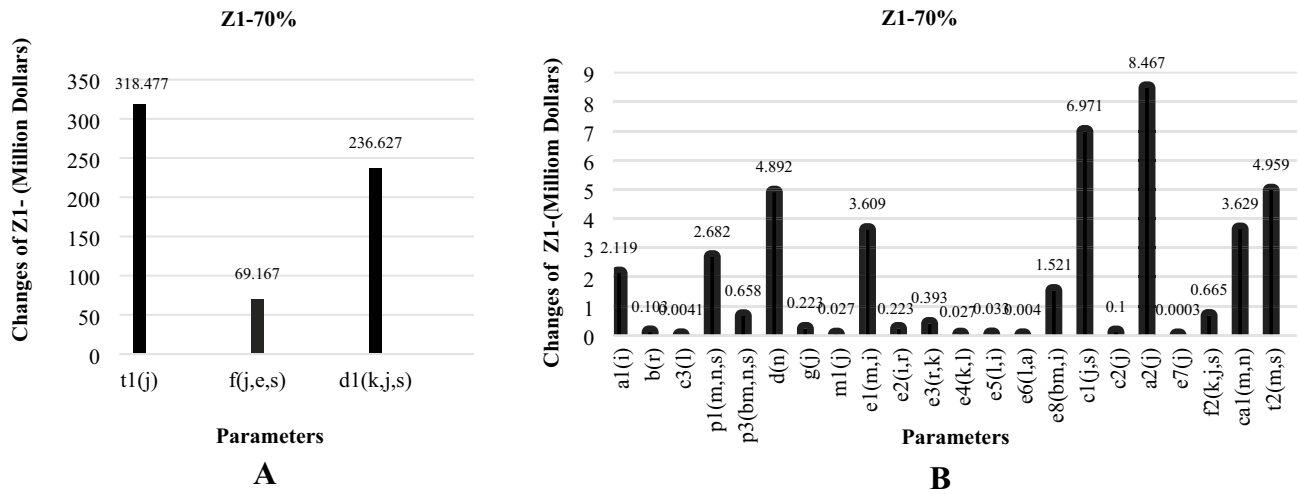


Fig. 6 Sensitivity analysis results related to the economic objective function at 70% nominal values of parameters: **A** The most effective parameters, **B** The less effective parameters

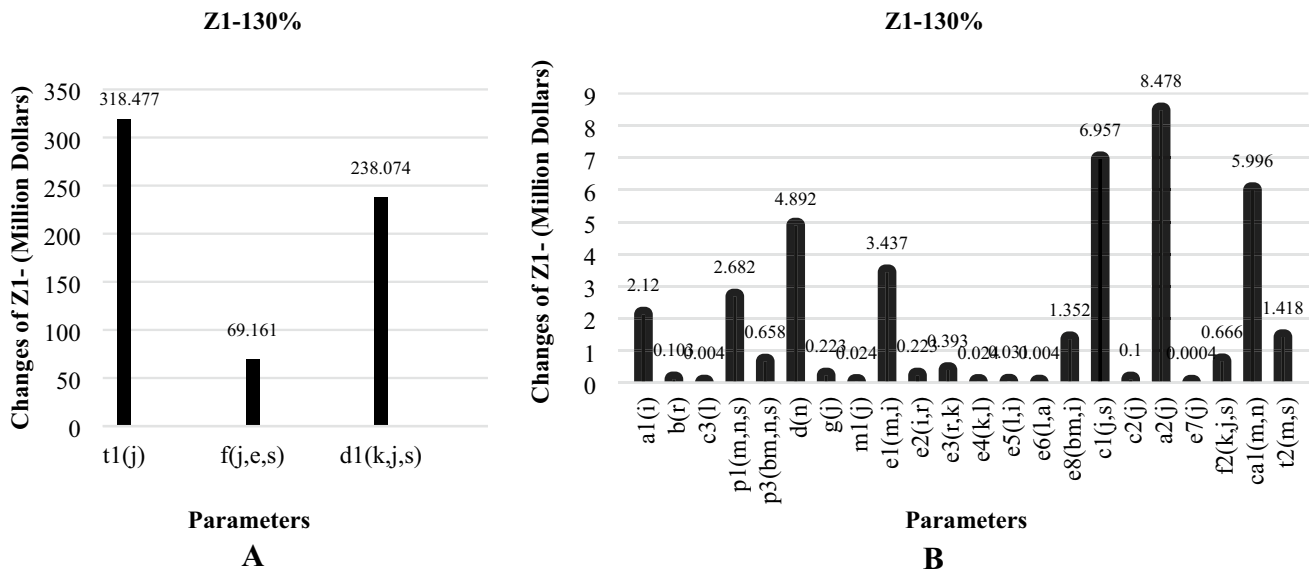


Fig. 7 Sensitivity analysis results related to the economic objective function at 130% nominal values of parameters: **A** The most effective parameters, **B** The less effective parameters

