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Designing an IoT-enabled supply chain network considering the perspective of the Fifth Industrial Revolution: Application in the medical devices industry☆

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ABSTRACT

The rapid growth of technology, environmental concerns, and disruptions caused by the COVID-19 pandemic have led researchers to pay more attention to an emerging concept called the fifth industrial revolution (I5.0). Despite the high importance of the I5.0, the literature shows that no study investigated the supply chain network design problem based on the I5.0 pillars. Hence, this research develops a multi-stage decision-making framework to configure a closed-loop supply chain based on I5.0 dimensions to cover this gap. In the first stage, the score of technologies that utilized in the supply chain is calculated using the analytic hierarchy process method. Afterwards, in the second stage, a mathematical model is proposed to configure the supply chain. Then, Furthermore, an efficient solution method, named the fuzzy lexicographic multi-choice Chebyshev goal programming method, is developed to obtain the optimal solution. In general, the main contributions of the current study can be divided into two major parts as follows: (i) the current study is the first research that incorporates the dimensions of the I5.0 into the supply chain network design problem, and (ii) this work develops a novel and efficient solution method. In this regard, the major problems and challenges that existed include the limitation of available resources in relation to Industry 5, especially in the field of the supply chain, as well as quantifying the elements of Industry 5.0 in the form of a mathematical programming model.

1. Introduction

In the last decade, due to dramatic changes in technology and the digital industry, fundamental changes have been made in the business environment, called the Fourth Industrial Revolution (I4.0) (Haseeb et al., 2019b; Sisodia and Jindal, 2021). The achievements of I4.0 have helped industries in many fields. For instance, the Internet of Things (IoT) has many applications in the industry, such as tracking and monitoring the products, which can help improve the collection/repairing the End-of-Used (EoU)/End-of-Life (EoL) products and waste management (Marques et al., 2019; Saha et al., 2017; Usak et al., 2020). In this regard, Subramanian et al. (2020) mentioned that utilizing the IoT can improve the efficiency of collecting operations in reverse logistics. Moreover, information Sharing Systems (ISSs) and online shops, especially during the recent pandemic (COVID-19), are other examples of technology applications in the I4.0 era. Regarding the online markets, it is predicted that online sales revenues will grow to 6.54 trillion dollars by 2023 (Subramanian et al., 2020). Therefore, the advantages of I4.0 are undeniable. However, besides the merits of I4.0, this is primarily a techno-economic vision that demonstrates how technological advancements affect industries (Nahavandi, 2019). Although I4.0 has extremely emphasized Artificial Intelligence (AI)-driven technologies and digitalization, it has less attention on crucial principles such as sustainability, resiliency, and the role of the human in the industry (Breque et al., 2021).

Sustainability is one of the well-known concepts in industries that implies simultaneous consideration of the economic, environmental, and social aspects (Eskandari-Khanghahi et al., 2018; Goodarzian et al., 2021; Haseeb et al., 2019a; Jermsittiparsert et al., 2019; Saengchai and Jermsittiparsert, 2019). Here, several real-world examples are provided that can clarify the importance of sustainability in industries. Concerning the concept of sustainable development, in terms of environmental goals, Adobe decreased its GHG emissions by 75%, Coca-Cola decreased water consumption by about 20%, and Dell reduced the energy intensity of its goods by 20% (Confino, 2014).

Besides, some disruptions, such as the COVID-19 pandemic, have demonstrated the vulnerabilities of today's industry. In this regard, the resiliency concept is introduced to cope with disruptions. In general, resilience is a set of strategies to deal with disruptions (Mamashli et al., 2021; Rajesh, 2020). Several real-world examples show the importance

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of resiliency in the industries, such as Nissan Motors company (see Rezapour et al., 2017) and also Nokia company (see Zsidisin and Wagner, 2010).

Over its ten years of life, I4.0 has emphasized more on AI-driven technologies and digitalization and less on the role of human beings in the industry (Breque et al., 2021). In this regard, I5.0 attempts to bring back human workers to the factory floors and apply human creativity to increase the efficiency of the processes (Nahavandi, 2019). A human-centric view tries to put the interests and needs of humans at the core of the production process. It implies that employing the new technologies does not trespass on workers' rights like human dignity, autonomy, and privacy (Breque et al., 2021). In Europe, various projects have been defined to examine the human-centric perspective of Industry 5.0 (e.g., FACTS4WORKERS and Rossini), which shows the importance of this approach in modern businesses (Breque et al., 2021).

Owing to the issues mentioned earlier, researchers and managers have recently introduced the concept of Industry 5.0 (I5.0). I5.0, which seeks to extend and complement the Fourth Industrial Revolution (I4.0) features, is established based on the three main pillars, namely (i) sustainability, (ii) resilience, and (iii) human-centricity (see Fig. 1) (Breque et al., 2021). Indeed, I5.0 is not a continuation or replacement of I4.0 but completes and expands its features. I5.0 focuses more on critically important features, such as sustainability, social fairness, and resiliency (Demir et al., 2019; Nahavandi, 2019). Albeit, it should be noted that although the concept of I5.0 has become more trend after the COVID-19 outbreak, the original idea of this phenomenon was introduced by Özdemir and Hekim (2018) as a concept in health care and with the key conceptual pillars of symmetrical innovation. In this regard, based on Özdemir and Hekim (2018), With symmetrical innovation, digital connectivity has been framed in the past without an upper bound limit or with notions such as connect until everything is connected to everything else. However, such extreme digital connectivity has a number of risks and drawbacks, such as domino effects and total collapse of the healthcare networks; or the creation of echo chambers that hinder creativity and innovation. Symmetrical innovation places a check on extreme digital connectivity and cautions that digital connectivity should be balanced with (I) the analog world and analog connections, and (II) digital connectivity needs to be mindful to prevent echo chambers, extreme digital connectivity, and domino effects that can cause the total collapse of the innovation ecosystems and health systems. Additionally, extreme digital connectivity can result in the concentration of political power in the hands of a few people or companies and poses a risk to democracy in a digital society. That is Industry 5.0, and the symmetrical innovation that is its key driver has both instrumental and normative (e.g., ethical) dimensions and advantages to ensure innovation ecosystems are democratic.

There have been a number of publications in the I5.0 literature covering areas of conceptualization, engineering education, manufacturing systems, production planning, architecture, medical fields, robotics, etc. (see Akundi et al., 2022; Aslam et al., 2020; Broo et al., 2022; Doyle-Kent and Kopacek, 2021; Fazal et al., 2022; Haleem and Javaid, 2019; Huang et al., 2022; Javaid et al., 2020; Leng et al., 2022; Maddikunta et al., 2021; Østergaard, 2018; Paschek et al., 2019; Romero and Stahre, 2021; Thakur and Sehgal, 2021; Wong et al., 2022; Xu et al., 2021). But, there is no study that has investigated the supply chain problem considering the I5.0 dimensions. However, in history, there has been a close relationship between SCs and industrial revolutions. For example, in the pre-industrial revolution era, goods were usually transported by animals such as horses. In contrast, with the invention of locomotives in the first industrial revolution and cars in the second industrial revolution, fundamental changes took place in transporting goods. The mentioned example indicates that when a new industrial revolution emerges, there is a need to rethinking in logistics activities. It has been indicated by Sazvar et al. (2021a,b) and Breque et al. (2021) that successful supply chains of the future will be those that incorporate the three I5.0 pillars (i.e., sustainability, resiliency, and human-centricity).

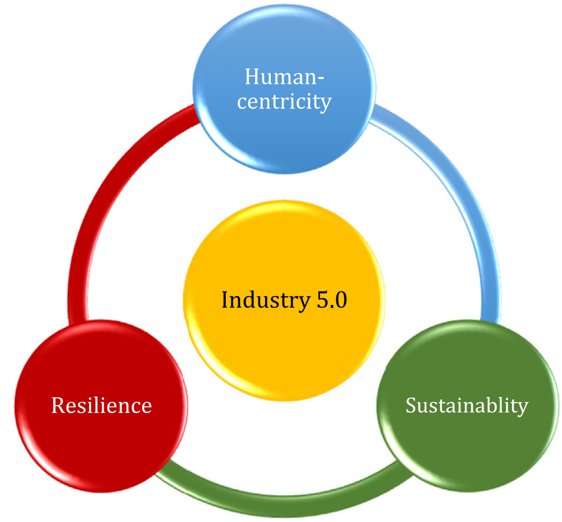


Fig. 1. The dimensions of the I5.0 (Breque et al., 2021).

Motivated by the above points and the real-world cases, the current study aims at configuring a Closed-Loop SCN (CLSCN) considering the I5.0 dimensions (CLSC 5.0). For this purpose, a Multi-Stage Decision-Making Framework (MSDMF) based on the Multiple Attribute Decision-Making (MADM) methods and a Multi-Objective Programming Model (MOPM) is suggested. In this way, at the outset, based on criteria of I5.0, the weight (score) of each technology, which is utilized in the production and recycling processes, is calculated employing the Analytic Hierarchy Process (AHP) method. Then, the optimal configuration of the CLSCN is obtained using the MOPM. Then, an efficient approach, namely the Fuzzy Lexicographic Multi-Choice Archimedean-Chebyshev Goal Programming (FLMCACGP) approach, is developed to obtain the optimal solution. The main advantages of this paper in comparison with the previous ones are as follows: (i) to the best of our knowledge, this is the first time that a study attempts to design a CLSCN based on the I5.0 pillars, (ii) this research develops an efficient solution method to solve the proposed MOPM, and (iii) this study selects the vaccine refrigerator, which its application and importance have been dramatically highlighted during the vaccination process in the COVID-19 pandemic, as a case study. Overall, the present work contributes to the literature by incorporating the pillars of the fifth industrial revolution into the SC network design problem. In other words, this study introduces supply chain 5.0 (for the first time). However, there are several difficulties and challenges along the way, such as existing limitations of resources regarding the I5.0, especially in the supply chain management area, and quantifying the I5.0 dimensions as a mathematical model. To overcome them, this research attempts to identify the most important indicators of I5.0 that are related to the supply chain by reviewing the literature and interviews with experts and then defining the proper parameters, variables, and equations to formulate the research problem. The mentioned points will be presented in Section 3.

In the current research, Section 2 provides the literature review. The proposed MSDMF is explained in Section 3. Section 4 presents the solution method. Also, the case study and outputs are provided in Section 5. Section 6 presents the conclusions of this study.

2. Literature review

Although researchers have focused on the SCN Design (SCND)problem in the last decade, no research work studied the SCND problem considering the dimensions of the I5.0. In this section, we practice reporting some related studies in the field of SCN in which some of the I5.0 dimensions (i.e., sustainability, resiliency, and human-centric) or I4.0 features are studied.

In the field of the Sustainable-Resilient SCN (SRSCN) problem, several studies were published during the last decade. For example, By considering the tire industry as a case study, a MOPM was suggested by Fazli-Khalaf et al. (2020) for configuring a closed-loop SRSCN. The main goals of the proposed model were to optimize the sustainability measures and maximize the reliability metric. Mehrjerdi and Shafiee (2020) offered a model based on the TOPSIS method and a mathematical model to configure a supply chain considering sustainability and resiliency for the automotive tire industry. Govindan and Gholizadeh (2021) proposed a robust model to configure reverse logistics with resiliency and sustainability features regarding big data. Shabbir et al. (2021) configured a closed-loop supply chain by suggesting a mathematical model. It should be noted that the authors incorporated the sustainability and resilience dimensions in their study. Also, a capacity planning approach is utilized by Sazvar et al. (2021a,b) to configure a sustainable and resilient SC. The authors solved the proposed model by the GP method. Nayeri et al. (2021) designed a responsive SCN with sustainability and resiliency aspects under hybrid uncertainty. They developed a new GP to determine optimal solutions. Lotfi et al. (2021) used robust optimization to design a SRSCN along with the risk for the car manufacturing industry. Vali-Siar and Roghanian (2021) designed an SRSCN in which disruptions related to the COVID-19 outbreak were considered. They employed the Lagrangian relaxation method to obtain the optimal solution. By selecting the case study of the textile industry, Tseng et al. (2022) investigated the data-driven SRSCN problem considering the industrial ambidexterity and disruption by combining the fuzzy Delphi method and the best-worst method. A sustainable and resilient SC was designed by Abbasian et al. (2022) for perishable products by developing a heuristic-based goal programming method. To do this, the authors investigated the location- inventory -routing problem and considered traffic conditions. Nayeri et al. (2022) incorporated the sustainability and resiliency concepts into the responsive and global supply chain by proposing a multi-objective programming model. The authors investigated the research problem under mixed uncertainty and developed a new solution method to obtain the optimal solution. Salehi et al. (2022) worked on the SRSCN problem for the biomass industry. The authors first prioritized the resilience factors and then proposed a model to design an SC network. Moreover, to tackle the uncertainty, they employed the robust optimization approach. Goodarzian et al. (2022) investigated the healthcare supply chain problem by considering resilience and sustainability features. In this regard, the authors first proposed a mathematical model to configure an SC network and then developed metaheuristic algorithms to solve the research problem. It should be noted that the authors used the simulation method to estimate the value of the demand parameter.

In view of I4.0 features in the SCN problem, Garrido-Hidalgo et al. (2019) studied reverse logistics for electric wastes and electronic equipment regarding the IoT. Indeed, they provided an end-to-end solution for reverse logistics based on IoT that enabled inventory monitoring through embedded sensors. Manupati et al. (2020) employed blockchain to monitor the performance of SC in both operational costs and emission levels. They offered a multi-objective mathematical model and used the NSGA-II to solve it. Dolgui et al. (2020) used blockchain technology to design an SCN with multiple logistics service providers. The proposed model tried to balance the trade-off between contract costs and SC's lead time using smart contracts. By considering the home appliance industry, Rahmanzadeh, Pishvaee, and Rasouli (2020) studied the tactical planning of SC within a blockchain platform by proposing a single objective fuzzy mathematical model. They presented a consensus mechanism using the blockchain platform, which enabled the companies to collect, assess, and register creative ideas. Gholizadeh et al. (2020) utilized big data for configuring a sustainable SCN under hybrid uncertainty. They proposed a fuzzy robust stochastic model and solved the research problem by employing a heuristic method. Erol et al. (2021) developed a decision-making framework to investigate the sustainability and resiliency in a blockchain-enabled SC. Nagarajan et al. (2022) examined the vehicle routing problem in a food logistics system considering the application of the IoT. To better understand, Table 1 classifies the related previous studies based on different attributes.

