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Analysis and evaluation of challenges in the integration of Industry 4.0 and sustainable steel reverse logistics network

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ABSTRACT

Industry 4.0 (I4.0) is a comparatively new phenomenon, and it is most probable that developing countries would face challenges in adapting it for improving the processes of supply chains and moving toward sustainability. The steel industry is the core of industrial growth, and it has an indispensable role in the development of countries. Steel is a highly recyclable product, meaning that it can be reused infinitely, increasing the significance of its reverse logistics. Although many studies have been conducted in the area of I4.0 and supply chain management, less attention has been devoted to finding and analyzing potential challenges of I4.0 technologies integration in steel reverse logistics activities. Therefore, this study is conducted to identify and analyse the challenges to efficient integration of I4.0 and sustainable steel reverse logistics system. Data collection is conducted with the assistance of qualified experts familiar with the steel supply chain and I4.0 concept. The interrelations of challenges are specified by Interpretive Structural Modeling, and the final ranking of challenges is determined through the Fuzzy Analytical Network Process. After validating the completed questionnaires, the absence of experts in I4.0, lack of clear comprehension of I4.0 concepts, training programs, and governmental policies and support are determined as the most critical challenges. Finally, the results and discussion, which can help practitioners in the efficient adoption of I4.0 to have a sustainable reverse logistics system, are presented.

1. Introduction

Global awareness and concerns regarding the environmental, economic, and social aspects of the operations and organisations made sustainable supply chains (SSCs) one of the significant research areas during past decades (Nayeri et al., 2020). Reverse logistics (RLs) management is understood to be one of the essential components for moving toward sustainability. RLs is defined as all operations regarding the reuse of materials and products (Sirisawat and Kiatcharoenpol, 2018). In other words, it is to plan, implement, and control the efficient and cost-effective stream of information and products from the consumption to the origin point for regaining their value or proper disposal (Liao, 2018). RLs adoption can help minimise the adverse environmental impacts through recycling and reusing end-of-life products. Other than that, it can have immense economic and social benefits as well (Shahparvari et al., 2021).

It has become common knowledge that the arising digital technologies could improve the efficiency of the operations of supply chains (SCs) worldwide (Govindan et al., 2018; Dubey et al., 2019). Both academia and practitioners have widely reported the potential benefits of the integration of digital technologies and SC management (Kamble et al., 2020b). Implementing these novel technologies can help SCs to perform more efficiently (Chiappetta Jabbour et al., 2020). The operations and SC management could be restructured through Industry 4.0 (I4.0), named after the 4th industrial revolution. The name refers to the prevailing trend of exchange of data and automation in manufacturing technologies, like the Internet of Things (IoT), cyber-physical systems, and cloud computing, which could lead to forming smart factories (Govindan et al., 2018; Koot et al., 2021).

Improving the productivity of production systems can be done using different approaches (Segerstedt, 1999). Adopting I4.0 initiatives to SC activities as one of the trends in the current time can enhance the overall

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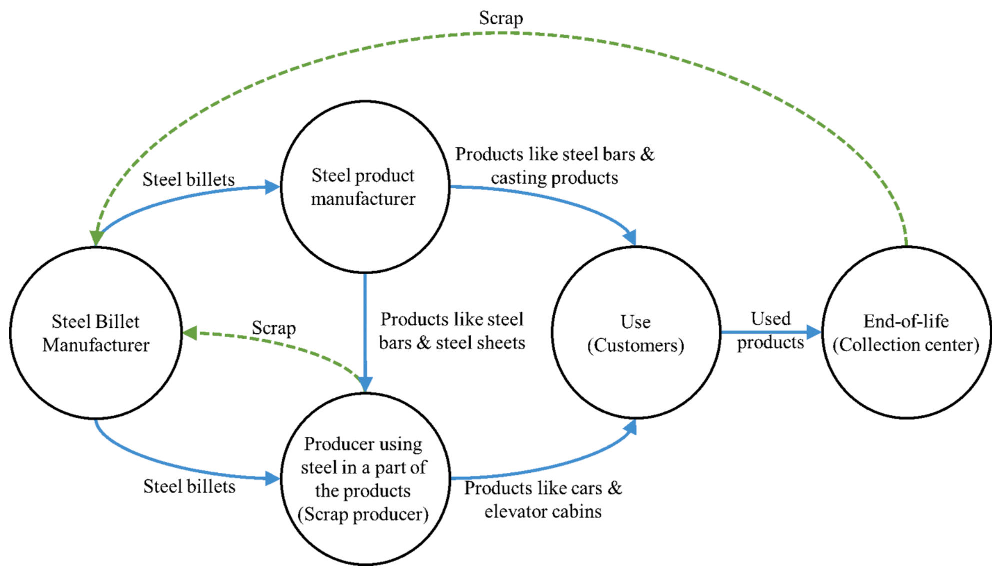

Fig. 1. The cycle of steel in the case study.

performance of the companies regarding sustainability (Luthra and Mangla, 2018). In terms of the economic dimension, reduction of cost through enhancement of productivity and a higher return rate of investments are potential advantages of I4.0-based technologies adoption in SCs (Ahmed et al., 2018). Researchers have also confirmed that I4.0 initiatives can significantly make benefits for the social sustainability of SCs (Badiezadeh et al., 2018). It promotes ethical association between different tiers of SCs by enabling transparency, increasing commitment to sustainability (Kamble et al., 2020a). Moreover, the technologies can support preliminary decision-making on technologies, processes, resource utilisation, and the downstream and upstream flows, which fall into the category of environmental dimension (Belaud et al., 2019). The technologies can monitor environmental indicators like carbon footprint and air pollutant emissions and provide more accurate environmental impact assessments, promoting a better understanding of environmental impacts on SSC management (Amjad et al., 2021).

I4.0 can offer insightful directions to promote the circular economy and RLs (Dantas et al., 2021). The technologies have the potential to be used in different operations of the RLs, like disassembly, recycling, recovery, and remanufacturing (Chiappetta Jabbour et al., 2020). I4.0 initiatives such as sensor-based infrastructure and big data can further boost efficiencies of product tracking, demand forecasting, and responsiveness of the RLs (Manavalan and Jayakrishna, 2019). Hence, there could be good opportunities for companies looking for a higher sustainable profile through the adaption of I4.0 technologies on their RLs.

One of the highest demanding construction and engineering products utilised practically in all aspects of our life is steel, which manufacturing process has significant environmental impacts as it consumes a great deal of energy and resources (Gu et al., 2015). In comparison with other recyclable products, steel is acknowledged as an inherently recyclable product, which means that it can be reused again in a closed-loop cycle (Pourmehdi et al., 2021). Steel recycling would reduce the need to mine and process direct reduced iron, ultimately reducing the consumption of water and energy besides the overall environmental degradation of the process (Baswaraj and Rao, 2020). An example cycle of steel, considering the conditions of the case study in this article, is shown in Fig. 1.

Studies on the area of SSC management and I4.0 had a notable rise in the past few years (Chalmeta and Santos-deLeón, 2020; Nia et al., 2020). However, there seems to be a lack of comprehensive investigation and evaluation of challenges in the adoption of I4.0 on RLs in a developing country. Hence, it seems essential for a major industrial sector like the steel industry to deal with different challenges of adopting I4.0 to reach sustainability.