objective function and the other parameters are removed. Figure 10 shows the change in the value of the social objective function versus the 70% change in these parameters relative to their nominal value in test problem number 12. Figure 10A demonstrates the effect of $pa1_i$, $pa2_r$, $pa3_l$, $ir1_i$, $ir2_r$, $ir3_l$ (Population density and unemployment rate in different areas) parameters. These parameters have the greatest impact on the social objective function. Figure 10B demonstrates the effect of $sl1_i$, $sl2_r$, $sl3_l$ parameters. These parameters have less impact on the social objective function. As an example of the explanation of Fig. 10, it should be said, when $pa1_i$ is

changed as much as 70% of its nominal value in test problem number 12, the social objective function changes as much as 68.158 SoS. Figure 11 is similar to Fig. 10, but Fig. 11 shows changes in the social objective function versus a 130% change in the parameters from their nominal value in test problem number 12.

The results of the sensitivity analysis reveal important and effective parameters on each of the objective functions. Managers and supply chain decision-makers need to pay more attention to these parameters when using the proposed model of this paper.

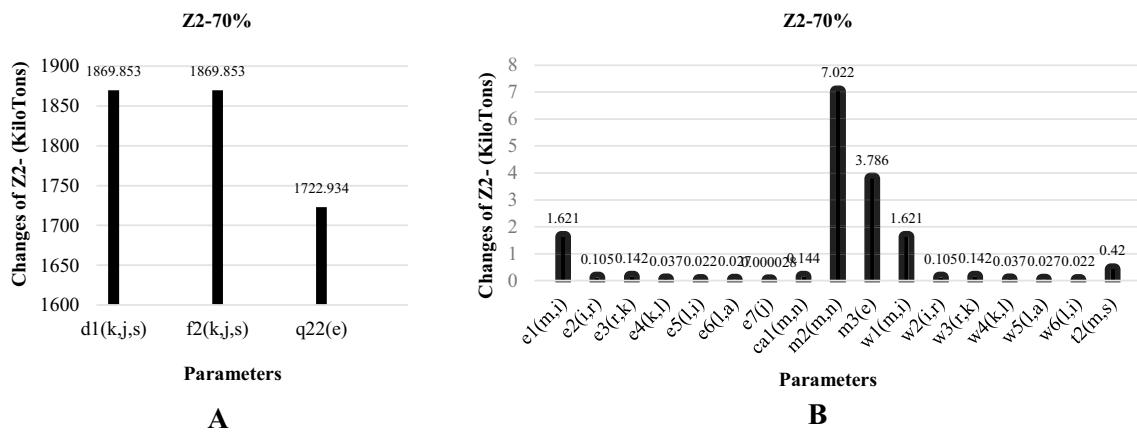


Fig. 8 Sensitivity analysis results related to the environmental objective function at 70% nominal values of parameters: **A** The most effective parameters, **B** The less effective parameters

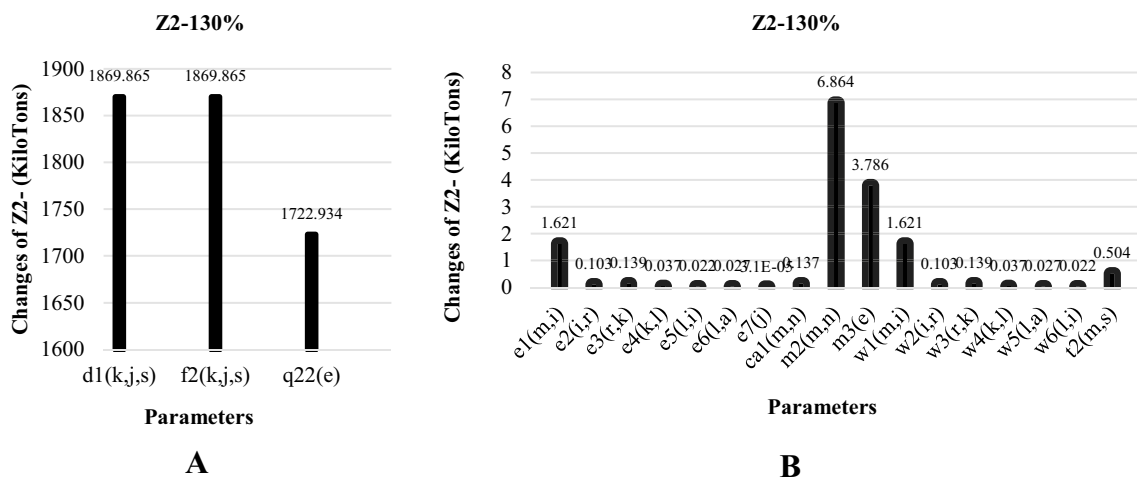


Fig. 9 Sensitivity analysis results related to the environmental objective function at 130% nominal values of parameters: **A** The most effective parameters, **B** The less effective parameters