According to the literature and Table 1, although several studies have been conducted in the context of the SCND problem, there are still some research gaps in this area. To the best of our knowledge, no study has explored the SCND problem when it comes to the I5.0 pillars. However, the industrial revolutions have always influenced the logistics processes throughout history. For example, before the first industrial revolution, there was a period of hunting and agriculture. Afterward, the first industrial revolution led to an enormous change in the transportation of goods conditions (due to the invention of the steam locomotive) (Demir et al., 2019; Pilevari, 2020). In the I4.0 era, researchers developed supply chain 4.0, in which the elements of I4.0 are incorporated into the SCs (Frederico, 2021). Therefore, it can be said that the I5.0 pillars will have a decisive role in future supply chains (Breque et al., 2021; Sazvar et al., 2021a). Furthermore, other factors create more motivations to incorporate the dimensions of I5.0 into the SCs. By way of example, there is an urgent need to re-think existing approaches due to three main reasons: (i) global warming, decreasing natural resources, and other environmental concerns, (ii) vulnerabilities of the current industries that have been highlighted or aggravated during the Coronavirus disease, and (iii) the fading role of human beings under the attitude of the I4.0.

To cover the gaps in the previous studies, in this paper, a multi-stage decision-making framework is proposed to configure a CLSC on the I5.0 dimensions (CLSC 5.0). To this end, at the outset, the scores of the employed manufacturing (recycling) technologies based on the I5.0 dimensions are calculated. Then, a multi-objective scenario-based model is proposed to design a CLSC 5.0. Eventually, a novel solution method, namely the fuzzy lexicographic multi-choice Archimedean-Chebyshev goal programming, is developed to obtain the optimal solution. In general, regarding the main novelties and contributions of the current work, it can be said this is the first effort to incorporate the pillars of the fifth industrial revolution into the SC network design problem. In other words, This research has introduced the concept of supply chain 5.0 for the first time. On the other hand, the present paper has developed a novel and efficient solution method to solve the multi-objective programming models called the FLMCACGP. Below, the main contributions of the current research are summarized.

- This research is the first one that proposes a multi-stage decision-making framework to configure an SCN based on the I5.0 pillars. In other words, the present work introduces supply chain 5.0.
- Developing an efficient solution method named fuzzy lexicographic multi-choice Archimedean-Chebyshev goal programming.
- Investigating the logistics system of the vaccine refrigerator as one of the most important and widely used medical devices in the Coronavirus disease outbreak.

3. The multi-stage decision-making framework for CLSC 5.0

In this section the steps of the proposed MSDMF are described. The proposed approach consists of two main stages: (i) measuring the scores (weights) of the technologies based on I5.0 criteria using the AHP method, (ii) designing a CLSCN using a scenario-based multi-objective mathematical model. Fig. 2 shows a diagram to better explain the developed methodology.

3.1. The first stage

As mentioned, unlike I4.0, which only focuses on the impact of technological advancements on industries, I5.0 emphasizes different aspects of technology and industry, such as sustainability, resiliency, and human-centricity dimensions (Breque et al., 2021). At the outset,

Table 1
Categorizing the related studies.

Study	Network structure			I5.0 pillars			I4.0 features	Case study	Solution method
	Forward	Reverse	CLSC	Sustainability	Resiliency	Human-centric			
Garrido-Hidalgo et al. (2019)		✓		✓			IoT	Electronic equipment	–
Mehrjerdi and Shafiee (2020)			✓	✓	✓		Information sharing system	Tire	ε-constraint
Manupati et al. (2020)	✓			✓			Blockchain	–	NSGA-II
Dolgui et al. (2020)	✓			–	–		Blockchain	–	Event-driven dynamic approach
Rahmanzadeh et al. (2020)	✓			–	–		Blockchain	Home appliance	Cplex
Gholizadeh et al. (2020)	✓			✓	–		Big Data	Dairy industry	Heuristic
Govindan and Gholizadeh (2021)		✓		✓	✓		Big Data	Transportation industry	Modified cross entropy
Shabbir et al. (2021)			✓	✓	✓				LP-Metric
Sazvar et al. (2021a,b)	✓			✓	✓			Vaccine	GP
Nayeri et al. (2021)	✓			✓	✓			Water heater	Multi-choice meta-GP
Vali-Siar and Roghanian (2021)			✓	✓	✓			Tire	Lagrangian relaxation
Nagarajan et al. (2022)	✓			✓			IoT	Food industry	Bee Colony algorithm
Tseng et al. (2022)	✓			✓	✓		–	textile industry	Hybrid approach
Current study			✓	✓	✓	✓	IoT, Information sharing system, Online customers, 3D printing	Vaccine refrigerator	Fuzzy Lexicographic Multi-Choice Archimedean-Chebyshev GP

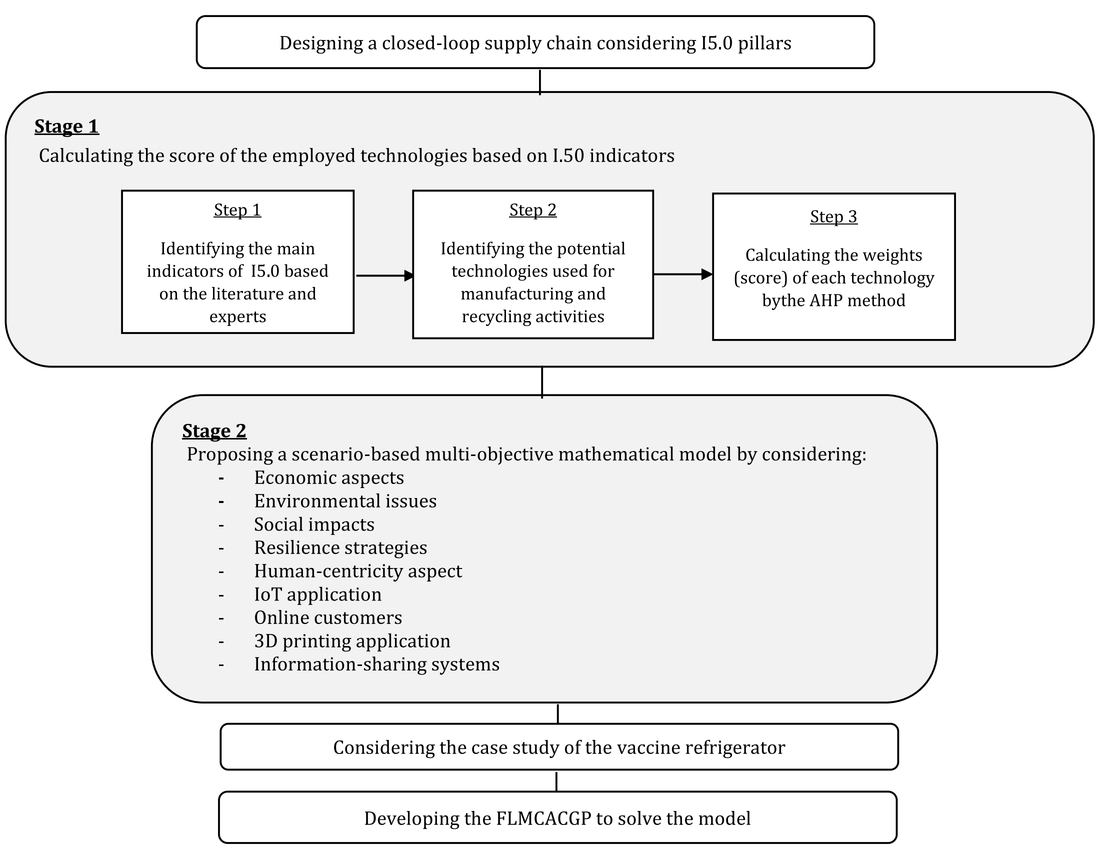


Fig. 2. The proposed decision-making framework for CLSC 5.0.

the scores (weights) of the technologies are calculated based on the I5.0 criteria. In this regard, the AHP method is employed. Fig. 3 shows the decision tree. The AHP method is well-known in the context, and interested readers can see Saaty (2008, 1988) for reading more details about this approach. In the following, the main indicators that have been considered in rating technologies are described.

(i) Sustainability

- Economic issues: this indicator demonstrates operational and maintenance costs of technologies (Xia et al., 2017).
- Environmental issues: this indicator implies the level of technology in environmental concerns, such as carbon emission, energy consumption, etc. (Xia et al., 2017).
- Social issues: this indicator shows the social impacts of technologies, such as their acceptability in society (Xia et al., 2017).

(ii) Resiliency

- Capacity recycle: this indicator shows the ability of technology to efficiently return to its original-normal situation after disruptions (Peng et al., 2021).
- Working autonomy: this indicator relates to the ability of technology to accomplish many operations with or without the human-in-the-loop automatically. It should be noted that working autonomy with human-in-the-loop is much more resilient (Kamarthi and Li, 2020).
- Speed: the ability of technology to be flexible in the system when the disruption occurs (Gu et al., 2015).

(iii) Human-centricity:

- Safety: this indicator demonstrates the capability of employed technology in safety indicators such as welfare and health protection for workers (Breque et al., 2021).
- Training: this indicator implies how much and what level of training a worker needs to adapt their skills to the technology (Breque et al., 2021).
- Collaboration: this indicator shows the capability of technology to collaborate with human beings (workers) (Breque et al., 2021). Collaboration means the ability to interact between the worker and the machine. This indicator demonstrates whether the employed technology involves the workers in the activities, and if so, whether the workers are satisfied with the type of participation in the activity. This indicator is generally related to how the worker communicates and works with the machine. For instance, one technology may involve the worker in performing the activity but leave the heavy and complex part of the work to the worker. On the other hand, another technology involves the worker in performing the activities but the main tasks of workers are easy and reasonable. Rationally, the second technology has a higher score in the collaboration indicator.

3.2. The second stage

Here, the research problem is described and formulated based on a scenario-based programming model. There are two main reasons using the scenario-based programming approach to formulate the research problem: (i) the scenario-based programming approach allows the model to consider various quantities for uncertain parameters through a finite number of scenarios (Jamali et al., 2021), and (ii) there are several studies that applied scenario-based programming to model the SCND problem that have achieved desirable results (see Fattahi et al., 2018; Pedram et al., 2017; Sabouhi et al., 2020a; Sazvar et al., 2021b).

The current study aims at designing a CLSCN in which the forward chain consists of Primary Suppliers (PSs), Backup Suppliers (BSs), plants, Distribution Centers (DCs), Demand Points (DPs), and Online Customers (OC). On the other side, the reverse chain involves Collection Centers (CCs), Recycling Centers (RCs), and disposal centers. The flow of materials and products in the proposed CLSCN are as follows. At the outset, the required raw materials are bought from the suppliers and shipped to the plants. In this part, if a PS loses its capability to provide the raw materials, the BSs are selected to purchase the needed raw materials. Afterwards, the products are manufactured and sent to the DCs to satisfy the demands of the customers. There are two types of customers, the first one is customers that buy the product in the market, and the second one is online customers who order the product using the internet. Inspired by the real world, the company only serves online customers whose distance from distribution centers is less than a predefined value ($Dmax$). Also, the shortage is not allowed for physical demand points, but it is allowed for online customers. In the reverse chain, the EoL/EoU products are collected and shipped to the CCs. In the CCs, the recyclable products are sent to the RCs, and the others are shipped to disposal centers. In the RCs, those materials that have been successfully recycled, are shipped to suppliers (to save raw material costs), and the others are shipped to the disposal center. In addition, in production centers, it is possible to use different production technologies (i.e., automatic machines, 3D printing, etc.). Each of which has its corresponding specification (i.e., setup cost, pollution, training cost, etc.) and are scored based on the I5.0 dimensions. t is also possible to use the IoT in production centers to track/monitor the products for better collection of the EoU and EoL ones. In this regard, although using the IoT has its related costs, it leads to saving in collecting and recycling costs (Subramanian et al., 2020). Moreover, different types of information sharing systems (e.g., the blockchain platform, the traditional system, etc.) can be established in the SCN, each of which has its corresponding setup cost and visibility. In this regard, employing information-sharing systems is one of the strategies that can be so helpful in weakening disruptions (Faisal et al., 2006), which makes trust, reduces risk, and increases visibility. Using information system discloses the supply chain problems and leads to increase resiliency (Mehrjerdi and Shafiee, 2020). In addition, it should be noted that we suppose that when the training of workers is performed, their performance is improved, and subsequently the defect rate reduces. Therefore, since the quantity of the required raw materials is equal to the ratio of the quantity of outputs over the production line efficiency (1-Defect rate) (Francis et al., 1992), by changing the defect rate, the quantity of the required raw material changes, too. Fig. 4 shows the considered CLSCN.

Before formulating the MOPM, the main elements considered to incorporate the I5.0 pillars in this research are described below.

(i) Sustainability is considered by the following elements:

- In this research, one of the considered environmental dimensions is GHG emission. There are two main reasons for this selection: (i) GHG emissions are known as one of the most important environmental factors that different governmental and international organizations have paid attention to Breque et al. (2021), (ii) the mentioned issue is in line with the selected case study of this research.
- Reverse logistics which leads to managing the EoL and EoU products and reducing environmental damages of SC (Garg et al., 2015).
- Inspired by the real world, job opportunity, as a factor of the social dimension, is also taken into account. Creating Job Opportunities (JO) has a critical role in the development of countries. On the other hand, more JOs cause to amplify the rate of local employment, which leads to preventing undesirable migration (Nayeri et al., 2021).
- This study considers the economic aspects based on the supply chain costs, such as establishment costs, production, and distribution costs, transportation costs, IoT costs, etc.
- Scoring the employed technologies based on the sustainability criteria at the first stage.

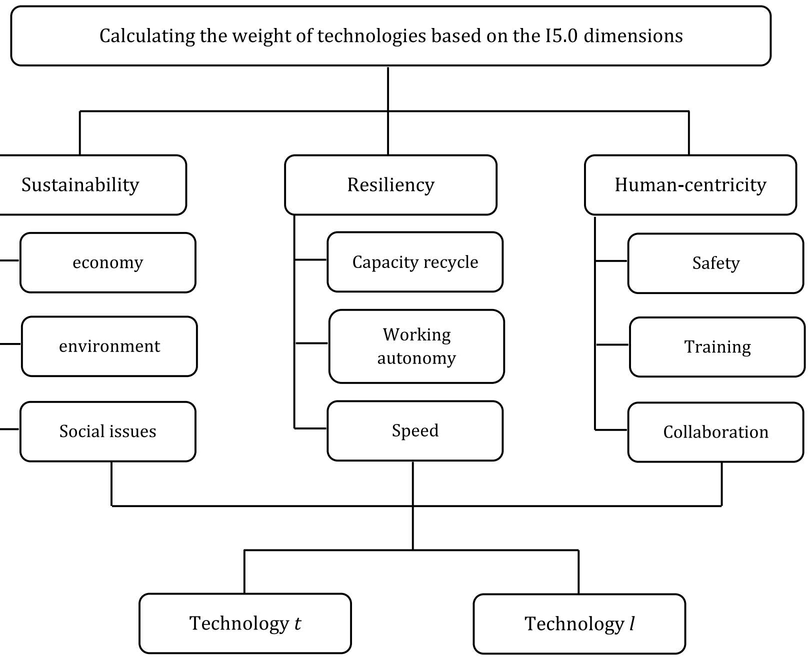


Fig. 3. The decision tree for measuring the score of technologies based on the I5.0 dimensions.