As I4.0 is a relatively new phenomenon in developing countries, the implementation of its initiatives is more challenging in comparison with a developed country. Therefore, it might require more effort for a proper understanding of this concept, its application patterns, and potential challenges (Hofmann and Rüsch, 2017). Even though the adoption of I4.0 is tricky, its beneficial impacts on sustainability surpass its challenges. Hence, the potential challenges for adopting I4.0 and balancing sustainability dimensions should be identified and adequately assessed. The evaluation and prioritisation of challenges can help managers deal with these challenges in adopting I4.0 initiatives efficiently. As shown in Table 1, during the past decade, several researchers have carried out studies for considering I4.0 technologies in SCs/RLs. However, none has discussed and investigated the associated challenges to the successful adoption of I4.0 technologies in steel RLs. In this regard, this research is conducted with the primary objective of identifying, analysing, and prioritising the existed challenges in the way of managers for efficient adoption of I4.0 to create sustainable steel RLs systems. The considered case study for investigating the validation of the presented study is the steel RLs systems of active reverse networks in Iran.

The remaining sections of the study are ordered as follows. The associated literature with the research, summarised table of literature, research gap, and challenges are presented in Section 2. The research approach is explored in Section 3. Section 4 represents the details of the problem description, data collection, analysis, and results. Lastly, the discussion and conclusion are presented in Sections 5 and 6, respectively.

2. Literature

This section provides a concise literature review of the application of

Table 1
Summary of the studies that show the adoption of I4.0 in SCs/RLs.

Study	Description	Area of application	Network	Sustainable	Approach
Luthra and Mangla (2018)	They identified and analysed several barriers for I4.0 adoption and prioritised them for practical adoption of I4.0 on an SSC by taking the Indian industry viewpoint.	–	SC	✔	AHP
Garrido-Hidalgo et al. (2019)	They presented an end-to-end resolution for RLs regarding collaboration among several IoT communication standards, allowing cloud-based inventory monitoring of waste electric and electronic equipment by installed sensors.	Waste electric and electronic equipment	RLs	–	–
Ghadimi et al. (2019)	They presented a multi-agent systems method for a sustainable supplier selection problem. The presented method provided a proper communication channel, structured information transfer, and clarity between manufacturers and suppliers.	Medical device	SC	✔	Multi-agent systems
Dev et al. (2020a)	They proposed a roadmap for improving the operations of sustainable RLs through the integration of I4a.0 and the circular economy.	–	RLs	✔	Mathematical Modelling
Dev et al. (2020b)	They modelled the RLs and explored the way that products are diffused in markets, influencing environmental and economic performances of production planning and inventory policy	–	RLs	–	Bass model
Bag et al. (2020)	They examined how I4.0 means influencing smart logistics and, consequently, green manufacturing capability, dynamic remanufacturing, and, accordingly, logistics sustainability.	Mining	Forward & Reverse Logistics	✔	Structural equation modelling
Yadav et al. (2020)	They presented a framework to overcome SSC barriers by I4.0 and circular economy regarding solution measures. They also presented sets of challenges and solution measures.	Automotive industry	SC	✔	Hybrid Best Worst Method - Elimination and Choice Expressing Reality
Sharma et al. (2021)	They conducted a study on challenges in achieving sustainability in SCs by evaluating the barriers and drivers for implementing I4.0 on manufacturing SCs.	–	SC	✔	AHP and DEMATEL
This study	We specify, analyse, and prioritise the existed challenges in the way of managers for efficient adoption of I4.0 to create a sustainable steel RLs system in a developing country.	Steel industry	RLs	✔	ISM and Fuzzy ANP

AHP = Analytical Hierarchy Process.
DEMATEL = Decision making trial and evaluation laboratory.
ISM = Interpretive Structural Modelling.
ANP = Analytical Network Process.

Table 2
Information on challenges.

Category	Challenge	Description	Code
Conceptual	Lack of clear comprehension of I4.0 concepts (Almada-Lobo, 2016; Hofmann and Rüsch, 2017)	A shared and thorough perception of I4.0 does not exist among practitioners and academia. Highly organised and focal studies are done in literature for finding a specific interpretation of I4.0. The importance of I4.0 adoption in the work environment is evident to managers. However, its exact effects and influences on achieving sustainability in the SC are ambiguous to them.	C1
	Poor understanding of I4.0 adoption pattern (Schmidt et al., 2015; Frank et al., 2019)	Managers that dealt with I4.0 infer its adoption pattern in specific ways regarding their interaction with it. The absence of a systematic decision approach during the transformation of organisations for effective adoption of I4.0 might cause multiple problematic issues for managers. The effect of I4.0 on reaching sustainability can be assured with a robust adoption pattern.	C2
	Meagre digital operations vision and strategy (Erol et al., 2016; Saatçioğlu et al., 2019)	The digital transformation of organisations is a significant part of I4.0 adoption, which is achieved with the help of a clear digital operations vision and mission. The vision and strategy for adopting I4.0 should be specified before the start of the transportation process. Developing an SSC requires an efficient transformation of the visionary ideas of I4.0 to a missionary level, which is struggling for organisations.	C3
Executive	Lack of appropriate management practices (Shamim et al., 2017)	The acceptance of changes caused by I4.0 is one of the crucial steps in the procedure. A proper management practice should be established for monitoring and handling the revolutionary alteration of business manners and SC activities. Managers should focus on acquiring extensive management knowledge for I4.0 driven sustainable development.	E1
	Lack of competency to adopt/implement new business models (Khan et al., 2017; Saucedo-Martínez et al., 2018)	Flexibility and customised systems are the requirements of competing in the global environment for contemporary industrial systems. Industries and organisations require the adoption of new business models to reach these goals. The analytics of big data from industries boosted the productivity of manufacturers. A solid base for planning new projects was presented due to predictions of new events based on big data. All the novel insights will not be functional, and just some cases are interesting out of millions. Hence exploring them would be challenging for data scientists to develop proper algorithms addressing novel business models.	E2
	Financial constraints (Theorin et al., 2017; Ghadge et al., 2020)	Financial restraints are considered a significant challenge among organisations that intend to develop their abilities regarding advanced machines and equipment, and sustainable process innovations in I4.0.	E3
	Absence of experts in I4.0 (Kiel et al., 2017)	Regardless of other challenges, the adoption of I4.0 requires competent specialists in all aspects of I4.0, so they would be able to practice it appropriately.	E4
	Uncertainty in the economic interest of digital investments (Kiel et al., 2017)	The principal emphasis in I4.0 is on technological proficiency, where the economic analysis is yet at its outset. Uncertainty in the return rate of investments could be perceived as a significant challenge to I4.0 drives to achieve SC sustainability.	E5
	Lack of training programs (Luthra et al., 2019)	The adoption of novel production technologies exposes gaps in the skills of employees in customised workplaces that employ a few people. Systematic educational programs are consequently required, and the lack of training will hinder growth and raise the risk of errors throughout processes. The training for human resources is a vital agent in achieving a competing authority.	E6
	Reluctant behaviour towards I4.0 (Müller et al., 2017; Luthra and Mangla, 2018)	Since the concept of I4.0 is still unfamiliar for many industries, managers resist accepting its possible benefits. Due to the ignorance of the advantages of adopting I4.0-based technologies and the unrealistic point of view that it conflicts with sustainability, they are reluctant to embrace them.	E7
	Employment disruptions (Kamble et al., 2018b)	Employment disruption is described as interruptions caused in employment because of the automation of processes and novel technologies. The jobs in manufacturing divisions are most likely to be automated, which results in a higher turnover rate. The remaining positions will comprise more knowledge-based, hard-to-plan, and short-term jobs.	E8
	Lack of digital culture (Ras et al., 2017; Simic and Nedelko, 2018)	One of the essential requirements for adopting I4.0 is digitisation. Moreover, the interdisciplinary nature of I4.0 requires digitisation for connecting the components of the network in a sustainable environment.	E9
Technical	Poor existing data quality (Santos et al., 2017; Simic and Nedelko, 2018)	The quality of data is one of the critical elements of the successful adoption of I4.0. Manufacturing systems, facilities, machines, and sensors are interconnected in I4.0, generating big data. The accessible big data assist decision-makers in practising I4.0 innovations to move toward sustainability, which might not be achievable without high data quality.	T1
	Problem in integration of technology platforms (Zhou et al., 2016; Gajšek and Sternad, 2020)	The integration of technology platforms is a critical step toward efficient productivity and communication. Industries face challenges in outlining a flexible interface for integrating independent elements. I4.0 systems have many distinct parts that should be connected and supported for efficient analysis and data transfer. Hence, it is essential to develop and devise a platform for integrating technologies and efficient I4.0 driven SSC.	T2
	Unavailability of universal standards and protocols for data sharing (Branke et al., 2016; Rajput and Singh, 2021)	Systems are commonly linked to an intelligence mechanism to interact efficiently in I4.0 drives. Manufacturers oblige to follow universal standards and protocols for data sharing to succeeding in this process. It has been noticed that there are no universal standards and protocols for data transfer in business networks that utilise sustainability-oriented information interface technologies.	T3
	Inadequate internet-based networks and digital infrastructure (Pfohl et al., 2017)	High calibre technology-based information facilities, infrastructure, and technologies are essential in the practical application of I4.0. Weak internet connections create inescapable obstacles to I4.0 initiatives. In most developing countries, these requirements might not be available evenly in different areas, hindering the extension of sustainability.	T4
Regulatory	Legal matters (Müller et al., 2017b; Karabegović et al., 2020)	I4.0 works with real-time exchange of data between a network of robots, computers, sensors, and humans interlinked to each other within the internet. The operation of this network might cause some intricate legal matters. Adoption of I4.0 in a sustainable environment should be secured regarding legal issues in the operations of organisations.	R1