Validation

The purpose of validation is to validate the structure of the model and the solutions. To the best of the authors' knowledge, when a model is solved by more than one method, the validity of the model can be measured using the following steps:

- 1- If the differences of the solutions in different methods are in the range that can be compared with each other (if do no controversial difference among the values of the solutions of the different methods), it can be concluded that the model structure is correct and the values of the solutions are logical. In this paper, the results in Table 9 do not show a controversial difference among the solu-

- tions of the two methods. Therefore, the correctness of the model structure and the solutions can be concluded.
- 2- The feasibility and optimality of each models can be checked. This approach can be used as a complement to the comparative approach of different solution methods. Figures 12, 13, 14, 15, 16 and 17 show samples of feasibility and optimality for the proposed models.

Figure 12, as an example, shows the optimality of the solutions provided by the WOB model in WSM, for test problem 1.

Figure 13, as an example, shows the feasibility of the constraint (13) in the WOB model in WSM for test problem 1.

Figure 14, as an example, shows the optimality of the WOB model in ϵ -constraint method for test problem 1.

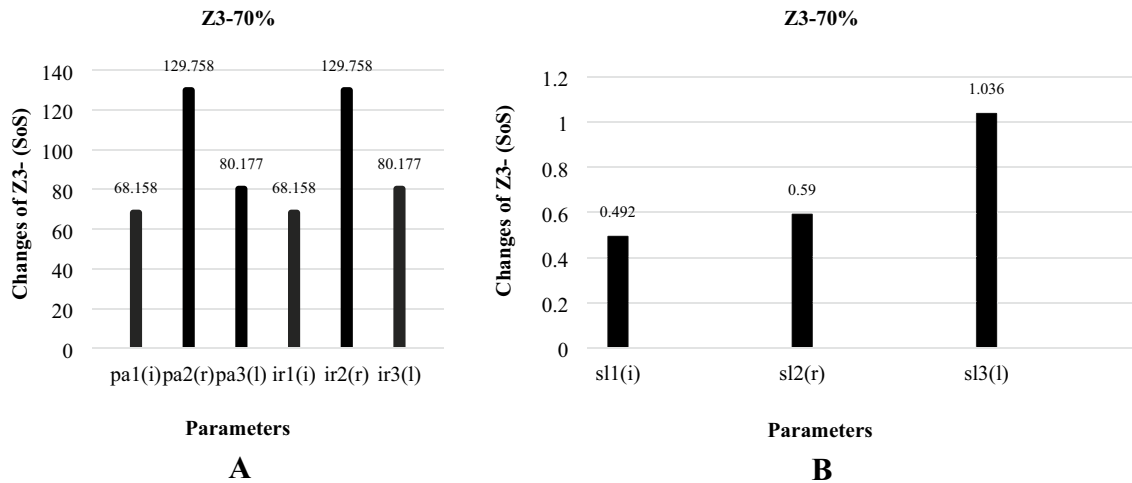


Fig. 10 Sensitivity analysis results related to the social objective function at 70% nominal values of parameters: **A** The most effective parameters, **B** The less effective parameters