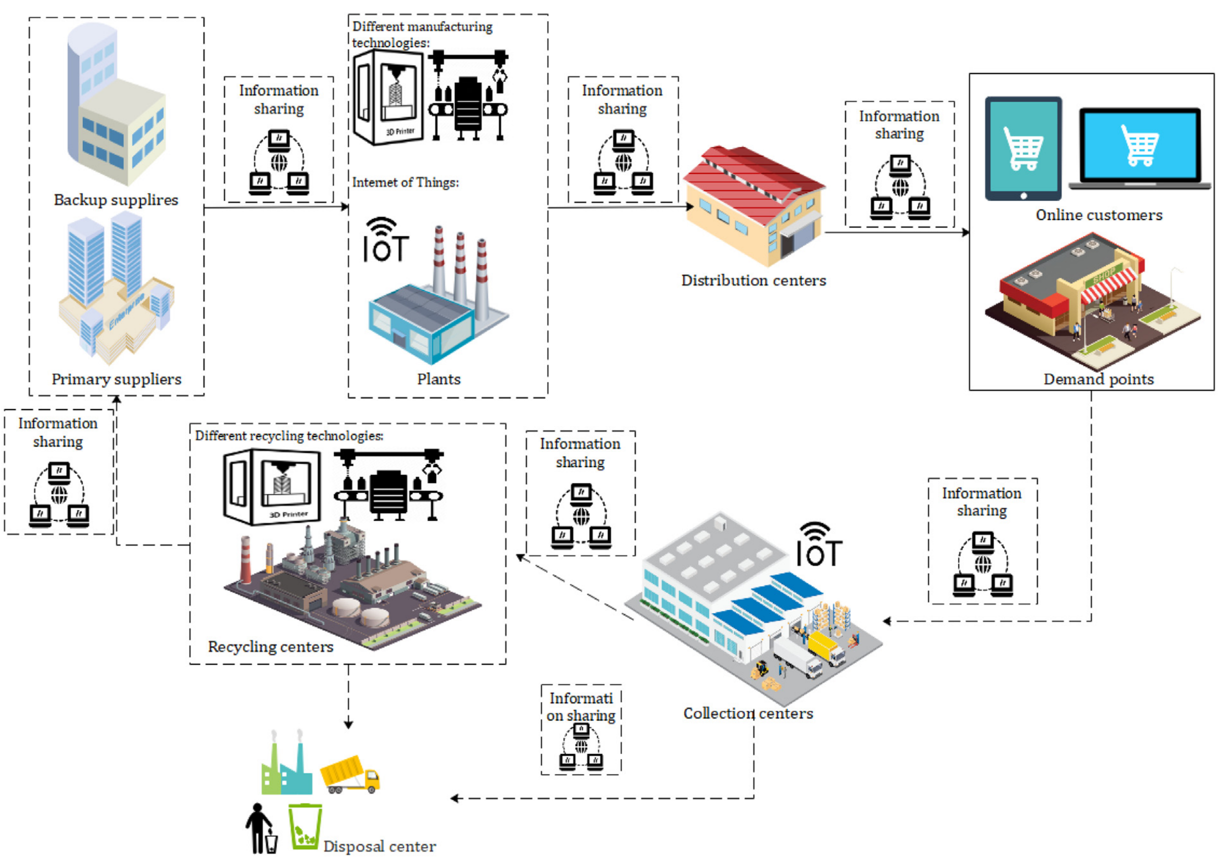


Fig. 4. The proposed CLSCN.

(ii) The resiliency aspect is considered by the following elements:

- Scoring the employed technologies based on the resiliency criteria at the first stage.
- Considering the rate of disrupted capacity (disruption scenarios) (Sabouhi et al., 2020b).
- Considering backup suppliers (Nayeri et al., 2022).
- Minimizing the node complexity that harms the resiliency of SC (Cardoso et al., 2015).
- Using information system in order to improve resiliency of the SCN (Mehrjerdi and Shafiee, 2021).

(iii) The human-centricity aspect is considered by the following elements:

- Training of workers to work with the employed technologies (Breque et al., 2021).
- Fatigue of workers (Ihsan et al., 2020); (Kołodziej and Ligarski, 2017).
- Scoring the employed technologies based on the human-centricity criteria at the first stage.

(iv) I4.0-based features

- Considering technologies such as IoT (for tracking and monitoring the products), and 3D printing (for manufacturing products).
- Establishing the information-sharing systems within SCN.
- Establishing infrastructures for online sales.

Based on the above descriptions, the following notations are defined to establish the proposed scenario-based MOPM:

Indices

i	Index of PSs
j	Index of BSs
m	Index of plants
k	Index of DCs
d	Index of DPs
o	Index of OCs
c	Index of CCs
b	Index of RCs
q	Index of disposal centers
r	Index of raw materials
t	Index of technologies utilized in manufacturing plants
l	Index of technologies utilized in RCs
f	Index of ISSs
s	Index of scenarios

(i) Sustainability parameters

(i-1) Parameters obtained from the first stage

sts_t	The score of manufacturing technology t in terms of sustainability
sls_l	The score of recycling technology l in terms of sustainability

(i-2) Cost-related parameters

FI_i	Contracting cost for PS i
FJ_j	Contracting cost for BS j
FM_{mt}	Fixed Cost of Establishing (FCE) plant k with technology t
FD_k	FCE for distribution center k
FC_c	FCE for collection center c
FR_{bl}	FCE for recycling center b with technology l
VI_{ris}	Cost of buying raw material r from PS i under scenario s
VJ_{rjs}	Cost of buying raw material r from BS j under scenario s
PM_{mts}	Cost of production in plant m with technology t under scenario s
DK_{ks}	Operating cost of DC k under scenario s
CC_{cs}	Operating cost of CC c under scenario s
CR_{bls}	Operating cost of RCs with technology l under scenario s
SHC_s	Cost of shortage under scenario s
SP_{rs}	Sale price for recycled raw material r under scenario s
TC_s	Transportation cost under scenario s

(i-3) Environmental parameters

tp_s	The pollution emitted by transportation activity under scenario s
mp_{ts}	The pollution emitted by manufacturing activity with technology t under scenario s
rp_{ls}	The pollution emitted by recycling activity with technology l under scenario s

(i-4) Social parameters

FJ_e	Fixed Job Opportunities (FJO) created by establishing facility e $(e, \in \{i, j, k, c\})$
FFJ_{mt}	FJO created by opening facility e with technology t $e, \in \{m, b\})$

(ii) Resilient-related parameters

(ii-1) Parameters obtained from the first stage

str_t	Score of manufacturing technology t in terms of resilience criteria
slr_l	Score of recycling technology l in terms of resilience criteria

(ii-2) disruption-related parameters

σ_{es}	Percentage of disrupted capacity for facility e under scenario s $(e, \in \{i, m, k, c, b\})$

(iii) Parameters related to ISS

Γ_{fs}	Percentage of disrupted information for ISS f under scenario s
CIE_f	Cost of establishing the information center for ISS f
CIS_f	Cost of establishing the information security system of ISS f
IEX_s	Percentage of information exchange in the whole SCN under scenario s

(iii) Human-centricity-related parameters

WTC	Cost of training of workers
$\phi 1$	Defect rate if training is performed
$\phi 2$	Defect rate if training is not performed
sth_t	Score of manufacturing technology t in terms of human-centricity criteria
slh_l	Score of recycling technology l in terms of human-centricity criteria

(iv) IoT-related parameters

$CIoT$	Cost for establishing the required systems to implement the IoT
ψ_s	Savings in collection costs under scenario s if the IoT is utilized
ξ_s	Savings in recycling costs under scenario s if the IoT is utilized
αd_{ds}	Return rate of the product for DP d under scenario s if the IoT system is established

$\alpha d'_{ds}$	Return rate of the product for DP d under scenario s if the IoT system is not established
αo_{os}	Return rate of the product for OC o under scenario s if the IoT system is established
$\alpha o'_{os}$	Return rate of the product for OC o under scenario s if the IoT system is not established
$\gamma 1_{ls}$	Percentage of materials that recycled successfully with technology l under scenario s if the IoT system is established
$\gamma 2_{ls}$	Percentage of materials that recycled successfully with technology l under scenario s if the IoT system is not established

(v) Other parameters

Dem_{ds}	Demand of DP d under scenario s
OD_{os}	Demand of OC o under scenario s
$PSCP_{ir}$	Capacity of PS i for raw material r
$BSCP_{jr}$	Capacity of BS j for raw material r
MCP_{mt}	Capacity of plant m with technology t
DCP_k	Capacity of DC k
CCP_c	Capacity of CC c
RCP_{bl}	Capacity of RC b with technology l
$Dis_{ee'}$	Distance between facility e and e' ($e, e' \in \{i, j, m, k, d, o, c, b, q\}$)
$Dmax$	Maximum acceptable distance to serve the online customers
MTW_{mt}	The required time for producing a product in the manufacturing site m with technology t
DTW_k	The required time for distributing a product in the DC k
CTW_c	The required time for collecting a product in the CC c
RTW_{bl}	The required time for recycling a product in the RC b with technology l
$TmaxM_{mt}$	Maximum allowable working time for each worker in plant m with technology t
$TmaxD_k$	Maximum allowable working time for each worker in DC k
$TmaxC_c$	Maximum allowable working time for each worker in CC c
$TmaxR_{bl}$	Maximum allowable working time for each worker in RC b with technology l
ur_r	Utilization rate of raw material r
β_s	Percentage of the product that can be recycled under scenario s
χ_{rs}	Quantity level of raw material r obtained from product recycling under scenario s
ws	Weight of sustainability criteria
wr	Weight of resilience criteria
wh	Weight of human-centricity criteria
sw	Weight of the social impacts
ew	Weight of the environmental impact
vw	Weight of the visibility of SC
nw	Weight of the node complexity
PS_s	Occurrence probability of scenario s

Decision variables

ZS_i	Binary variable that is equal to 1 if PS i is selected
ZB_j	Binary variable that is equal to 1 if BS j is selected
ZP_{mt}	Binary variable that is equal to 1 if plant m is established with technology t
ZD_k	Binary variable that is equal to 1 if DC k is established
ZC_c	Binary variable that is equal to 1 if CC c is established
ZR_{bl}	Binary variable that is equal to 1 if RC b is established with technology l
ZH	Binary variable that is equal to 1 if the training of workers is performed
ZSC_f	Binary variable that is equal to 1 if information security center of ISS f is established
ZI_f	Binary variable that is equal to 1 if ISS f is established
$ZIoT$	Binary variable that is equal to 1 if the required system for IoT is established
XRP_{rims}	Quantity of raw material r sent from PS i to plant m under scenario s
XRB_{rjms}	Quantity of raw material r sent from BS i to plant m under scenario s
XPD_{mtks}	Quantity of product sent from plant m with technology t to DC k under scenario s
XDD_{kds}	Quantity of product sent from DC k to DP d under scenario s
XDO_{kos}	Quantity of product sent from DC c to OC o under scenario s
XDC_{dcs}	Quantity of returned product sent from DP d to CC c under scenario s
XOC_{ocs}	Quantity of returned product sent from OC c to CC c under scenario s
XCR_{cbls}	Quantity of returned product sent from CC c to RC b with technology l under scenario s
XCQ_{cqs}	Quantity of returned product sent from CC c to disposal center q under scenario s
XRS_{rblis}	Quantity of recycled material r sent from RC b with technology l to PS i in scenario s
XRQ_{rblqs}	Quantity of material r sent from RC b with technology l to disposal center q under scenario s
OSH_{os}	Quantity of shortage for OC o under scenario s

MWL_{mt}	Average working time for each worker in the manufacturing site m with technology t
DWL_k	Average working time for each worker in the DC k
CWL_c	Average working time for each worker in the CC c
RWL_{bl}	Average working time for each worker in the RC b with technology l
NC	Node complexity of the SCN
VSI_{fs}	The amount of visibility in the supply chain when ISS f is established under scenario s

Relation (1) aims to minimize the total cost, including the cost of contracting with suppliers, the fixed costs of establishing facilities, the cost of the training, the cost of establishing IoT, the costs of purchasing raw materials, the operating costs of plants, DCs, CCs, and RCs, the cost of shortage, and the costs of the transportation process. The revenue obtained from selling the recycled raw materials has been deducted from the total costs in the last part.

$$
\begin{aligned}
MinZ1 = & \sum_i FI_i.ZS_i + \sum_j FJ_j.ZB_j + \sum_{m,t} FM_{mt}.ZP_{mt} \\
& + \sum_k FD_k.ZD_k + \sum_c FC_c.ZC_c \\
& + \sum_{b,l} FR_{bl}.ZR_{bl} + \sum_f CIE_f.ZI_f \\
& + \sum_f CIS_f.ZSC_f + WTC.ZH + CIoT.ZIoT \\
& + \sum_s PS_s.\Bigg(\sum_{r,i,m} VI_{ris}.XRP_{rims} + \sum_{r,j,m} VJ_{bis}.XRB_{rjms} \\
& + \sum_{m,t,k} PM_{mts}.XPD_{mtks} \\
& + \sum_{d,k,o} DK_{ks}.(XDD_{kds} + XDO_{kos}) \\
& + \sum_{d,c,k,o} (CC_{cs} - \psi_s.ZIoT).(XDC_{dcs} + XOC_{ocs}) \\
& + \sum_{b,l,c} (CR_{bls} - \xi_s.ZIoT).XCR_{cbls} + \sum_o SHC_s.OSH_{os} \\
& + \sum_{r,i,m} TC_s.Dis_{im}.XRP_{rims} \\
& + \sum_{r,j,m} TC_s.Dis_{jm}.XRB_{rjms} + \sum_{k,m,t} TC_s.Dis_{mk}.XPD_{mtks} \\
& + \sum_{k,d} TC_s.Dis_{kd}.XDD_{kds} \\
& + \sum_{k,o} TC_s.Dis_{ko}.XDO_{kos} + \sum_{d,c} TC_s.Dis_{dc}.XDC_{dcs} \\
& + \sum_{o,c} TC_s.Dis_{oc}.XOC_{ocs} \\
& + \sum_{b,c,l} TC_s.Dis_{cb}.XCR_{cbls} + \sum_{q,c} TC_s.Dis_{cq}.XCQ_{cqs} \\
& + \sum_{r,b,i,l} TC_s.Dis_{bi}.XRS_{rblis} \\
& + \sum_{r,b,l,q} TC_s.Dis_{bq}.XRQ_{rblqs} - \sum_{r,b,l,i} SP_{rs}.XRS_{rblis} \Bigg)
\end{aligned} \tag{1}
$$

The second objective function, relation (2), minimizes the total environmental damages and maximizes the positive social impacts (see Box I).