(*continued on next page*)

Table 2 (*continued*)

Category	Challenge	Description	Code
	Profiling and complexity concerns (Erol et al., 2016; Ras et al., 2017)	The globalisation of SCs made them structurally complex, making the perception of the basic procedures, their interactions, and data interpretation to acquire digitisation arduous for the workforce. The lack of competence of managers in handling the complexity associated with data analysis, the usage of space, time, and specific instructions in productive I4.0 adoption can be challenging for organisations. This absence of precise roadmaps and directions supporting its implementation makes I4.0 uncertain for delivering an SSC.	R2
	Lack of governmental policies and support (Raut et al., 2019)	Governmental policies and regulations are critical for developing an SSC through I4.0. There is a lack of clear governmental guidelines and regulations on I4.0 in most developing countries. Moreover, governments are uncertain of the probable outcomes of I4.0. As a result, government parties and policy analysts have not unveiled the roadmap to reach smarter and more sustainable business functions.	R3
	Problem of coordination and collaboration (Pfohl et al., 2017; Luthra et al., 2020)	Collaboration and transparency between members of an SC are essential for understanding the organisational policies of adopting I4.0 and enhancing sustainability. Facilities should have efficient coordination and collaboration with each other for more reliable interaction. Their communications should have high adaptability issues of software and hardware, standardised interfaces, and synchronised data for practical synchronisation.	R4
	Security concerns (Wang et al., 2016; da Silva and Barriga, 2020)	One of the I4.0 traits is creating a connection across manufacturing environments and making SCs more productive and, conversely, making the SC vulnerable to intruders. One of these vulnerable places is the supplier, which can be attacked by phishing intrusions and stealing privileged credentials, causing a vast data leak. The primary vulnerability of an SC is at its top, causing an exposure in other processes through their interactive elements. Security is the principal requisite for transforming a company or SC into a smarter one.	R5

I4.0 for improving the efficiency of SCs to highlighting the existing research gaps in this area of research. The introduction of I4.0 and its adoption have greatly influenced industrial systems due to its numerous benefits, and it attracted the attention of scholars and practitioners (Dalenogare et al., 2018). Academic research on I4.0 is still in its initial stages, but some of the recently presented literature reviews explored the opportunities of I4.0 in logistics (Raj et al., 2020). I4.0 and sustainability have grown to be the eminent propellers of SCs to promote sustainable systems and enhance productivity. I4.0 is believed to be a modern business mindset, helping enterprises and communities progress towards sustainability (de Sousa Jabbour et al., 2018a).

In the literature, researchers identified factors that show the correlation between I4.0 and sustainability. For instance, cost savings stemmed from improving material and operational competencies, enhanced resource utilisation, and information sharing, which improves forecast accuracy and reduce or prevent waste generation due to that are some of I4.0 effects on sustainability (Mastos et al., 2020). de Sousa Jabbour et al. (2018b) proposed a framework for enhancing the use of the principles of the circular economy in organisations through I4.0. They unveiled the way different I4.0 tools could underpin the strategies of the circular economy. Ghadimi et al. (2019) presented a Multi-Agent Systems method to approach sustainable supplier selection for providing structured information exchange, proper communication channels, and visibility among manufacturers and suppliers. An examination of the ways I4.0 tools influence smart logistics and, consequently, green manufacturing capability, dynamic remanufacturing, and, accordingly, logistics sustainability was done by Bag et al. (2020). Bai et al. (2020) examined different I4.0 technologies from the perspective of adoption and sustainability and presented an evaluation framework for sustainability based on integrating multiple environmental, economic, and social attributes. A roadmap for improving sustainable RLs through the integration of I4.0 and the circular economy was presented by Dev et al. (2020a). Their study uncovered two critical dimensions being the distribution of green products in markets and the real-time data sharing in the RLs.

Hofmann and Rüsch (2017) argued that since the adoption of I4.0 might not have short term benefits for companies, managers would face different challenges in implementing I4.0 on their logistics systems. Haddud et al. (2017) analysed the possible challenges and benefits of integrating I4.0 and SCs and the influence of I4.0 on an organisation and its whole SC. Kamble et al. (2018b) investigated the possible barriers to adopting I4.0 in India. They identified and classified the critical challenges that revealed the direct and indirect correlation of specified barriers in implementing I4.0. Critical challenges for the efficient application of I4.0 in an SSC in the emerging economy of India were analysed and prioritised by Luthra and Mangla (2018). A framework for overcoming SSC management challenges through I4.0 and the circular economy was developed by Yadav et al. (2020). They identified several challenges and solutions and verified the applicability of their framework through an automotive case.