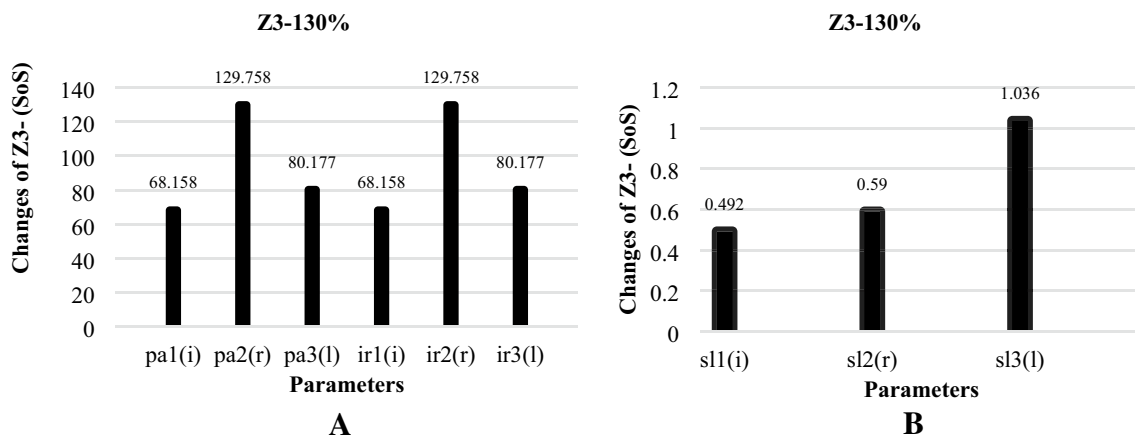


Fig. 11 Sensitivity analysis results related to the social objective function at 130% nominal values of parameters: **A** The most effective parameters, **B** The less effective parameters

Figure 15, as an example, shows the feasibility of the constraint (8) in the WOB model in ϵ -constraint method for test problem 1.

Figure 16, as an example, shows the optimality of the WB model in WSM for test problem 1.

Figure 17, as an example, shows the feasibility of the constraint (5) in the WB model in WSM for test problem 1.

Figures 12, 13, 14, 15, 16 and 17 show the validity of the proposed models in this paper. Also, in “[Comparison of Wob and Wb models and discussion of their performances](#)” subsection, the results of this paper are compared with other previous researches, which also confirms the validity of the proposed models.

Conclusions

Copper demand has increased in recent years due to the growth of industrialization. Responding to increased demand requires making more accurate decisions (especially strategic ones) based on scientific principles in the copper supply chain. But, to the best of the authors’ knowledge, there is no mathematical model about copper SCND. In fact, network design specifies configuration and structure of a supply chain. Therefore, it is necessary to implement network design decisions in accordance with the conditions of each industry. Copper industry, is as a subset of mining industries, has certain features that need to be considered in its supply chain network design. These features include the following:

S O L V E S U M M A R Y			
MODEL	SSF	OBJECTIVE	ZF
TYPE	MIP	DIRECTION	MINIMIZE
SOLVER	CPLEX	FROM LINE	260
**** SOLVER STATUS	1	Normal Completion	
**** MODEL STATUS	1	Optimal	
**** OBJECTIVE VALUE		0.3499	

Fig. 12 Optimality of the WOB model in WSM for test problem 1

(i) Copper can be recycled over and over without losing its properties. Therefore, its network structure needs to be as closed-loop so that copper scrap can be recycled. (ii) This industry is highly profitable; therefore, the issue of supply chain profit maximization needs to be considered in its network design. (iii) The activities of copper industry have high negative environmental impacts, so it is necessary to design its network to minimize the harmful environmental effects caused by the activities of this industry. (iv) As an important industry, it is responsible for the society in which it operates, thus it is necessary to pay attention to the needs of stakeholders when designing the network. (v) Copper mineral resources are not equally distributed on the land; this matter increases the vulnerability of copper mines against natural disasters such as earthquakes. Therefore, in its supply chain network design, it is necessary to pay attention to supply chain resiliency against catastrophes.

Theoretically, in this paper, a resilient sustainable closed-loop SCND model is presented for copper industry. The economic, environmental, and social aspects of SD are considered: Profit is maximized, water consumption in production processes and the emission of air pollutants of supply chain activities are minimized, and potential facilities are established fairly among different areas with various levels of security and unemployment rates. Also, backup mines are used in modeling to reduce the effects of disruption on copper mines. Two models, WOB model and WB model, are formulated using MILP and their performances

Fig. 13 Feasibility of the constraint (13) in the WOB model in WSM for test problem 1

$$\sum_k \sum_j U_{kljs} = \sum_i V_{lis} + \sum_a WW_{las} \quad \forall l, s \tag{13}$$

: s=3, l=2

$$U(1,2,1,3) + U(2,2,1,3) + U(3,2,1,3) + U(1,2,2,3) + U(2,2,2,3) + U(3,2,2,3) =$$

$$300.500 + 332.500 + 0 + 375 + 491 + 0 = 1499$$

$$V(2,1,3) + V(2,2,3) = 0 + 0 = 0$$

$$WW(2,1,3) + WW(2,2,3) = 1499 + 0 = 1499$$

S O L V E S U M M A R Y			
MODEL	example1	OBJECTIVE	Z1
TYPE	MIP	DIRECTION	MAXIMIZE
SOLVER	CPLEX	FROM LINE	252
**** SOLVER STATUS	1	Normal Completion	
**** MODEL STATUS	1	Optimal	
**** OBJECTIVE VALUE		7956664.5081	

Fig. 14 Optimality of the WOB model in -constraint method for test problem 1

are compared to each other. To solve the problem, first, the WOB model is solved using ϵ -constraint method and WSM, concluding that WSM has a better performance in the proposed model. Then, the WOB and WB models are solved using WSM. The results show that the WB model performs better in economic, environmental, and social aims in 66%, 25%, and 58% of cases, respectively.