Relation (3) aims to maximize the normalized weighted difference between SC visibility and the node complexity as a resilience index of the SCN.

$$
\begin{aligned}
MinZ3 = & vw.\left(\frac{MaxV - \sum_{f,s} Ps_s.VSI_{fs}}{MaxV - MinV} \right) \\
& + nw.\left(\frac{NC - MinNC}{MaxNC - MinNC} \right)
\end{aligned} \tag{3}
$$

The fourth objective function (4) maximizes the scores of the utilized technologies according to I5.0 pillars.

$$
\begin{aligned}
MaxZ4 = & ws.\left(\sum_{m,t} sts_t.ZP_{mt} \right) + wr.\left(\sum_{m,t} str_t.ZP_{mt} \right) \\
& + wh.\left(\sum_{m,t} sth_t.ZP_{mt} \right) \\
& + ws.\left(\sum_{b,l} sls_l.ZR_{bl} \right) + wr.\left(\sum_{b,l} slr_l.ZR_{bl} \right) \\
& + wh.\left(\sum_{b,l} slh_l.ZR_{bl} \right)
\end{aligned} \tag{4}
$$

Capacity constraints: Relations (5) -(10) show the capacity constraints of the supply chain facilities. Relations (5) and (6) show the capacity constraints for the primary and backup suppliers, respectively. Relations (7) and (8) respectively show the capacity constraint for plants and the DCs. Relations (9) and (10) demonstrate the capacity constraints for CCs and RCs, respectively.

$$\sum_m XRP_{rims} \le \left(1 - \sigma_{is}\right).PSCP_{ir}.ZS_i \qquad \forall r, i, s \tag{5}$$

$$\sum_m XRB_{rjms} \le BSCP_{jr}.ZB_j \qquad \forall r, j, s \tag{6}$$

$$\sum_{k,t} XPD_{mtks} \le \sum_t \left(1 - \sigma_{ms}\right).MCP_{mt}.ZP_{mt} \qquad \forall m, s \tag{7}$$

$$\sum_{o,d} (XDD_{kds} + XDO_{kos}) \le \left(1 - \sigma_{ks}\right).DCP_k.ZD_k \qquad \forall k, s \tag{8}$$

$$\sum_{b,q,l} (XCR_{cbls} + XCQ_{cqs}) \le \left(1 - \sigma_{cs}\right).CCP_c.ZC_c \qquad \forall c, s \tag{9}$$

$$\sum_{b,q,r,i} (XRS_{rblis} + XRQ_{rblqs}) \le \sum_l \left(1 - \sigma_{bs}\right).RCP_{bl}.ZR_{bl} \qquad \forall b, s \tag{10}$$

Constraints related to human-centricity aspect:

Relation (11) is associated with the training of workers. In this regard, Constraint (11) calculates the quantity of the purchased RMs from the PSs or BSs. In this constraint, the quantity of purchased raw materials depends on the training of workers through coefficients $\phi 1$ and $\phi 2$.

$$
\begin{aligned}
& \left(\sum_i XRP_{rims} + \sum_j XRB_{rjms} \right).((1 - \phi 1).ZH + (1 - \phi 2).(1 - ZH)) \\
& = \sum_{k,t} ur_r.XPD_{mtks} \qquad \forall r, m, s
\end{aligned} \tag{11}
$$

On the other hand, constraints (12)–(19) are related to workers' fatigue. In this regard, as Ihsan et al. (2020) and Kołodziej and Ligarski (2017) mentioned, the fatigue effect is one of the most important indicators of the workers' health issues, which directly depends on the workload and working time of a worker. To incorporate this issue in the research problem, we have first calculated the average working time of each worker in each facility in relations (12)–(15). For example, for the manufacturing sites, the average working time of each worker have calculated based on the ratio of average total working time over the number of available workers. Then, to prevent excessive fatigue of workers in a facility, the value of the average working time of each worker should be smaller than a predefined value.

$$MWL_{mt} = \frac{\sum_{k,s} Ps_s.MTW_{mt}.XPD_{mtks}}{MFJ_{mt}} \qquad \forall m, t \tag{12}$$

$$
\begin{aligned}
&MinZ2\\
&= ew.\Bigg(\Bigg(\sum_{s} PS_s.\Bigg(\sum_{m,t,k} mp_{ts}.XPD_{mtks} + \sum_{b,l,c} rp_{ls}.XCR_{cbls}\\
&+ tp_s.\Bigg(\sum_{r,i,m} Dis_{im}.XRP_{rims} + \sum_{r,j,m} Dis_{jm}.XRB_{rjms} + \sum_{k,m,t} Dis_{mk}.XPD_{mtks} + \sum_{k,d} Dis_{kd}.XDD_{kds}\\
&+ \sum_{k,o} Dis_{ko}.XDO_{kos} + \sum_{d,c} Dis_{dc}.XDC_{dcs} + \sum_{o,c} Dis_{oc}.XOC_{ocs} + \sum_{b,c,l} Dis_{cb}.XCR_{cbls} + \sum_{q,c} Dis_{cq}.XCQ_{cqs}\\
&+ \sum_{r,b,l,i} Dis_{bi}.XRS_{rblis} + \sum_{r,b,l,q} Dis_{bq}.XRQ_{rblqs}\Bigg)\Bigg) - MinEi\Bigg)/(MaxEi - MinEi)\Bigg)\\
&+ sw.\left(\frac{MaxSoc - \sum_i IFJ_i.ZS_i + \sum_j JFJ_j.ZB_j + \sum_{m,t} MFJ_{mt}.ZP_{mt} + \sum_k KFJ_j.ZD_k + \sum_c CFJ_c.ZC_c + \sum_{b,l} RFJ_{bl}.ZR_{bl}}{MaxSoc - MinSoc}\right)
\end{aligned}
\tag{2}
$$

Box I.

$$DWL_k = \frac{\sum_{d,o,s} Ps_s.DTW_k.(XDD_{kds} + XDO_{kos})}{KFJ_j} \quad \forall k \tag{13}$$

$$CWL_c = \frac{\sum_{d,o,s} Ps_s.CTW_c.(XDC_{dcs} + XOC_{ocs})}{CFJ_c} \quad \forall c \tag{14}$$

$$RWL_{bl} = \frac{\sum_{k,s} RTW_{bl}.XRS_{rblis}}{RFJ_{bl}} \quad \forall b,l \tag{15}$$

$$MWL_{mt} \le TmaxM_{mt} \quad \forall m,t \tag{16}$$

$$DWL_k \le TmaxD_k \quad \forall k \tag{17}$$

$$CWL_c \le TmaxC_c \quad \forall c \tag{18}$$

$$RWL_{bl} \le TmaxR_{bl} \quad \forall b,l \tag{19}$$

Constraints related to IoT: Constraints (20) and (21) respectively calculate the amount of the products returned from offline and online customers to the CCs according to whether IoT is established or not. Constraint (22) calculates the amount of the materials sent from the RCs to the PSs. Eq. (23) shows the quantity of the materials sent from the RCs to the disposal center. In constraints (22) and (23), the impact of IoT is embedded.

$$\sum_c XDC_{dcs} = (\alpha d_{ds}.ZIoT + \alpha d'_{ds}.(1 - ZIoT)).Dem_{ds} \quad \forall d,s \tag{20}$$

$$\sum_c XOC_{ocs} = (\alpha o_{os}.ZIoT + \alpha o'_{os}.(1 - ZIoT)).\sum_k XDO_{kos} \quad \forall o,s \tag{21}$$

$$\sum_i XRS_{rblis} = \sum_c (\gamma 1_{ls}.ZIoT + \gamma 2_{ls}.(1 - ZIoT)).\chi_{rs}.XCR_{cbls} \quad \forall b,l,r,s \tag{22}$$

$$\sum_q XRQ_{rblqs} = \sum_c \left(1 - (\gamma 1_{ls}.ZIoT + \gamma 2_{ls}.(1 - ZIoT))\right) \times \chi_{rs}.XCR_{cbls} \quad \forall b,r,l,s \tag{23}$$

Other flow balance constraints:

Relation (24) shows the amount of product shipped from the plants to the DCs. Constraint (25) calculates the amount of product sent from the DCs to the demand points. Eq. (26) calculates the amount of product shipped to the online customers and the shortage amount. Constraint (27) guarantees that the DCs send the product to an online customer only if it has been located within the maximum considered distance. Constraint (28) demonstrates each plant can only be established by one technology.

$$\sum_{m,t} XPD_{mtks} = \sum_d XDD_{kds} + \sum_o XDO_{kos} \quad \forall k,s \tag{24}$$

$$\sum_k XDD_{kds} = Dem_{ds} \quad \forall d,s \tag{25}$$

$$\sum_k XDO_{kos} + OSH_{os} = OD_{os} \quad \forall o,s \tag{26}$$

$$XDO_{kos} \le BigM.\max\{0, \frac{Dmax - Dis_{ko}}{Dmax}\} \quad \forall k,o,s \tag{27}$$

$$\sum_t ZP_{mt} \le 1 \quad \forall m \tag{28}$$

Relation (29) determines the amount of product shipped from the CCs to the RCs. Constraint (30) shows the amount of product sent from the CCs to the disposal center. Constraint (31) indicates that each RC can be established by only one technology.

$$\sum_{l,b} XCR_{cbls} = \sum_{o,d} \beta_s.(XDC_{dcs} + XOC_{ocs}) \quad \forall s,c \tag{29}$$

$$\sum_q XCQ_{cqs} = \sum_{d,o} (1 - \beta_s).(XDC_{dcs} + XOC_{ocs}) \quad \forall c,s \tag{30}$$

$$\sum_l ZR_{bl} \le 1 \quad \forall b \tag{31}$$

Constraints related to ISS: The visibility of the information shared through an ISS is shown in relation (32). Constraint (33) shows that a sharing system can only be established if its security system is established. Relation (34) guarantees the implementation of the ISS. Also, Eq. (35) shows the establishment of the information security system. See Mehrjerdi and Shafiee (2020) to read more about these constraints.

$$VSI_{fs} = \left(1 - \Gamma_{fs}\right).IEX_s.ZI_f \quad \forall f,s \tag{32}$$

$$ZI_f \le ZSC_f \quad \forall f \tag{33}$$

$$\sum_f ZI_f = 1 \tag{34}$$

$$\sum_f ZSC_f = 1 \tag{35}$$

Node complexity constraints:

Relation (36) measures the node complexity of the total number of established facilities (the number of nodes in the network) that harms the SC resiliency (Cardoso et al., 2015).

$$NC = \sum_i ZS_i + \sum_j ZB_j + \sum_{m,t} ZP_{mt} + \sum_k ZD_k + \sum_c ZC_c + \sum_{b,l} ZR_{bl} \quad \forall f \tag{36}$$

The proposed model is a non-linear one due to relations (1), (11), and (21)-(23). Since the non-linear models have some complexity to solve and need more CPU time, the suggested MOPM is converted to a linear one with the help of some operations research techniques (see Supplementary Materials-Part A).

4. Solution method

Goal Programming (GP) is an efficient method to solve the MOPMs (Aalaei and Davoudpour, 2016; Asadi et al., 2022). There are different versions of GP, such as multi-choice GP, Archimedean GP, etc. One of the efficient variants of GP is Lexicographic Archimedean-Chebyshev GP (LACGP). The main advantage of this method is providing a good compromise between the opposite views of optimizing equity and efficiency regarding the achievements of the targets (Arenas-Parra et al., 2010; Romero, 2001). Consequently, the Archimedean solution provides maximum efficiency (the maximum aggregate achievement), the Chebyshev option provides maximum equity (the most balanced solution between achievements of different goals), and the lexicographic term creates a balance between these parts (Romero, 2001). The formulation of the LACGP method is as follows.

$$\begin{aligned}
&Lex\min\left\{\tau_1.D + \left(1-\tau_1\right).\left(w_1.\left(d_1^+ + d_1^-\right)\right), \ldots, \tau_j.D \right.\\
&\qquad + \left(1-\tau_j\right).\left(w_j.\left(d_j^+ + d_j^-\right)\right), \ldots, \tau_Q.D\\
&\qquad \left. + \left(1-\tau_Q\right).\left(w_Q.\left(d_Q^+ + d_Q^-\right)\right)\right\}\\
&w_j.\left(d_j^+ + d_j^-\right) \le D \qquad j \in 1,\ldots,Q\\
&F_j(x) - d_j^+ + d_j^- = G_j \qquad j \in 1,\ldots,Q\\
&h(x) \le=\ge b
\end{aligned} \tag{37}$$

where $F_j(x)$ is the mathematical expression of jth objective function (OF), G_j demonstrates the desired goal (target) for jth objective function, d_j^+ and d_j^- respectively show positive and negative deviation of the jth OF from its goal (target), w_j represents the weight (importance) of the jth objective function, τ_j is the weight (importance) of the unwanted deviation type (Archimedean and Chebyshev), and D denotes the maximum deviation. It should be noted that "$h(x) \le=\ge b$" shows the system's constraint sets, and Q is the number of OFs. For more information, see (Romero, 2001).

Besides its merits, the LACGP method has some drawbacks. For example, it only considers one value, as a goal, for each OF. However, since the business environment is along with imprecision/uncertainty, Decision-Makers (DMs) would rather determine several goals for each OF (Nayeri et al., 2020). Also, the traditional lexicographic method supposes that the attribute values are always certain, and this method is a bit inflexible (Liu and Chi, 1995; Nunkaew and Phruksaphanrat, 2014). On the other hand, previous fuzzy multi-choice GP methods have the function of binary serial numbers (S(B)) (see Bankian-Tabrizi et al. (2012), Hocine et al. (2020)). This function leads to a drastic increase in the complexity of the method (Chang, 2008; Jadidi et al., 2015). In this regard, to eliminate the mentioned drawbacks and improve the traditional LACGP, the current research aims to develop a new version of GP, namely the Fuzzy Lexicographic Multi-Choice Archimedean-Chebyshev GP (FLMCACGP) method. The main advantages of this method are as follows.

- Since this method is a multi-choice one, it considers multiple targets for each OF, allowing DMs to tackle uncertainty/imprecision of the market space (Jadidi et al., 2015).
- Unlike the previous fuzzy multi-choice GP methods (see Bankian-Tabrizi et al. (2012), Hocine et al. (2020)), the proposed method does not use a function of binary serial numbers ($S(B)$), which can considerably decrease the complexity of the model and the CPU time (Chang, 2008; Jadidi et al., 2015). In this regard, for a problem with n goals and each goal with m aspiration levels, $S(B)$ leads to generating $n\left\lceil \frac{\ln m}{\ln 2}\right\rceil$ extra binary variables in the model (Chang, 2008). Hence, the proposed method in the current study has less complexity.
- Since the proposed method is a lexicographic Archimedean and Chebyshev one, it creates a proper compromise among efficiency and equity terms for goals (Arenas-Parra et al., 2010; Romero, 2001).
- Since the proposed method considers fuzzy lexicographic, its flexibility is increased. Also, it makes the drawbacks of the traditional LACGP fixed (Liu and Chi, 1995; Nunkaew and Phruksaphanrat, 2014).