The studies mentioned in this paragraph focus on applying fuzzy-based multi-criteria decision-making approaches in the area of SCs and I4.0 to validate the practicality of these approaches. Jeng (2015) used fuzzy DEMATEL to form the casual relationship map for the supply chain collaboration problem of manufacturing firms in Taiwan. Uygun and Dede (2016) evaluate the performance level of green SC management using the combination of fuzzy DEMATEL, ANP, and TOPSIS. Sirisawat and Kiatcharoenpol (2018) proposed integrating fuzzy AHP and TOPSIS to prioritise solutions for RLs challenges electronics industry of Thailand. A study focusing on the sustainable evaluation of suppliers using the integration of fuzzy AHP and TOPSIS based on a case from agrifood in France was conducted by Liu et al. (2019). Yıldızbaşı and Ünlü (2020) proposed combining fuzzy AHP and TOPSIS to evaluate the performance level of SMEs toward the utilization and application of I4.0. Altan Koyuncu et al. (2021) suggested using fuzzy TOPSIS for selecting I4.0 maturity models for a solar cell company. A study focusing on the analysis of barriers for mass customisation in the I4.0 environment was conducted by Dwivedi et al. (2021). Hossain and Thakur (2021) suggested combining fuzzy AHP and DEMATEL to benchmark healthcare SC by implementing I4.0.

Gu et al. (2019) proposed a decision framework to assist steel manufacturers, which were facing social and political pressures and extreme market conditions, in choosing the most productive RLs strategy, and efficiently manage the resource of scrap. An optimisation model to maximise the total profit and service levels and minimise adverse environmental effects of a sustainable steel RLs system under uncertain

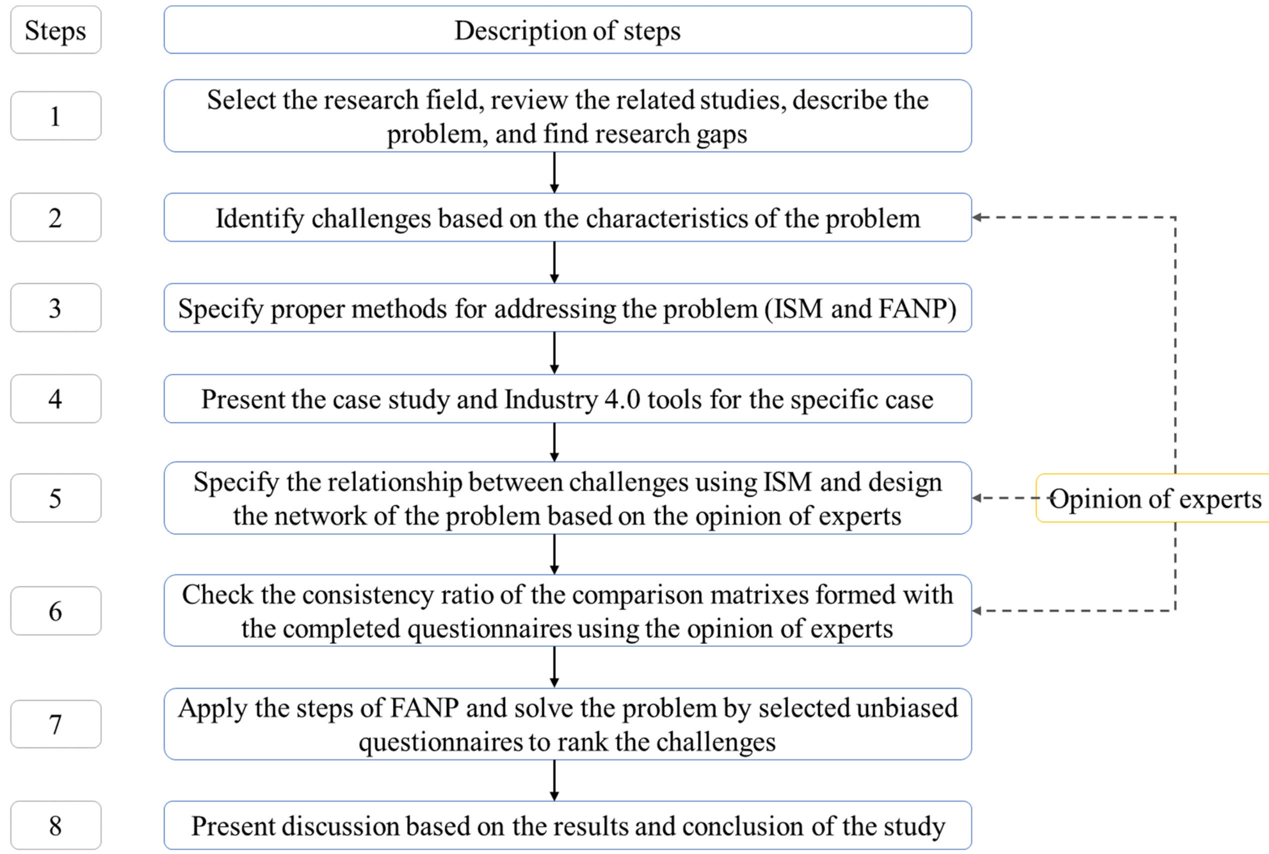

Fig. 2. The approach of the present research.

demand was presented by Antucheviciene et al. (2020). Pourmehdi et al. (2020) presented a mathematical model addressing uncertain demand and the amount of scrap to optimise the steel sustainable closed-loop SC. They suggested the change of retailers to hybrid centres and production technology for reaching a balance in sustainability dimensions, which also highlighted the indispensable role of RLs. Finally, a real-world case of I4.0 adoption for reaching sustainability on a steel RLs system was presented by Mastos et al. (2020). Their study showed that processes such as automatic monitoring and negotiation could reduce CO_2 emissions and response time and improve resource availability. Finally, some of the studies that show the correlation between I4.0 and SCs or logistics systems are summarised in Table 1.

2.1. Research gap

Based on the literature, a significant portion of research on I4.0 focused on the manufacturing sector and neglected the influence of I4.0 on SCs (Manavalan and Jayakrishna, 2019). According to Table 1, some previous studies addressed the integration of SSCs and I4.0 and presented valuable results. The literature yet appears to be limited, and additional research is needed to study the sustainability impacts of I4.0, especially on the RLs system. Also, the concept of I4.0 is comparatively new in developing countries and requires a precise outline for proper comprehension and application (Hofmann and Rüsch, 2017).

Hence, this research is done with the primary objective of examining and evaluating challenges in the application of I4.0 on the RLs systems in a developing country. The main contributions of the paper are threefold: firstly, it identifies and defines a comprehensive list of the steel RLs and I4.0 technologies integration challenges; secondly, it analyses the interrelations among the challenges using a structured technique (ISM) followed by ranking the identified challenges by FANP to provide recommendations for industrial practitioners and policymakers; thirdly, it solves a real case problem in a growing area of research, which is finding the most significant potential challenges in the way of experts for integrating Industry 4.0 and steel reverse logistics. This research would have significant importance for companies intending to improve their sustainability profile of the network and help the economy of their country. Finding the most applicable criteria, using qualified experts, and applying the most suitable approaches to have the most realistic results, and finally finding a practical approach for addressing all aspects of the problem could be considered as the contribution of the study.