Practically, the comparison of the non-resilient and resilient models shows that the resilient model has performed better in economic and social aspects of SD, but in the environmental aspect it has performed worse. In fact, using a resiliency strategy aids the supply chain to increase its responsiveness in the event of a disaster. In other words, with increasing responsiveness, the amount of satisfied customer demand increases. In the proposed resilient model in this paper, increasing the amount of satisfied demand has also increased the profit of the supply chain. It demonstrates the economic advantage of the proposed resilient model. Also, the proposed resilient model has been able to create more benefits in the social aspect of SD in the society, which indicates the superiority of this model over the non-resilient model. But in the environmental aspect, in the resilient model, the existence of backup mines causes the complexity and breadth of the supply chain structure. Also, the activity of backup mines and the entry of raw materials extracted from them into the production cycle is associated with water

Fig. 15 Feasibility of the constraint (8) in the WOB model in -constraint method for test problem 1

$$\sum_i Q_{irjs} = \sum_k TT_{rkjs} \quad \forall r, j, s \quad (8)$$

: r=2, j=1, s=3

$$Q(1,2,1,3) + Q(2,2,1,3) = TT(2,1,1,3) + TT(2,2,1,3) + TT(2,3,1,3)$$

$$976.250 + 0 = 300.500 + 332.500 + 343.250$$

S O L V E		S U M M A R Y	
MODEL	SSF	OBJECTIVE	ZF
TYPE	MIP	DIRECTION	MINIMIZE
SOLVER	CPLEX	FROM LINE	261
**** SOLVER STATUS		1 Normal Completion	
**** MODEL STATUS		1 Optimal	
**** OBJECTIVE VALUE		0.3587	

Fig. 16 Optimality of the WB model in WSM for test problem 1

consumption and air pollution. Therefore, a worse performance of the resilient model compared with the non-resilient model would be reasonable.

The results of this paper create some managerial insights that managers can benefit from in strategic planning. They are listed below: (i) Copper supply chain profit is maximized by designing a mathematical model for its supply chain network. (ii) Recycling copper scrap and using it in production saves costs, water, and energy consumption. It also saves the use of this non-renewable resource and does not endanger the rights of future generations. (iii) The use of backup mines in disasters such as earthquakes will help the supply chain to better respond to customer needs which can increase customer loyalty in the long-term.

This paper can be developed in different aspects for the future. For example, although fixed facilities such as mines are highly impacted by disasters and disruptions, it is clear that each facility of the supply chain can be vulnerable to the disruption risk. In this paper, disruption risk is

only examined on mines. However, in the future, the impact of this type of risk can be examined on other supply chain facilities. Another issue is that different catastrophes can have different levels of impact on supply chain facilities. For example, the effects of man-made attacks or floods are different from earthquakes. In this paper, the impact of the earthquake disaster is examined. But in future works, the impact of other catastrophes can be considered into the mathematical model in a variety of scenarios. Another way to develop this research could be considering the economic issues of imports and exports in the mathematical model. In fact, the products of copper industry are used globally, and countries that do not have copper mineral resources are required to import its products. In addition, countries with copper resources can usually supply more copper products than they need. Therefore, considering the economic issues of imports and exports in the copper supply chain can be an attractive area for further research in this field. Generally, copper mines are divided into two categories: underground and open-pit on which conditions of use and the effect of the disaster can vary in the different types. This division can be considered in future studies. In the process of preparing copper products, some by-products are also produced that can be used in other industries. How copper industry related to those industries is a topic that can be addressed in future studies.

It should be noted that no research is free from limitations. Therefore, this paper is not an exception. In this paper, access to all data took too much time.

Fig. 17 Feasibility of the constraint (5) in the WB model in WSM for test problem 1

$$per1 \times \sum_r \sum_j Q_{irjs} = \sum_j Q_{ijs}^2 \quad \forall i, s \quad (5)$$

: i=2, s=1, per1=0.15

$$0.15 * (Q(2,1,1,1) + Q(2,2,1,1) + Q(2,1,2,1) + Q(2,2,2,1)) = Q(2,1,1) + Q(2,2,1)$$

$$0.15 * (939.500 + 0 + 1221 + 0) = 324.075 + 0$$

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