According to the above discussions, the developed FLMCACGP can be formulated as follows. Where λ_j demonstrates the achievement degree of objective j, y_j denotes a continuous variable, MED_j is the maximum expected deviation for jth OF determined by DM, $Umin_j$ and $Umax_j$ show the range of jth aspiration level, and e_j^- and e_j^+ respectively represent the positive and negative deviations of y_j from $Umin_j$ (for minimization objective functions). It should be noted that PIS_j and NIS_j respectively are the positive and negative ideal solutions for objective function j that are incorporated in the model for normalizing the FLMCACGP objective function.

$$\begin{aligned}
&Lex\max\left\{\lambda_1 - w_1.\left(\frac{e_1^+ + e_1^-}{PIS_1 - NIS_1}\right), \ldots, \lambda_j \right.\\
&\qquad - w_j.\left(\frac{e_j^+ + e_j^-}{PIS_j - NIS_j}\right), \ldots, \lambda_Q\\
&\qquad \left. - w_Q.\left(\frac{e_Q^+ + e_Q^-}{PIS_Q - NIS_Q}\right)\right\}\\
&\lambda_j \le 1 - \frac{\tau_j.D + \left(1-\tau_j\right).\left(w_j.\left(d_j^+ + d_j^-\right)\right)}{MED_j} \qquad j \in 1,\ldots,Q\\
&F_j(x) - d_j^+ + d_j^- = y_j \qquad j \in 1,\ldots,Q\\
&w_j.\left(d_j^+ + d_j^-\right) \le D \qquad j \in 1,\ldots,Q\\
&y_j - e_j^+ + e_j^- = Umin_j \qquad j \in 1,\ldots,Q\\
&Umin_j \le y_j \le Umax_j \qquad j \in 1,\ldots,Q\\
&h(x) \le=\ge b
\end{aligned} \tag{38}$$

It should be noted that the values of the parameters of the solution method are selected based on the following approach.

- The value of w_j, which demonstrates the importance (weight) of the jth objective function, was selected based on the experts' opinions.
- The value of τ_j, which shows the importance (weight) of the unwanted deviation type (Archimedean and Chebyshev), was selected based on the literature.
- For the minimization (maximization) objective functions, the value of PIS_j was calculated by solving a sub-problem to minimize (maximize) jth objective function.
- For the minimization (maximization) objective functions, the value of NIS_1 was calculated by solving a sub-problem to maximize (minimize) jth objective function.

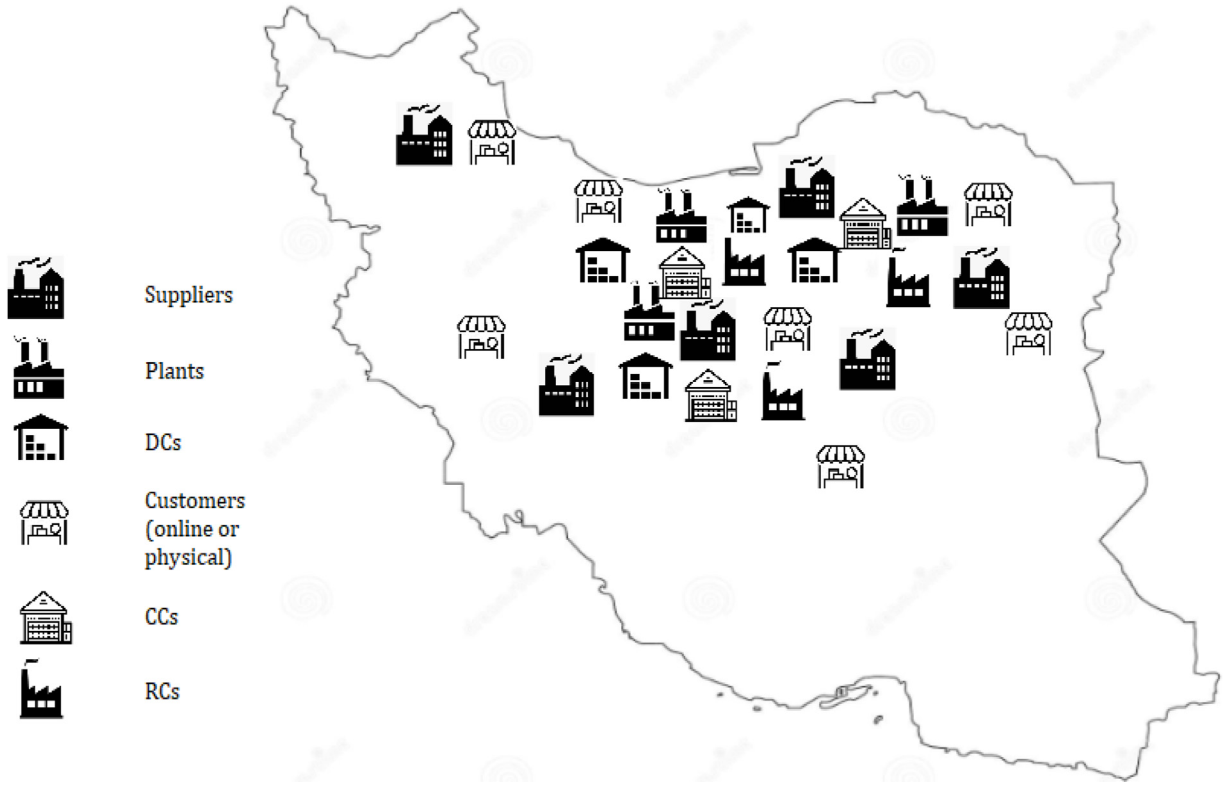


Fig. 5. The SCN of the selected case study.

Table 2
Profiles of respondents.

	Country	Position	Working year	Education level
The leader of group 1	Iran	IT Manager	9 years	MSc. in Information technology management
The leader of group 2	Iran	Logistics Manager	7 years	PhD. in industrial and system engineering
The leader of group 3	Iran	CEO	15 years	MSc. in industrial management

5. Computational results

5.1. Case study

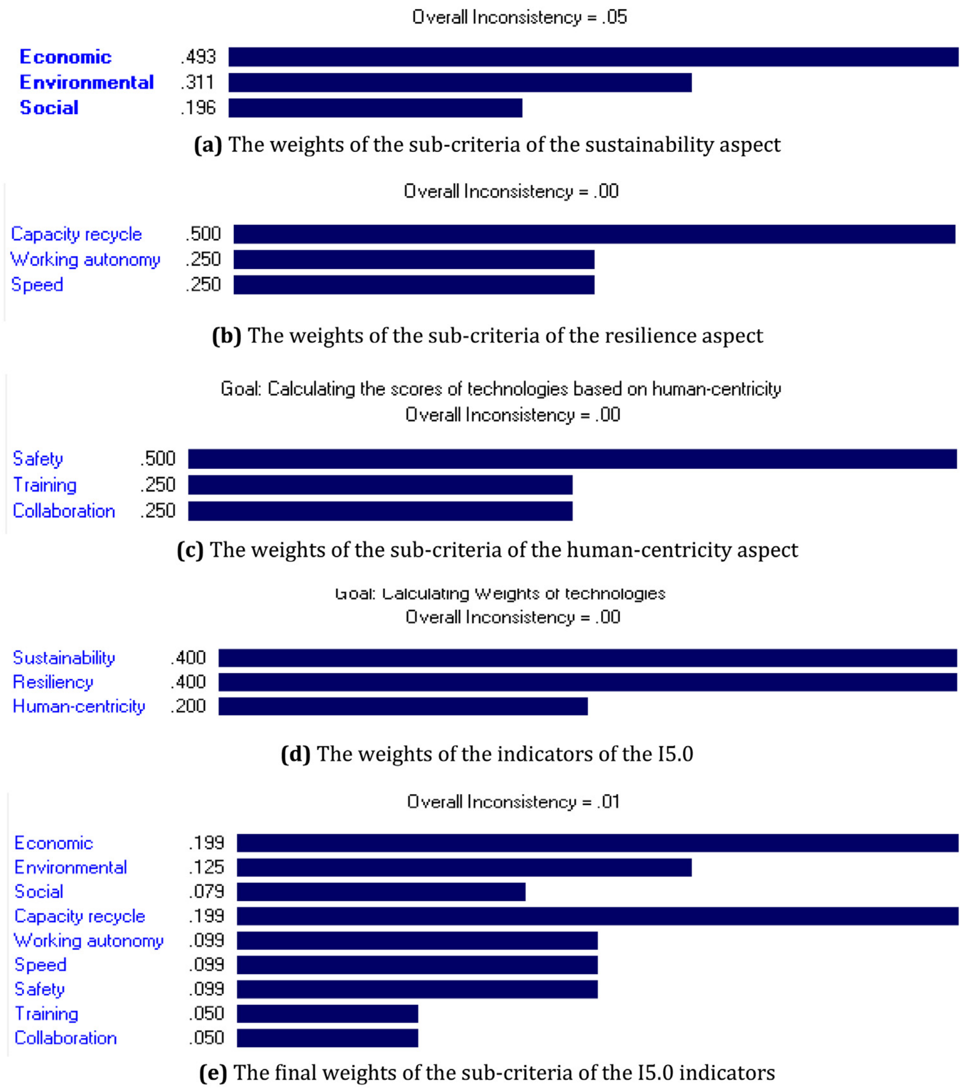
The Coronavirus disease outbreak has led to a drastic disruption all over the world. After months of trying, researchers succeeded in developing a corona vaccine that has significantly reduced mortality. One of the highly demanding products during the vaccination is the vaccine refrigerator. Therefore, in this research, we select the mentioned product as a case study, and one of the prestigious companies in the medical devices industry in Iran, "*Ebtekar Tajhiz Teb*" is chosen. This company has been located in Mazandaran province and produces various medical devices such as the vaccine refrigerator. It is a knowledge-based company under the supervision of the Ministry of Health of Iran.

In addition to increasing the demand for the vaccine refrigerators, the recent pandemic has led to some challenges such as dealing with disruptions for the case company. On the other hand, industrial futurology is in line with the company's policies to achieve a competitive advantage. Therefore, the senior managers are interested in implementing the pillars of the I5.0 in this company. Fig. 5 shows the SCN of the selected case study. In the current work, three scenarios (i.e., the most optimistic, the most possible, and the most pessimistic) are considered, which were widely utilized in the previous papers (see Fathollahi-Fard et al. (2020), Nayeri et al. (2021), Paydar et al. (2017), Pedram et al. (2017)). In this company, three technologies, namely 3D printing, fully-automatic machines, and semi-automatic machines, are candidates for the plants and RCs. Also, two types of information sharing systems are considered: (i) the information system using blockchain technology and (ii) the traditional system (client–server systems). It should be noted that the first type (blockchain platform) has more security, greater transparency, and higher accessibility, but it costs more setting up rather than the traditional one (Hou, 2017); (Ølnes et al., 2017). The other input data as well as more information about the case study, are given in the Supplementary Materials Part-B. In the current research, some of the parameters, such as demand, cost-related parameters, size of the problem, capacities, utilization rate of raw materials, etc., were estimated based on the expert's opinion of the selected company (*Ebtekar Tajhiz Teb*). On the other hand, some parameters, such as GHG emissions, the number of job opportunities, the percentage of disrupted capacity, etc., were estimated based on the literature. Moreover, for the environmental impacts, Life cycle assessment (LCA) is employed.

5.2. Numerical results

5.2.1. Results of the first stage

In this section, the obtained results from the AHP method are presented. The related data (the pair-wise comparison vectors) have been gathered from three groups of experts, and the profile of the leader of each group has been presented in Table 2. Also, the AHP method is implemented in the Expert Choice software. Figs. 6 and 7 illustrate the outputs of the first stage. Based on Fig. 6, the sustainability and resiliency indicators are the most important criteria, and human-centricity is placed in the third position. Among the sustainability sub-criteria, the economic aspect is the most important one. On the other side, capacity recycling is the most important indicator among



(a) The weights of the sub-criteria of the sustainability aspect

(b) The weights of the sub-criteria of the resilience aspect

(c) The weights of the sub-criteria of the human-centricity aspect

(d) The weights of the indicators of the I5.0

(e) The final weights of the sub-criteria of the I5.0 indicators

Fig. 6. The weights of the indicators.

the resiliency sub-criteria. Also, regarding human-centricity criteria, safety is the most significant sub-criteria. Fig. 7 shows the score of each technology based on each criterion.

5.2.2. Results of the second stage

At the second stage, the proposed MOPM is formulated and implemented in the LINGO software in an Intel Core i7 PC with RAM 8. According to the experts' opinions, the weights of OFs are considered $w_1 = 0.35, w_2 = 0.2, w_3 = 0.2,$ and $w_4 = 0.25$. Solving the problem needs several steps. At the outset, several sub-problems must be solved to calculate the parameters of the solving method, such as $Umin_j$ and $Umax_j$. Then, the final model (FLMCACGP model) should be solved to achieve the results. Fig. 8 shows the obtained results step-by-step. It should be noted that the cost parameters and the first objective function currency is Rial, which is the local currency of Iran (1$ = 250000 Rial). Based on the obtained results, primary suppliers 1, 2, 4 & 6, and backup supplier 2 are selected. Furthermore, plant 1 with technology 2 (fully-automatic machine) and plant 2 with technology 1 (3D printing) are established. On the other side, DCs 1, 2, and 3 are opened, and both RCs 1 & 2 are established with technology 2. The results demonstrate that the binary variable related to the training of workers is equal to one ($ZH = 1$). Eventually, an information sharing system using blockchain technology is selected, and the IoT system is also established.

5.3. Sensitivity analysis

This section is dedicated to conducting sensitivity analysis. It should be noted that sensitivity analyses on the demand and disruption rate have been reported in the Supplementary Materials (Part-C).