The goal of this study is to specify, analyse, and prioritise the challenges in the way of managers for the efficient adoption of I4.0 to create a sustainable steel RLs system. The considered case study for investigating the validation of the presented study is the steel RLs system of active networks in Iran. Confirming the validation of the challenges, classifying them into different categories, finding the interrelation between them, and prioritising them were done with the assistance of experts. The specification of the interrelations and final ranking of the challenges based on the validated data were determined through the integration of interpretive structural modelling (ISM) and fuzzy analytical network process (FANP).

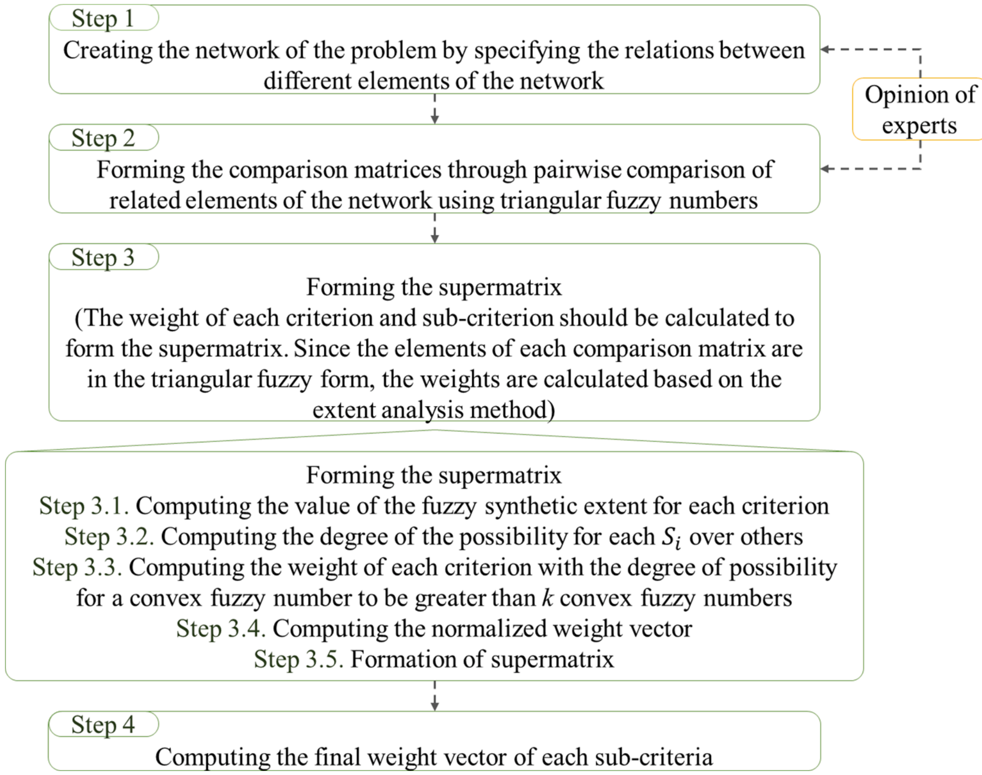

Fig. 3. The steps of the FANP approach.

2.2. *Industry 4.0 and reverse logistics integration challenges*

Careful consideration of the related studies on the area of I4.0 application on manufacturing systems and SCs leads to specifying twenty-one challenges for the adoption of I4.0 on RLs systems. According to the opinion of experts, these challenges are divided into four categories. The category, a short description, and the given code to each challenge are presented in Table 2.

3. Research approach

The summarised approach adopted in the present research is represented in Fig. 2. It can be divided into eight steps. The first step of the presented study is determining the research scops, conducting a thorough review of the related studies, describe the problem and present the research gap on the integration of I4.0 and SSCs and their influence on each other. The second step is identifying the challenges for the purpose of the study according to examined related studies and the experts' opinions. The third step is choosing the proper approaches to address the problem. The selected approaches are the ISM and FANP explored in detail in Sections 3.1 and 3.2, respectively.

Step four is describing the case study and the practical I4.0 based technologies to address the case. Step five specifies the relationship between challenges applying ISM, determining the design of the network of the problem according to experts' opinion. In step six, the consistency ratio of the comparison matrixes formed with the completed questionnaires is checked. Steps two, five, and six are done with the collaboration of qualified experts from the steel industry. In step six, the problem is explained to the selected experts, and the questionnaires, which forms the pairwise matrices, are distributed between the experts to be filled. After collecting the filled questionnaires, these data should be validated based on the consistency ratio of the matrices. The experts are selected through a selection procedure choosing only the ones that satisfy some specified conditions. These prerequisites are that the potential experts at least must have four years of experience in the area of steel SC management or closely related to it, and they should be familiar with I4.0 concepts and applications. Step seven is the application of the FANP approach, solving the problem according to the validated data. The final step is presenting a discussion according to the outcomes and the conclusion of the study.

3.1. *Interpretive structural modelling (ISM)*

Warfield first developed the ISM approach to transform a complicated system into a visualised hierarchical form (Warfield, 1974). The ISM model is used in converting any ambiguous plot, problem, or articulated mental systems into understandable models for more reliable decision-making (Chandra and Kumar, 2019). The ISM model can determine the directional links that help understand the linking factors based on driving and dependence power. The procedure of the ISM is mentioned in the following (Zheng et al., 2017).

Step 1: Developing the structural self-interaction matrix (SSIM)

The relationship between two elements of *i* and *j* is denoted using the following four symbols:

V: meaning that element *i* has an influence on element *j*.

A: meaning that element *j* has an influence on element *i*.

X: meaning that both elements have an influence on each other.

O: meaning that none of the elements has an influence on the other one.

The SSIM is formed based on the opinions of experts regarding the

Table 3
The SSIM.

	R5	R4	R3	R2	R1	T4	T3	T2	T1	E9	E8	E7	E6	E5	E4	E3	E2	E1	C3	C2
C1	O	O	V	O	O	O	O	O	O	V	O	O	A	O	X	O	O	O	O	0
C2	O	X	O	V	O	O	O	A	O	O	V	O	A	O	X	O	O	O	O	
C3	O	O	V	O	O	O	O	A	V	A	O	A	O	X	O	O	A	A		
E1	O	O	O	O	O	O	O	O	V	O	O	O	V	O	A	V	X			
E2	O	A	O	A	O	O	O	A	O	O	O	O	O	O	A	O				
E3	O	O	A	O	O	V	O	O	O	A	O	X	O	A	O					
E4	O	V	A	V	O	O	O	V	O	A	O	A	X	V						
E5	O	O	V	O	O	O	O	O	A	V	O	V	O							
E6	O	O	A	O	O	O	O	O	O	A	O	A								
E7	O	O	A	O	O	O	A	O	O	A	A									
E8	O	X	O	X	O	O	O	O	O	O										
E9	O	O	V	O	O	V	V	O	O											
T1	A	O	A	O	O	A	A	O												
T2	O	X	O	X	O	V	O													
T3	A	O	A	O	A	A														
T4	A	O	A	O	O															
R1	A	O	O	O																
R2	O	A	O																	
R3	A	O																		
R4	O																			

contextual relationship between elements and the mentioned symbols.