5.3.1. Advantages of the IoT

This section is dedicated to investigating the impact of the IoT system on the research problem. For this purpose, the research problem is solved in two different ways: (1) the IoT system is established, and (2) the IoT system is not established. Since the IoT system affects the collection and recycling rates and costs, we analyze the difference between the total costs, revenue from selling recycled materials to suppliers, collection costs, and recycling costs in the mentioned modes. Fig. 9 shows the obtained results. Based on this figure, the IoT system has a significant impact on saving the costs in the logistics processes. In this regard, when the IoT system has established, the total costs, collection costs, and recycling costs decreased. On the other side, establishing the IoT system has increased the revenue from selling recycled materials to suppliers because IoT increases the rate of successful material recycling by timely identification of EoL and EoU products. Using an IoT system has resulted in about a 3% decrease in costs and about a 30% increase in revenue from selling recycled materials to suppliers. This behavior

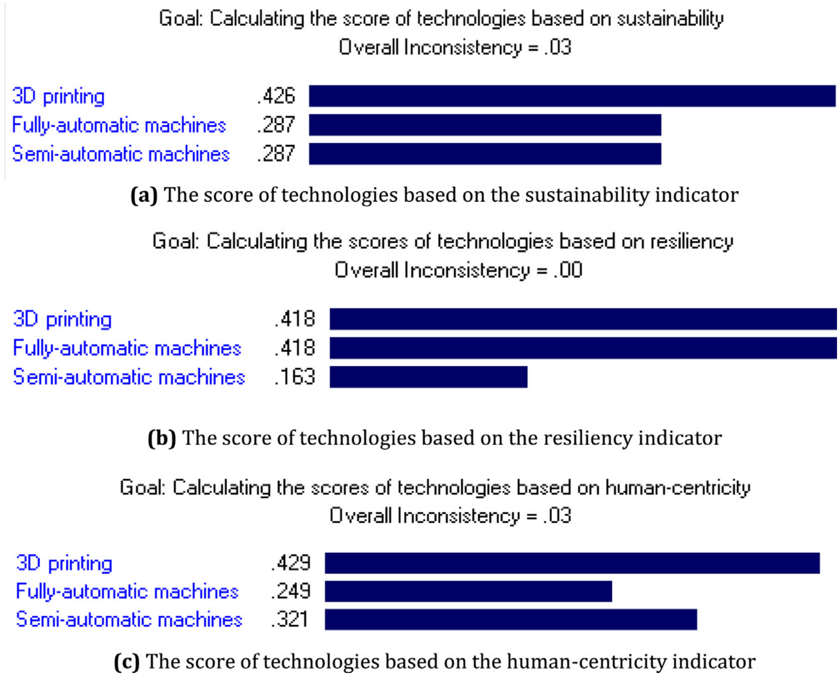


Fig. 7. The scores of the technologies based on each criterion.

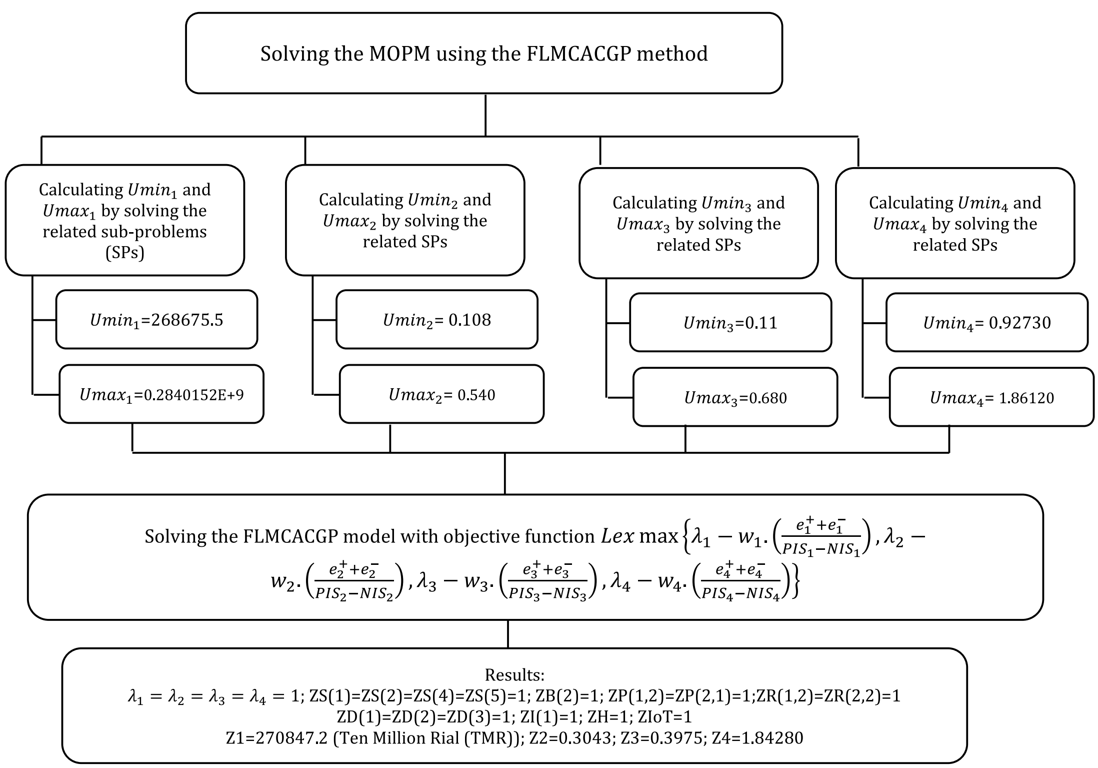
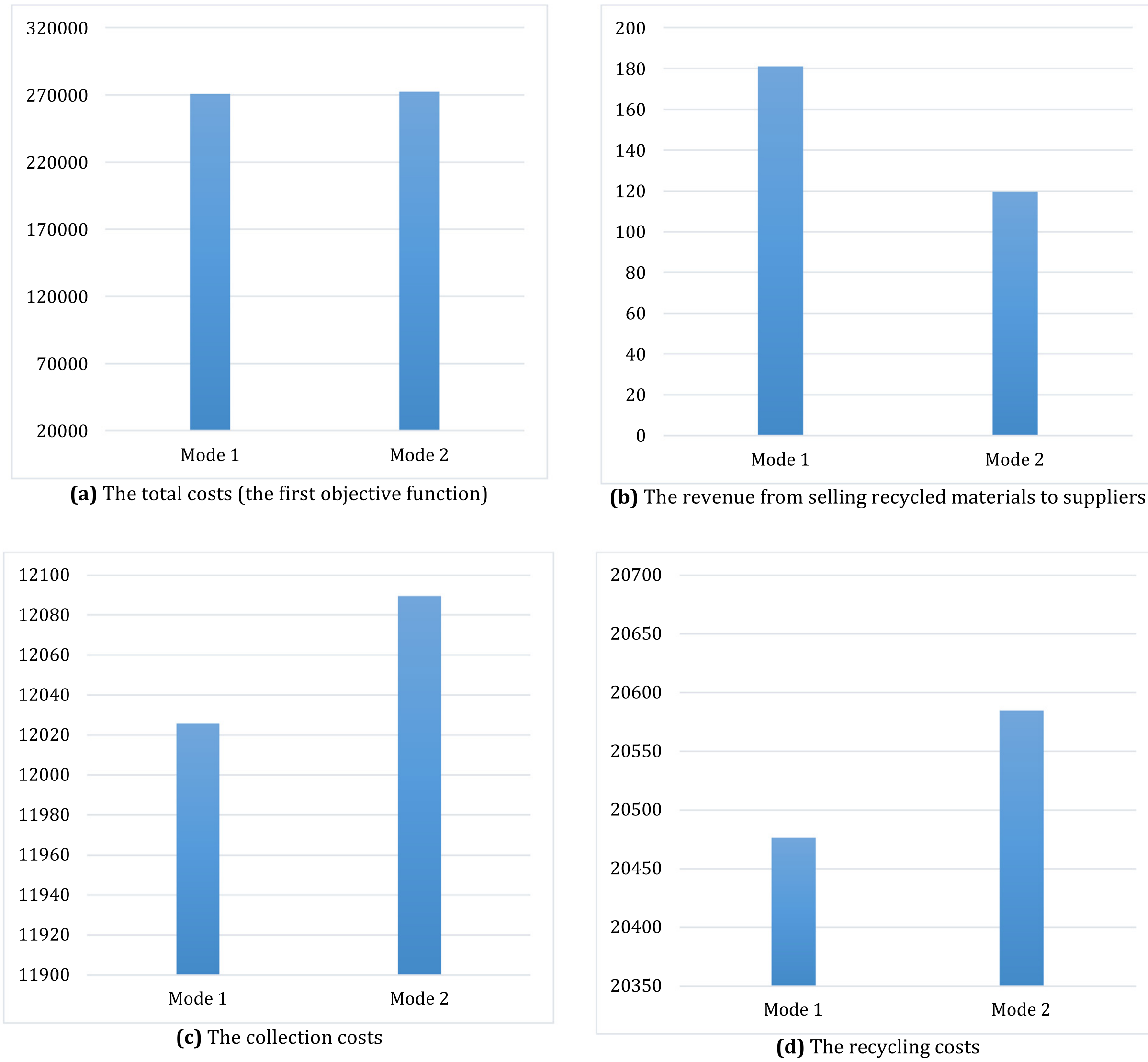


Fig. 8. The achieved results from the second stage of the research problem.

is observed because the establishment of the IoT system can save collection and recycling costs based on ψ_s and $\xi_s$parameters, and also let to increase the rate of successful material recycling (see parameter $\gamma 1_{Is}$).

5.3.2. *Advantages of training workers*

In this section, we demonstrate the role of training workers as an indicator of the human-centricity aspect of the problem. As defined and formulated in the proposed model, the training of workers influences the defect rate. It means if the training is performed, the defect rates are lower, and thus fewer raw materials need to purchase (see constraint (11)). Hence, in this section, we compare the purchasing costs of the logistics system in two different modes: (i) with training workers and (ii) without training workers. As shown in Fig. 10, training significantly impacts the purchasing cost and, consequently, the total cost. In this regard, the training of workers has led to an 18% decrease in purchasing



(a) The total costs (the first objective function)

(b) The revenue from selling recycled materials to suppliers

(c) The collection costs

(d) The recycling costs

Fig. 9. Analyzing the impact of the IoT system.

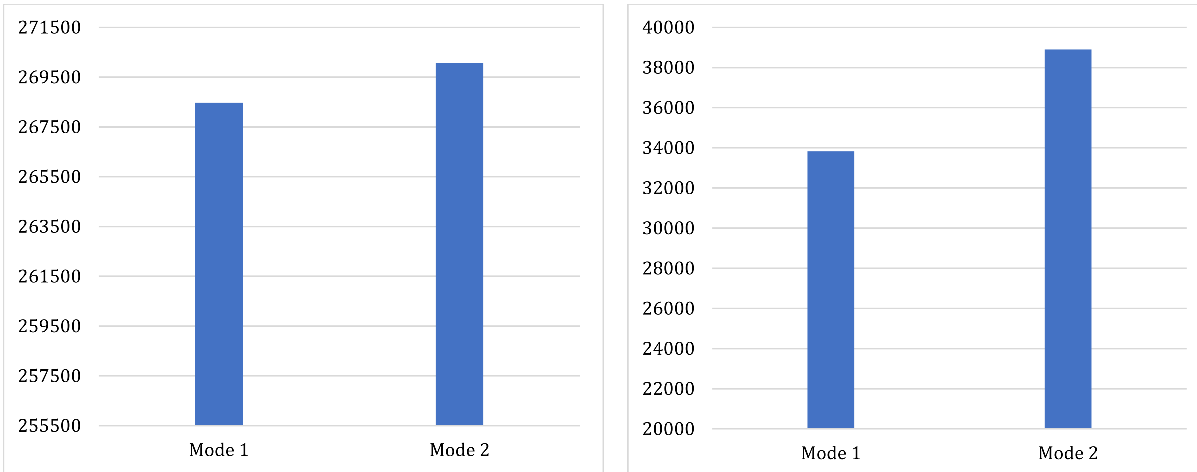
costs. This point shows that although the training may seem like an unnecessary cost at first glance, it can significantly save the system's total costs.

5.3.3. Sensitivity analysis on the first stage

This section is dedicated to conducting the sensitivity analysis for the first stage. For this purpose, we examine the rank of each technology in three different modes. These modes are as follows: Mode 1: ($Ws = 0.8, Wr = 0.1, Wh = 0.1$), Mode 2: ($Ws = 0.1, Wr = 0.8, Wh = 0.1$), and Mode 3: ($Ws = 0.1, Wr = 0.1, Wh = 0.8$), where Ws, Wr, and Wh show the weights of the sustainability, resiliency, and human-centricity aspects, respectively. Fig. 11 depicts the results. According to this figure, 3D printing technology has the best score in all modes. However, when the importance of the resilience indicator increases, the fully automatic machine outperforms the semi-automatic one. On the other side, by increasing the importance of the human-centricity aspect, the score of the semi-automatic machine becomes better than the fully automatic machine.

5.3.4. Change in weight of goals

This section tries to investigate the influence of the weights of the OFs on the results. To this end, five different modes are examined, and the results are reported in Table 3. This table shows the impact of changing the weights of the OFs in the decision variables. Table 3 demonstrates the impact of changing the weights of the OFs in their values. Based on the achieved results (Table 3), In the first mode in which the weight of Z1 (the total cost) is significantly higher than others, the model only employs the semi-automatic machine for the plants and RCs. Also, in this mode, the model prefers to utilize the traditional information sharing system rather than the blockchain platform due to its lower setup cost. In mode 2, which considers the second OF as the most important goal, the model prefers to employ only 3D printing technology for the manufacturing sites and RCs. On the other side, in this mode, the traditional information system is implemented. In mode 3 in which the weight of the third OF is significantly higher than others, the fully automatic machine is employed for the production center, the semi-automatic machine is utilized for the RCs, and the blockchain platform is applied for information sharing. In mode 4, which considers the fourth OF as the most important goal, the model prefers to use only 3D printing technology for the plants and RCs. On the other hand, the model employs the blockchain platform for information sharing. It should be noted that mode 5 is the base case that its results have been provided previously. The outputs show that when the traditional SC in which the cost objective is the most important goal shift to an



(a) The total costs **(b)** The purchasing costs

Fig. 10. Analyzing the impact of the training of workers.

Table 3
The impact of the weights of the goals on the decision variables.

Mode	Weights				Production center			Recycling center			Information-sharing system	
	$w1$	$w2$	$w3$	$w4$	3D printing	Fully-automatic	Semi-automatic	3D printing	Fully-automatic	Semi-automatic	Blockchain platform	Traditional system
1	0.7	0.1	0.1	0.1			✓			✓		✓
2	0.1	0.7	0.1	0.1	✓			✓				✓
3	0.1	0.1	0.7	0.1		✓				✓	✓	
4	0.1	0.1	0.1	0.7	✓			✓			✓	
5 (base case)	0.35	0.2	0.2	0.25	✓	✓			✓		✓	

SC 5.0 in which different dimensions (i.e., sustainability, resiliency, and human-centricity) are considered, the model prefers to employ new technologies such as 3D printing and blockchain.

5.3.5. Impact of information-sharing technology

In this section, the impact of different information-sharing technologies on the problem has been examined. In this way, the model is solved in two different modes: (i) considering the traditional information-sharing systems and (ii) considering the blockchain platform. It should be noted that for better analysis, the results are investigated in three different scenarios. Fig. 12 illustrates the achieved results. As can be seen in this figure, although using the blockchain platform leads to more costs, it results in a significant increase in the visibility of the SC. In this regard, managers should be aware that increasing the visibility of the SC can be a powerful tool for weakening disruptions and preventing huge losses. So, they can assign enough budget to establish the appropriate information-sharing system within their SCs.