Step 2: Forming the reachability matrix

The initial reachability matrix is developed using the following directions for transforming the SSIM into a binary matrix:

Cell (*i, j*) and cell (*j, i*) should be transferred into 1 and 0, respectively, if *V* is assigned to the cell (*i, j*) in SSIM.

Cell (*i, j*) and cell (*j, i*) should be transferred into 0 and 1, respectively, if *A* is assigned to the cell (*i, j*) in SSIM.

Both cells (*i, j*) and (*j, i*) should be transferred into 1, if *X* is assigned to the cell (*i, j*) in SSIM.

Both cells (*i, j*) and (*j, i*) should be transferred into 0, if *O* is assigned to the cell (*i, j*) in SSIM.

The final reachability matrix is formed according to SSIM by considering the transitivity of relations, meaning that if element *i* influences element *j*, and element *j* has an influence on element *k*, then element *i* has necessarily an influence on element *k*. Moreover, elements' dependence and driving power are computed by adding up the number of ones in the columns and rows.

Step 3: Partitioning the reachability matrix

The antecedent and reachability sets for each element are calculated from the final reachability matrix. The antecedent and reachability sets are determined by the column-sum and row-sum of an element and its associated elements in the final reachability matrix. Consequently, the intersection set is formed by determining mutual elements of antecedent and reachability sets. After doing the same process in several iterations, various levels are formed.

The top-level elements will not have an influence on the other elements in the hierarchy digraph. Hence, the intersection set of antecedent and reachability sets for the elements in a specific level will be equivalent to the reachability set (Farris and Sage, 1975). After determining the top-level elements, these elements are excluded from being considered, and the next level of the remaining elements is specified. This process is continued until all levels of the digraph are formed. The top-level elements are located at the top of the digraph, and so on.

Step 4: Forming the hierarchical digraph of ISM

At this step, a digraph is developed following the prioritised reachability matrix. The digraph is obtained by presenting the different levels of elements obtained from the previous step. The top-level elements are located at the top of the digraph, and the second-level elements are placed in second place and so on until all elements are considered in the presented digraph.

3.2. Fuzzy analytic network process (FANP)

In the ANP approach, the relations between different challenges are addressed for realistically assessing them. The ANP was presented as an extension of the AHP by Saaty and Vargas (2006) for coping with the interrelation of different elements of the decision network, which can affect their final score and rankings (Saaty and Vargas, 2006). FANP was proposed to appropriately consider the potential uncertainty in experts' preference in pairwise comparisons. The main reason for using fuzzy logic in decision-making processes, using the opinion of experts, is the existing ambiguity and vagueness in the opinion of experts when they express themselves regarding the superiority or inferiority of one criterion over another (Uygun et al., 2014; Wang et al., 2021). The FANP approach presented by Saaty and Vargas (2006), and the extent analysis method introduced by Chang (1996) are explored in detail by many studies suck as Pourmehdi et al. (2021) and Mistarihi et al. (2020). These steps are summarised in Fig. 3.

4. Case study

Since the adoption of I4.0 initiatives is a complicated process, where different factors affect each other, researchers acknowledge the notion that studies addressing the challenges of the implementation of I4.0 are mainly unexplored in the existing literature and require additional exploration (Horváth and Szabó, 2019). Moreover, according to the research related to the challenges of implementing I4.0, these challenges have only been studied independently and mainly from a technological perspective. Also, considering a specific type of network or industry and evaluating these challenges could present more realistic results. Since the steel industry is a major part of the economy and has an immense influence on the development of a country, careful consideration of all these challenges for efficient application of I4.0 in a developing country to enhance the efficiency and sustainability of the steel RLs system seems necessary.

A case study in active steel RLs systems in Iran is evaluated to verify the applicability of the presented study. The considered manufacturers aim to use I4.0 initiatives on their RLs processes to have sustainable and efficient RLs systems. The determined manufacturers produce steel

Table 4
Final reachability matrix.

	C1	C2	C3	E1	E2	E3	E4	E5	E6	E7	E8	E9	T1	T2	T3	T4	R1	R2	R3	R4	R5	DP
C1	1	1	1	1	1	1	1	1	1	1	O	1	1	1	1	1	O	1	1	1	O	18
C2	1	1	O	1	1	O	1	1	1	1	1	O	O	1	O	O	O	1	O	1	O	12
C3	O	O	1	0	0	1	1	1	1	1	O	1	1	0	1	1	O	O	1	O	O	11
E1	1	1	1	1	1	1	1	1	1	1	O	O	1	O	O	1	O	O	1	O	O	13
E2	O	O	1	1	1	1	0	1	1	O	O	O	1	0	O	O	O	0	1	0	O	8
E3	O	O	1	0	O	1	1	0	1	1	O	0	1	O	1	1	O	O	0	O	O	8
E4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	O	1	1	1	O	19
E5	O	O	1	O	O	1	1	1	1	1	O	1	1	O	1	1	O	O	1	O	O	11
E6	1	1	O	1	1	O	1	1	1	0	1	1	O	1	O	O	O	1	1	1	O	13
E7	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1	O	1	1	1	O	16
E8	O	1	1	O	1	1	1	O	1	1	1	O	O	1	O	O	O	1	O	1	O	11
E9	1	1	1	1	1	1	1	1	1	1	O	1	1	1	1	1	O	1	1	1	O	18
T1	O	O	1	0	O	1	O	1	O	1	O	1	1	O	0	0	O	O	1	O	0	7
T2	O	1	1	1	1	O	1	1	O	O	1	O	1	1	1	1	O	1	1	1	O	14
T3	O	O	1	O	O	1	1	1	1	1	O	0	1	O	1	0	O	O	0	O	0	8
T4	O	O	O	O	O	0	O	1	O	1	O	0	1	0	1	1	O	O	0	O	0	5
R1	O	O	O	O	O	O	O	O	O	1	O	O	1	O	1	O	1	O	O	O	0	4
R2	O	1	1	1	1	O	1	O	O	1	1	O	O	1	O	1	O	1	O	1	O	11
R3	1	1	1	1	1	1	1	1	1	1	O	0	1	1	1	1	O	1	1	1	0	17
R4	O	1	1	1	1	O	1	O	O	1	1	O	O	1	O	1	O	1	O	1	O	11
R5	O	O	O	O	O	1	1	1	1	1	O	O	1	O	1	1	1	O	1	O	1	11
De	8	12	16	12	13	14	17	16	15	18	7	7	16	11	12	14	2	11	13	11	1	

DP = Driving Power.
De = Dependence.

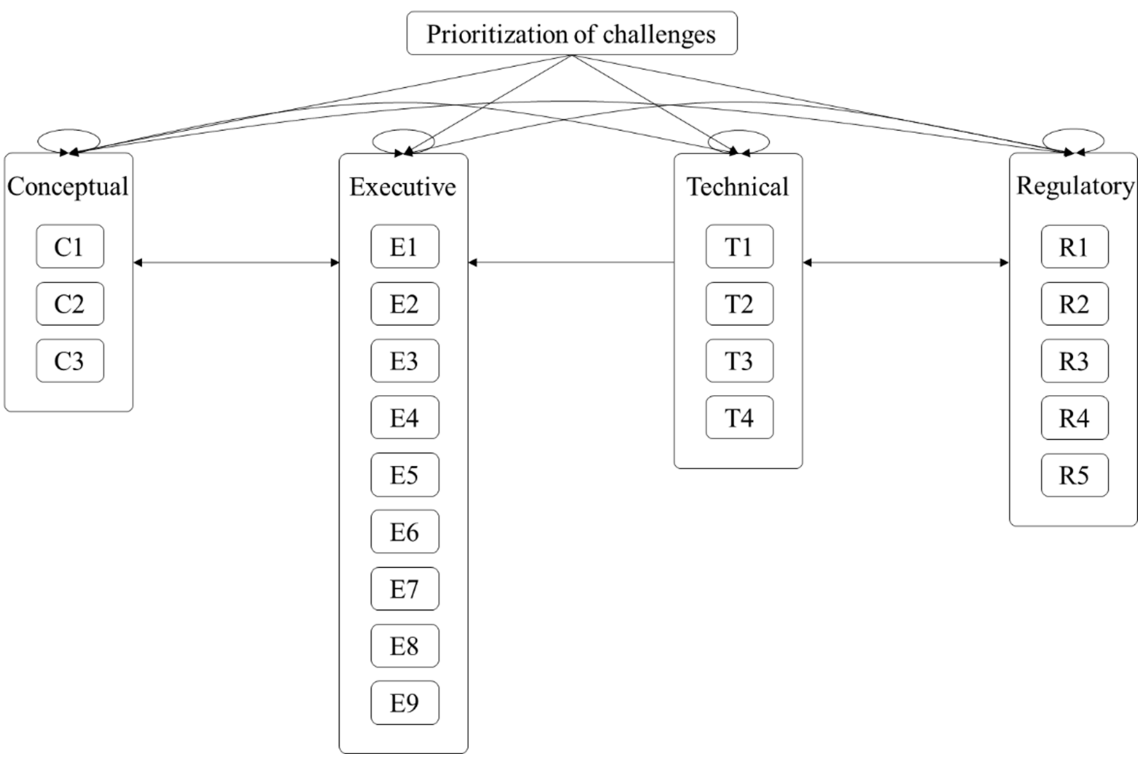

Fig. 4. The designed network for challenges.

Table 5
Final ranking and score of each challenge.

Challenge	C1	C2	C3	E1	E2	E3	E4	E5	E6	E7	E8
Rank	2	7	10	8	14	20	1	6	3	9	18
Score	0.129	0.048	0.031	0.042	0.016	0.003	0.216	0.060	0.119	0.040	0.008
Challenge	E9	T1	T2	T3	T4	R1	R2	R3	R4	R5	
Rank	5	15	11	17	19	21	16	4	12	13	
Score	0.075	0.015	0.026	0.009	0.004	0.002	0.014	0.092	0.021	0.020	

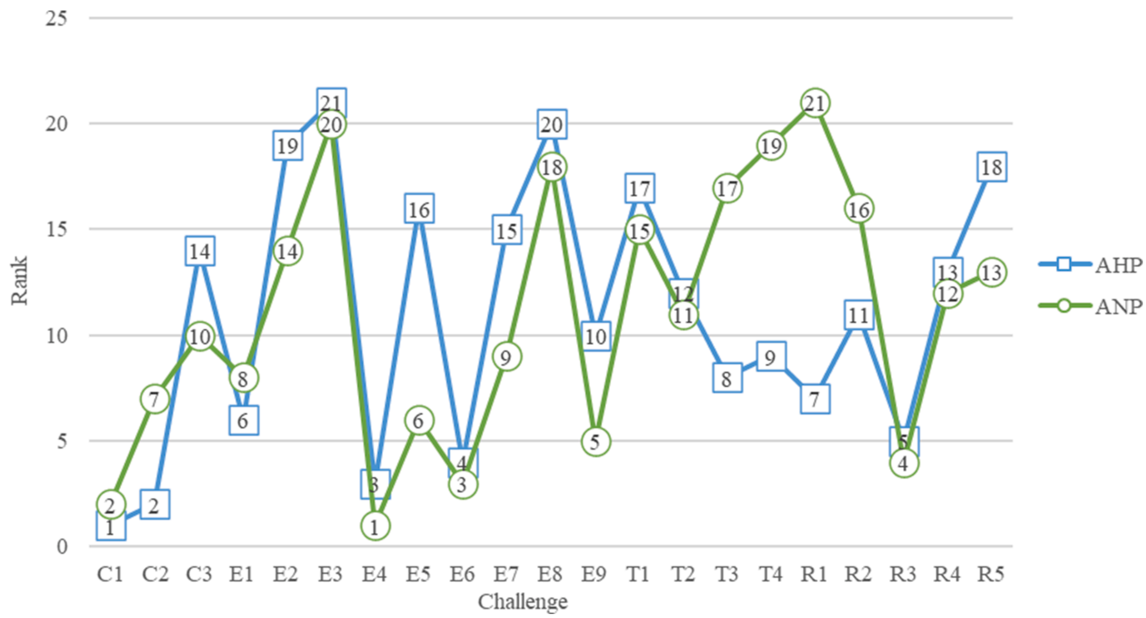

Fig. 5. Ranking of challenges based on FAHP and FANP.

billets with the main raw material of scrap, which is produced from the final products of the steel SC or in the processes of manufacturing different products with steel. Currently, the purchasing managers of these companies frequently check the level of their inventory. When they feel that they need to purchase scrap, they start to negotiate with their associates for purchasing their required scrap, which may not be the most efficient approach or even works in favour of the dimensions of sustainability. Hence, they intend to change their approach and make it more efficient and sustainable through I4.0, where it is anticipated that they would face challenges.

4.1. Data collection

The prioritisation of the determined challenges is done in two steps. The first step specifies the relationship between challenges through the ISM approach, explored in Section 3.1. The final score of challenges utilised for their ranking is computed using FANP, explored in Section 3.2. The opinion of the qualified experts is utilised in both the mentioned methods.

These experts are selected following the considered requirements. The selection requirements led to mainly selecting production and senior managers of steel producers and their scrap providers from three major steel manufacturer and their primary scrap provider companies in Iran. Also, due to the conditions, four academic researchers that satisfied the requirements were selected as experts. In general, twenty experts were specified, so their opinion could be used in the process of finding the relationship between challenges and prioritising them. The information about the qualification of the selected experts is presented in Table A1.

4.2. Determining the interrelation of challenges

In this step, a designed questionnaire was given to the experts. In this survey, the experts were asked to give their opinion about the relationship between challenges. The experts were asked to decide whether, in their opinion, one challenge can have an influence on the rest of the challenges, and vice versa, for each challenge. Hence, they must answer a total of twenty-one questionnaires, converted to the SSIM. For example, they have to say whether challenge C1 can have an influence on challenge C2 and whether challenge C2 can have an influence on challenge C1. If the answers to both questions are yes, it means that these challenges can have an influence on each other, creating a two-way relationship.