5.3.6. Impact of the maximum allowable working time

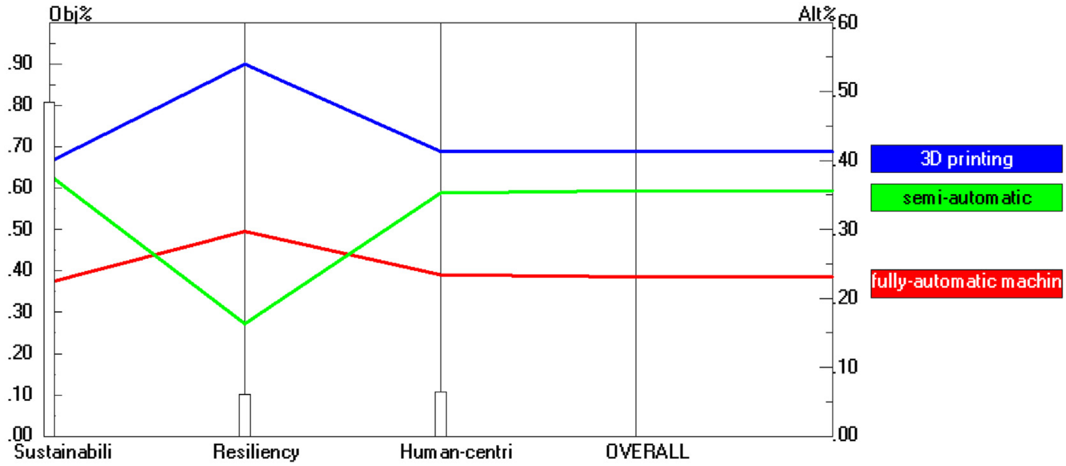
This section investigates the impact of the parameters related to the workers' fatigue on the outputs. For this purpose, by considering different values for the maximum allowable working time parameter, the model has been solved. Fig. 13 shows the number of needed workers based on different values for the maximum allowable working time parameter to prevent increasing the total cost. In this regard, we have fixed the total cost equal to its optimum value and calculated the number of needed workers in different situations (various values for the parameter Tmax). As shown in Fig. 13, by increasing the value of the maximum allowable working time parameter, fewer workers are needed. Although needing fewer workers means fewer costs, managers should know that this is not a good strategy for two major reasons. The first reason relates to the social and human-centricity aspects. When customers see the company has a weak performance in the mentioned aspects by creating fewer job opportunities and ignoring the workers' health issues, their tendency for buying the company's products reduces, and subsequently the market share of the company decreases in long term. On the other side, the second reason relates to the performance of workers. Logically, when the workload of workers is too much, their fatigue increases. This issue leads to an increase in mistakes and a decrease in their efficiency. Undoubtedly, the mentioned points lead to increasing the operational costs of the SC and subsequently decreasing the total profits.

5.4. Advantages of the proposed stochastic model

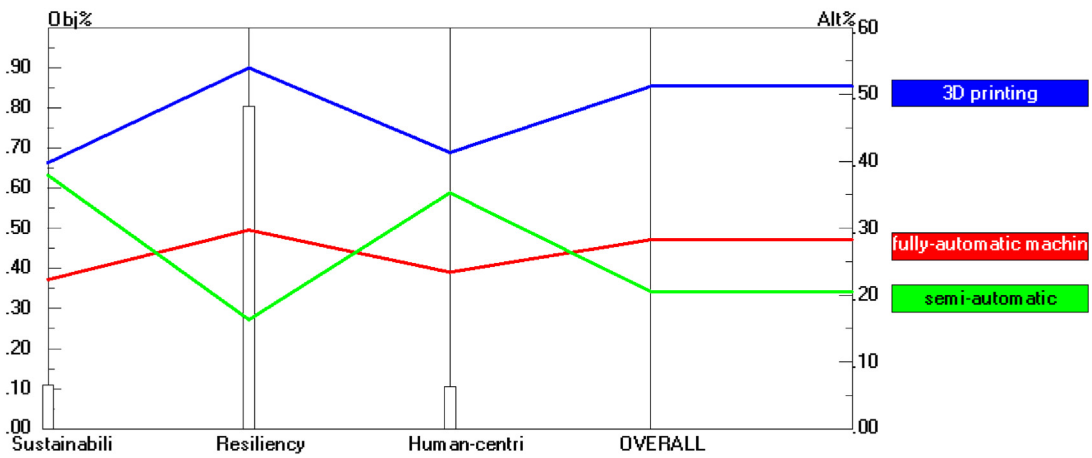
Since the present work has proposed a stochastic model, this section aims at examining its efficiency. To show the advantages of the proposed scenario-based model, its performance is compared with the expected value approach. To do this, the Value of the Stochastic Solution (Birge, 1982; Sabouhi et al., 2020b) metric, abbreviated by VSS, is applied as follows:

$$VSS = EV - SV \tag{39}$$

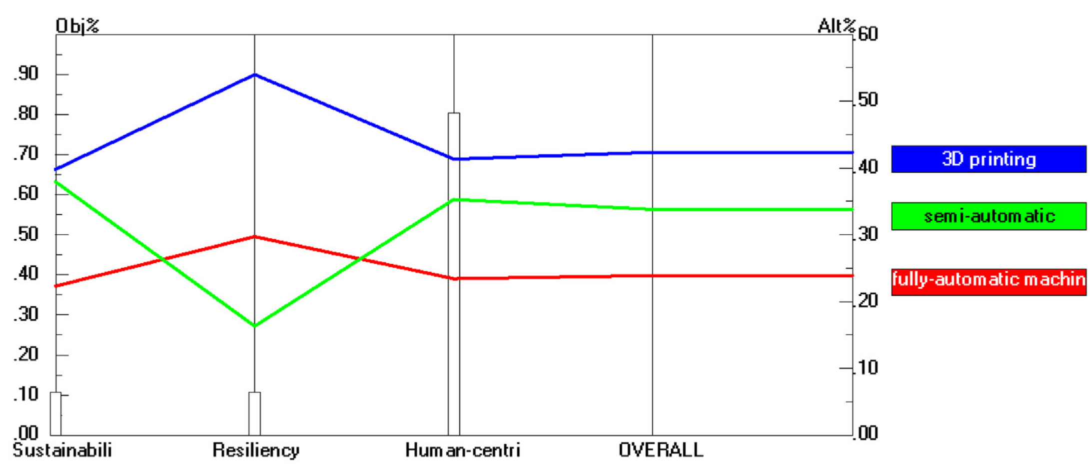
where EV represents the value of the objective function under the expected value approach and SV denotes the value of the objective function under the stochastic approach. It should be noted that to calculate EV, first, the expected values of the parameters are measured, and then the problem is solved (Sabouhi et al., 2020b). In general, EV measures the maximum cost the decision-maker would be prepared to pay to ignore uncertainty (Birge, 1982; Sabouhi et al., 2020b). Here, several test problems in different sizes are generated (the size of test problems is increased in ascending order) and solved using the stochastic and expected value approaches (only with the first objective function). Fig. 14 illustrates the obtained results. Fig. 14(a) shows the values of the VSS metric that indicates the better performance of the scenario-based approach compared with the expected value approach; because in all test problems, the value of VSS is positive that indicates $EV > SV$ (i.e., the objective function of stochastic approach is lower



(a) Mode 1



(b) Mode 2



(c) Mode 3

Fig. 11. The results of sensitivity analysis on the first stage.

than the objective functions of expected value approach). To better understand, Fig. 14(b) depicts the Cost Increase Percentage (CIP) for each test problem that is calculated based on Eq. (32). These metrics have been selected in the current work because this study has proposed a scenario-based programming model, and these metrics can help to measure its efficiency and performance.

$$CIP = \frac{|EV - SV|}{\text{Min}(EV, SV)} \times 100 \tag{40}$$

5.5. *Effectiveness of the proposed FLMCACGP*

Since the present study has developed a novel solution method (i.e., FLMCACGP), its effectiveness should be examined. In this regard, comparing with traditional methods is a good way to measure the performance of a new method that has been suggested in the literature. Since the present study has developed a novel solution method (i.e., FLMCACGP), its effectiveness should be examined. In this regard,

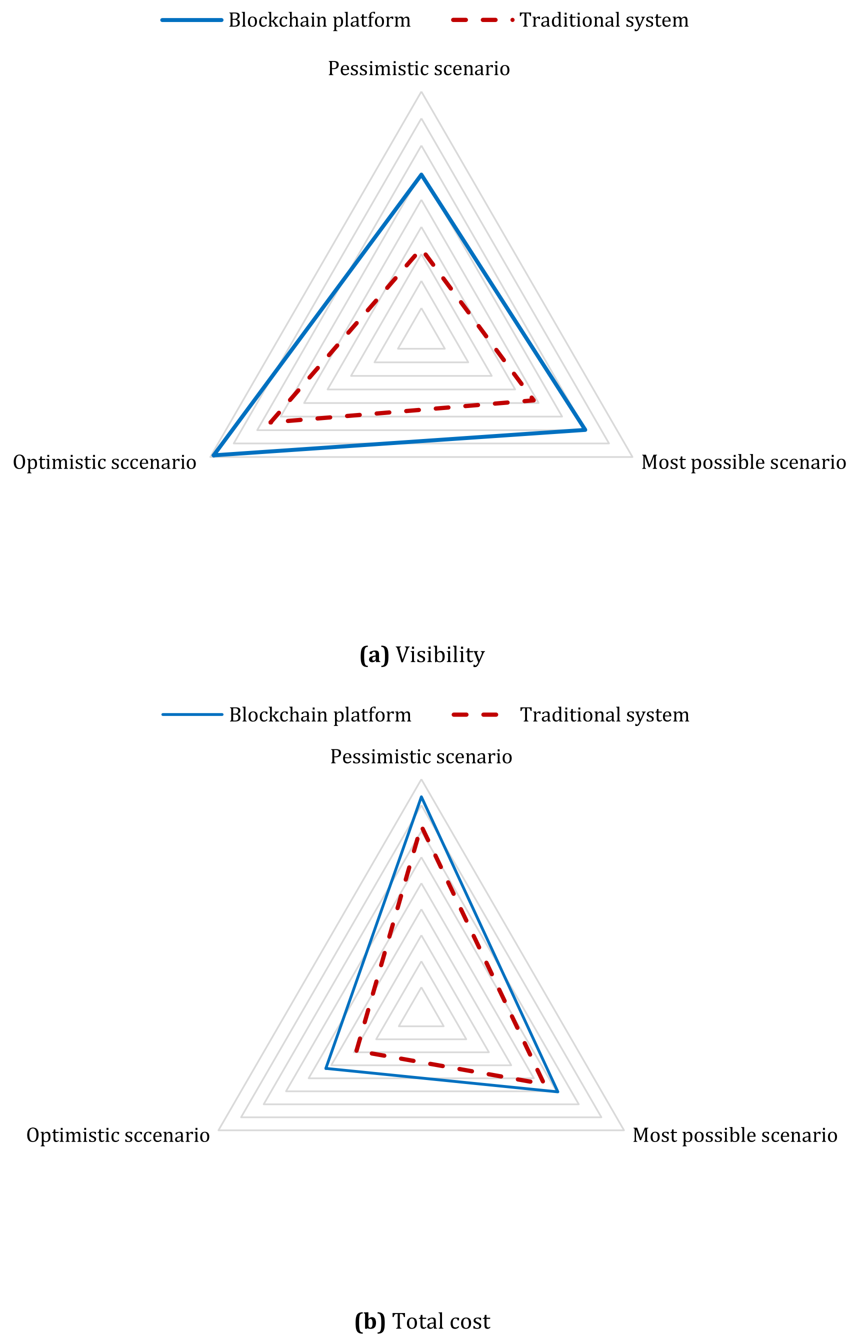
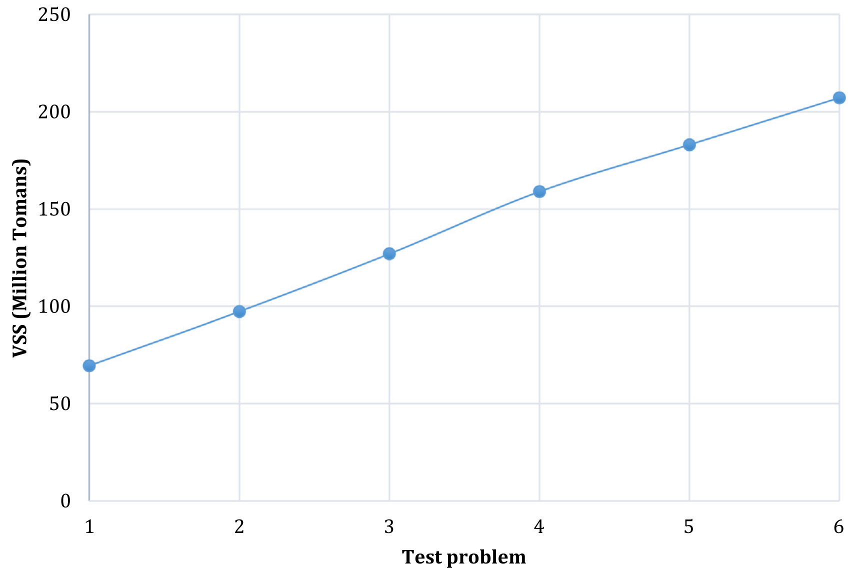


Fig. 12. Comparing different information-sharing technologies.

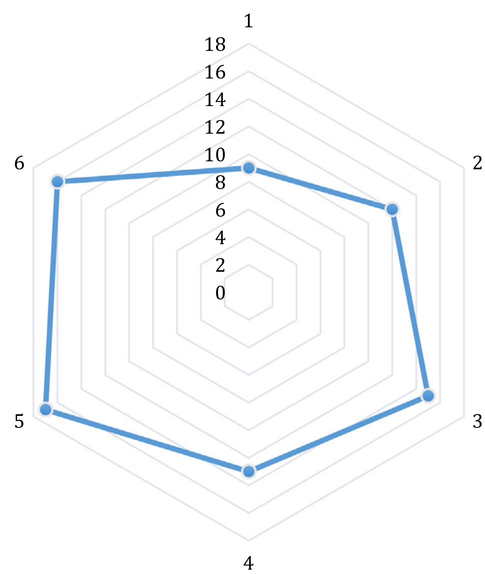
comparing with traditional methods is a proper way to measure the performance of a new method, which has been suggested in the literature. The first and second metrics (deviation and achievement degree) show the capability of the method to achieve the determined goals, and the third metric (complexity) demonstrates the capability of the method to solve in a reasonable time by commercial software, such as LINGO. In this regard, the research problem is solved by the two other similar methods: the Traditional Fuzzy Multi-Choice GP (TFMCGP) method (Bankian-Tabrizi et al., 2012) and the Traditional LACGP (TLACGP) (Romero, 2001). Table 4 compares the obtained results from the different methods (it should be noted that for the TFMCGP, three aspiration levels have been considered for each objective function). The obtained results indicate the superiority of the proposed FLMCACGP method to the traditional ones. As shown in Table 4, compared to the TFMCGP, the proposed method achieves a higher λ_j (achievement degree), which shows the better performance of the FLMCACGP. On the other side, the developed method has outperformed the TLACGP method in terms of deviations (d_j^+, d_j^-). In this regard, based on the achieved results, all of (d_j^+, d_j^-) are equal to zero for the proposed FLMCACGP. Eventually, as shown in the last row of Table 4, compared to TFMCGP, the proposed FLMCACGP has less complexity due to the lower number of extra binary variables.

5.6. Evaluating the performance of the proposed methodology using synthetic instances

In this section, we solve the proposed model by the developed FLMCACGP in different instances to examine its performance. In this regard, 10 instances have been generated and solved using the FLMCACGP method. The outputs have been presented in Table 5. As shown in this



(a) The values of the VSS metric



(b) The CIP metric

Fig. 13. The performance of the proposed stochastic model.

Table 4
Comparing the results of the FLMCACGP, TFMCGP, and TLACGP.

	FLMCACGP	TFMCGP	TLACGP
λ_1	1	0.9893	–
λ_2	1	0.9739	–
λ_3	1	0.9620	–
λ_4	1	0.9953	–
(d_1^+, d_1^-)	(0,0)	–	(181.22,0)
(d_2^+, d_2^-)	(0,0)	–	(0.231,0)
(d_3^+, d_3^-)	(0,0)	–	(0.192,0)
(d_4^+, d_4^-)	(0,0)	–	(0,0.165)
(e_1^+, e_1^-)	(113.5,0)	–	–
(e_2^+, e_2^-)	(0.185,0)	–	–
(e_3^+, e_3^-)	(0.162,0)	–	–
(e_4^+, e_4^-)	(0,0.142)	–	–
Extra binary variables $(=n\left\lceil\frac{\ln m}{\ln 2}\right\rceil)$	0	$4 \times \left\lceil\frac{\ln 3}{\ln 2}\right\rceil = 8$	0

table, in all instances, the developed method has obtained the proper achievement degree and deviation that demonstrates the efficiency and performance of the proposed approach.

6. Conclusions

Recently, researchers have introduced the concept of the I5.0, which is established based on three main pillars, namely sustainability, resiliency, and human-centricity. This is because I4.0 emphasizes the role of the new technologies in the industries and ignores important issues such as sustainable development and the role of industry in society. However, the literature showed that no research investigated the SCND problem in the I5.0 era. Hence, this research aimed to develop a multi-stage decision-making framework based on the AHP method and a MOPM to design a CLSCN considering the I5.0 pillars. Afterwards, due to the importance of medical devices during the Coronavirus disease pandemic, a case study in this industry (the vaccine refrigerator) was considered. Then, a new solution method, namely fuzzy lexicographic

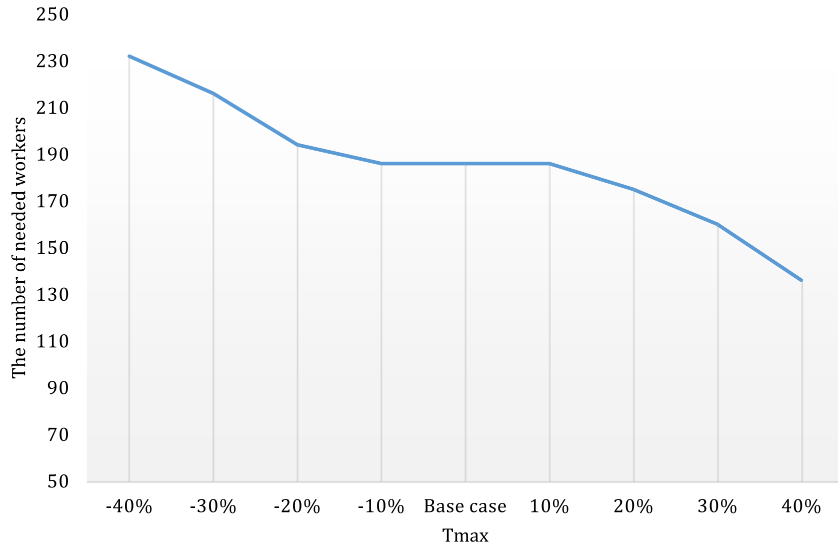


Fig. 14. The number of needed workers under different values for the maximum allowable working time.

Table 5
Evaluating the performance of the developed method.

Instance No.	$(\lambda_1,\lambda_2,\lambda_3,\lambda_4)$	(d_1^+,d_1^-)	(d_2^+,d_2^-)	(d_3^+,d_3^-)	(d_4^+,d_4^-)	(e_1^+,e_1^-)	(e_2^+,e_2^-)	(e_3^+,e_3^-)	(e_4^+,e_4^-)
1	(1,1,1,1)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)
2	(1,1,1,1)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)
3	(1,1,1,1)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)
4	(0.98.0.99,1,1)	(0,0)	(0,0)	(0,0)	(0,0)	(78.4,0)	(0.043,0)	(0.02,0)	(0,0)
5	(0.99,1,0.98,0.99)	(0,0)	(0,0)	(0,0)	(0,0)	(95.8,0)	(0.072,0)	(0.066,0)	(0,0.08)
6	(1,1,1,1)	(0,0)	(0,0)	(0,0)	(0,0)	(53,0)	(0,0)	(0.06,0)	(0,0)
7	(0.98,0.98,1,1)	(108.5,0)	(0.088,0)	(0.025,0)	(0,0.10)	(94.2,0)	(0.043,0)	(0.038,0)	(0,0.05)
8	(1,0.99,1,0.98)	(206,0)	(0.103,0)	(0.072,0)	(0,0.12)	(14.3,0)	(0.14,0)	(0.1,0)	(0,0.08)
9	(1,1,1,1)	(175.8,0)	(0.094,0)	(0.066,0)	(0,0.09)	(22,0)	(0.092,0)	(0,0)	(0,0)
10	(0.99,1,0.99,1)	(236,0)	(0.103,0)	(0.072,0)	(0,0.12)	(71.5,0)	(0.06,0)	(0.125,0)	(0,0.3)

multi-choice Archimedean-Chebyshev goal programming, was developed to solve the suggested MOPM. The outputs showed the efficiency of the developed solution method that has a better performance than the traditional ones. The outputs showed that sustainability and resiliency are the most important criteria, and also economic, capacity recycling, and safety are the most important sub-criteria in the case SC. The sensitivity analysis showed that an increase in the disruption rates has a negative effect on the supply chain performance. Also, the obtained results indicated that the total costs, environmental damages, and node criticality were increased by enhancing the demand sizes. Eventually, establishing the IoT system leads to significant cost savings based on the achieved results.

6.1. Managerial implications

Since the research problem is a decision-making one that has investigated a real-world case study, its managerial insights are important, especially for industrial practitioners. Hence, here, the managerial implications of the current research are presented. The main managerial implications of the present paper can be listed as follows.

- This research can provide a very good perspective to industrial managers regarding implementing the dimensions of the fifth industrial revolution in their supply chains. In this regard, this study has defined and provided the main criteria and sub-criteria of the I5.0. Also, a two-stage approach to model the I5.0 pillars, has been defined in the research problem. Supply chain managers can benefit from this research to see the impact of considering I5.0 dimensions in their SCNs.
- According to Fig. 8, although establishing the IoT system has its corresponding cost, it has led to significant savings in the collection and recycling costs. Hence, managers should know that using new technologies may seem costly at first glance; however, it can reduce their logistics costs and increase productivity in the long term. Indeed, reconciling managers with modern technologies can be a proper way to improve the performance of their supply chain processes.
- Table 2 gives a proper perspective to managers for understanding the role of the weights of the objective functions in the outputs. In this regard, managers can incorporate their opinions into the problem by setting the value of weights. However, supply chain managers should be aware that an extreme focus on the economic aspects may lead to losing their market share in the long term due to ignoring important factors such as sustainability and resiliency.
- Based on Fig. 9, the workers' training can lead to a significant decrease in purchasing costs. In this regard, SCs' managers should be aware that the training is not to be considered cost, but rather an 'investment' for the firm, which is one of the main goals of the I5.0. This study can give managers a good view of the positive impact of the training on their company's productivity.
- According to the results (See Supplementary Materials-Part C.1), an increase in demand negatively impacts environmental issues. So, managers can utilize manufacturing technologies or transportation modes with lower pollution. However, the higher cost of these facilities (manufacturing technologies and transportation

modes) usually discourages managers from using them. Managers must know that presenting a green image from their company can increase customers' loyalty in the long term and thus increase profits.

- Results (See Supplementary Materials-Part C.2) indicated the negative impact of increasing the disruption rates on the supply chain metrics. Therefore, managers should find solutions and ways to deal with these negative effects in the I5.0 era. In this regard, allocating budgets to increase the reliability of the facilities and contracting with backup facilities can be good strategies to cope with the mentioned condition.
- Beyond the engineering realm, as mentioned in this research, one of the most crucial principles that I5.0 focus on, is social fairness, human rights, and ethics. In this regard, managers should know that looking at medical equipment as a commercial item, especially in a situation like Corona disease, is not the right approach, because according to "United Nations (2008). The right to health", Health is a universal human right, but a commodity is not. Therefore, when health becomes a commodity, its status as a human right is threatened. As recognized by the 1948 Universal Declaration of Human Rights, even though financial and commercial issues are crucial, the fact that health is "a part of the right to an adequate standard of living" should not be neglected by managers. Furthermore, the right to health was considered as a human right in the 1966 International Covenant on Economic, Social, and Cultural Rights (Springer and Özdemir, 2022).

6.2. Theoretical implications

This work contains several theoretical insights that are presented in this section. Since supply chain activities are always influenced by industrial revolutions, this study has proposed a multi-stage decision-making model to design an SCN considering the I5.0 pillars. In this regard, at the outset, the scores of technologies employed in the SC were calculated based on the I5.0 indicators using the AHP method. The indicators have included sustainability, resiliency, and human-centricity. Afterwards, a scenario-based MOPM was proposed to configure a closed-loop SCN. In the studied SCN, different manufacturing/recycling technologies, such as 3D printing and fully-automatic machines, were considered, each of which has advantages and disadvantages according to I5.0 indicators. In addition, in the supply chain under study, it was also possible to use the IoT to track the sold products and better collect the EoL and EoU products. Also, the strategies that were used to incorporate resiliency in the SC were (i) considering disruption scenarios, (ii) establishing the information sharing system, (iii) contracting with the backup suppliers, and (iv) minimizing the node complexity.

Actually, this is the first research that has designed a SCN considering sustainability, resiliency, and human-centricity aspects. Besides, the present work proposed an efficient solution approach, namely the fuzzy lexicographic multi-choice Archimedean-Chebyshev goal programming method. This method has several advantages, such as (i) allowing DMs to tackle uncertainties of the market space by considering multiple targets for each objective, (ii) decreasing the complexity compared to other previous fuzzy multi-choice GP methods by eliminating the function of binary serial numbers, (iii) creating a good compromise among efficiency and equity aspects for goals, and (iv) increasing the flexibility of the lexicographic term. Since the obtained results showed the superiority of the developed method over the traditional ones, this paper has a significant theoretical contribution to the solution approach. Eventually, in this study, the vaccine refrigerator, one of the widely-used equipment in the Coronavirus disease pandemic era, was selected as a case study that can give a proper theoretical perspective on the logistics activities of this crucial product.

Another important theoretical point that should be mentioned is related to the concept of symmetrical innovation, which was discussed in the original reference of I5.0 (Özdemir and Hekim, 2018). As mentioned in the introduction section, symmetrical innovation is a key concept in the I5.0 area that leads to extending digital connectivity. However, this point may result in some risks and drawbacks that are mentioned in the introduction section. In this regard, implementing the information-sharing systems between all of the supply chain members considered in this paper can lead to improving cooperation and coordination among them. The mentioned point can solve the concentration of political power issues in supply chains. Moreover, I5.0 and its key driver (i.e., symmetrical innovation) have both instrumental and normative (e.g., ethical) dimensions, which have been partially included in this research by considering the human-centricity and social aspects. Nevertheless, future studies can add more elements from the mentioned point in the current work.

6.3. Comparing the obtained results with the relevant studies

In this section, we compare the results of this research with other similar papers. In this regard, the outputs showed the negative impact of increasing the disruption rates on the supply chain metrics. Similar behavior was also observed in Mamashli et al. (2021), Nasrollah et al. (2022), Nayeri et al. (2021), which indicates the validity of the suggested model and achieved results. On the other side, according to the results, increasing the demand parameter has a negative impact on the environmental metric. A similar result can be seen in Gholizadeh et al. (2020), Nasrollah et al. (2022), Nayeri et al. (2022, 2021). However, the mentioned studies did not consider several concepts incorporated in this work, such as I4.0 technologies and human-centricity. This study showed the crucial role of the information-sharing systems in the resiliency of the SC network, which was confirmed in previous studies, such as Mehrjerdi and Shafiee (2021), Taheri and Moghaddam (2022). Eventually, the results of the present work indicated the positive role of using the IoT in reverse logistics activities, which has been discussed and confirmed by Breque et al. (2021), Subramanian et al. (2020). Albeit, it should be noted that the mentioned studies did not evaluate this point using a mathematic method, but this study measured this point using a mathematical programming model.

6.4. The limitations of this work

Similar to each academic article, the current research has some limitations. Overall, the main limitations of this work can be divided into two major parts as follows: (i) the limitations in real applications, and (ii) the limitations in theoretical parts. Regarding the first part, the main limitation of this work in terms of the real applications is convincing managers, especially managers with a traditional view, to allocate funds to implement the dimensions of the fifth industrial revolution. Moreover, another limitation of this work in the field of the real application is that some companies do not have the necessary infrastructure, especially in the technology sector, to implement the dimensions of Industry 5.0. On the other side, the second limitation of this work is to miss the symmetrical innovation concepts. On the other hand, we can point to the time-consuming implementation of the proposed solution method. Also, the proposed solution method does not consider the decision-maker's preferences, which can be incorporated using a utility function.

Future studies can consider more scenarios and develop metaheuristic or heuristic algorithms to solve the research problem. Also, future research can add the concept of responsiveness to the current study and examine the interrelationship among the I5.0 pillars and responsiveness measures. In addition, adding the global supply chain factors to this study can be another idea for future papers. Researchers also can added the ethics and normative standpoint to the present work. Finally, future works can focus on adding the concept of symmetrical innovation to the current study.

CRediT authorship contribution statement

Sina Nayeri: Conceptualization, Methodology, Software, Writing – original draft, Visualization. **Zeinab Sazvar:** Supervision, Investigation, Writing – review & editing. **Jafar Heydari:** Conceptualization, Methodology, Validation, Visualization.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.engappai.2023.106113.

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