Since there is more than one expert, the average of their opinions should be considered, meaning that more than half of the experts should be unanimous regarding their answers to a question. This means that in this problem, if only eleven experts or more were unanimous, their opinions were validated. In situations where there was a tie between the opinions of experts, virtual conferences were held between them so they could convince each other to reach a single opinion or at least have eleven unanimous opinions. The SSIM, based on the opinion of the experts, is presented in Table 3.

Although twenty-one challenges are considered for the study, Table 3 has twenty rows and columns indicating that the influence of a challenge on itself would not be considered in the evaluation process. After applying the second step of the ISM, the final reachability matrix, presented in Table 4, would be given.

The ISM method categorises the challenges into four levels. The challenges at the last level are the most independent ones, which are lack of training programs, digital culture, and governmental support and policies. The challenges at this level drive the challenges of the level above them. The challenges in the middle levels are mainly the ones that act as linkages in the whole problem, and they mostly have high driving and dependence power. Poor existing data quality, which is the challenge at the top level, is dependent on other challenges below it for its influence on the final goal of the problem.

Following the previous step and applying the following two steps of ISM would present the determined levels of the challenges. The levels and the elements of each level are presented in Table A2.

4.3. Ranking the challenges

The SSIM of the ISM approach is used to determine the influence of challenges on each other, so the network of challenges, which is a prerequisite for the FANP, would be formed. Hence, the interrelationship of challenges can be determined through the ISM, but it cannot be used to prioritise the challenges based on their influence, which is the primary goal of the problem. Therefore, the ANP approach is applied to rank the challenges based on their influence on the integration of I4.0 and sustainable RLs systems. The network of challenges presented in Fig. 4 is formed based on the opinion of experts and the ISM. After presenting the challenges and their relationships, the required twenty-four comparison matrices are filled with the judgment of the same qualified experts from the case study. The twenty-four comparison matrices are divided into three sets. The first set has only one matrix that determined the influence of challenge categories on each other. The second set has four matrixes, each of which specifies the influence of challenges on each other in a challenge category. The third and last set has nineteen members determining the influence of challenges on each other from different challenge categories. After collecting the questionnaires, the consistency ratio of each matrix is computed. In cases of having matrices with a consistency ratio bigger than 0.1, the expert was asked to fill the questionnaires related to the specified matrices with a consistency ratio bigger than 0.1 again.

After applying the steps of the FANP method based on verified information, the unweighted supermatrix, which is utilised for determining the final rank of challenges, would be formed. The unweighted supermatrix is presented in Table A3. The final score and ranking of the challenges extracted from the limit supermatrix, which is the result of the final step of the FANP approach, are presented in Table 5.

The final results show that the most significant challenges are the absence of experts in I4.0, lack of clear comprehension of I4.0 concepts, and lack of training programs, respectively. Moreover, the final ranking of challenges, according to FAHP and FANP, are presented in Fig. 5 to show the effects of interrelation between challenges on their final ranking. As mentioned, the main reason for using the ISM and FANP is to address the interrelation of challenges adequately. The FAHP is chosen for the comparison because its main difference with the FANP is the lack of interrelations between the elements of the network, showing the effects of interrelation between challenges on their final ranking.

5. Discussion

One of the other contributions of the presented study is to provide tailored insights for managers who intend to adopt I4.0 for the sustainable future of their RLs systems in developing countries. The study presents clear insights for managerial parties of SCs that intend to adopt I4.0 initiatives to enhance the overall efficiency of their reverse flow through creating intercommunication amongst SC associates. The result singles out the challenges that are the most significant ones. Moreover, discussion of these results and managerial implications provides solutions for the efficient adoption of I4.0. Since the weights of the challenges that are ranked one to four are more than half of the weights of all the challenges, it is evident that finding solutions for these four challenges can significantly improve the application of I4.0. Hence, some potential strategies are presented for addressing these challenges in the following.

- The final results of computing scores of challenges show that the absence of experts in I4.0 (E4) and lack of training programs (E6) are the first and third most significant challenges in adopting I4.0. E4 has the highest driving power among the other challenges, and E6 has the driving power of 13. This means their improvement significantly alleviates the pressure of I4.0 adoption and positively influences other challenges. According to the SSIM of ISM, these challenges have a two-way relationship, so the managers can simultaneously ease the pressure of adopting I4.0 by proper strategies for addressing these challenges. One of the most critical decisions could be using novel competent educational approaches (Salah et al., 2019) and hiring experts (Stachová et al., 2019) from developed or even developing countries like India that are interested and successful in the application of I4.0 (Stroiteleva et al., 2019). These experts can also perform as instructors and hold training programs for the experts of the company so they could work independently in the future (Coşkun et al., 2019).
- Lack of clear comprehension of I4.0 concepts (C1) is the second most critical challenge and the challenge at the third level of the ISM hierarchy. It also has the second-highest driving powers, among other challenges, implying that this challenge has an influence on most of the other challenges. This challenge is in the third level of the ISM hierarchy, and because of having strong driving power and dependence, it creates a linkage between the challenges of levels four and two. Since these kinds of challenges are influenced by some challenges and have an influence on others, they should be properly considered for presenting more practical solutions. This challenge stems from the small number of studies related to the concept of I4.0 (Beier et al., 2020). The managers of companies that intend to utilise I4.0 initiatives on their system can encourage practitioners and academia through the financial and implicational support of researchers aiming to study these issues. Also, training experts in this field could ease the pressure of this challenge (Kamble et al., 2018a; Xu et al., 2018).
- Lack of governmental policies and support (R3) is ranked as the fourth most significant challenge by the FANP and was categorised at the last level of the ISM hierarchy. It is an independent challenge, affecting some of the other challenges due to having high driving power. In most developing countries, especially in Iran, most industries work under the direct supervision of the government, and government policies directly affect them. This means that these policies can have a significant influence on the industry (Sutthichaimethee et al., 2019). Due to the uncertainties regarding the understanding and application of novel means and methods of production planning and control, the reluctance toward them is penetrated to all levels of society. The government and policy analysts are not exceptions. Hence, they do not consider these kinds of new technologies and do not create policies for supporting their application (Aggarwal et al., 2019).

Based on the study conducted by Mastos et al. (2020), steel manufacturers can use the following suggested component of I4.0 for moving toward more sustainable RLs systems.

- IoT fill level sensors deployed for scrap containers in collection centres and scrap producers
- A real-time supervision system for fill level of scrap containers
- A notification system informing the manufacturer about scrap accumulation and shipping
- A visual and data analytics platform for the manufacturer to optimise its planning operations
- An online ecosystem for automatic negotiations among scrap producers and collection centres, and the manufacturer

6. Conclusion

Studies have been conducted in the area of I4.0 from the technical perspective regarding the challenges in the adoption of I4.0. Although some studies evaluated these challenges and tried to prioritise them, the existing gap for a proper evaluation of I4.0 adoption challenges in RLs systems in developing countries is filled by this research. RLs is a significant part of current SCs, and its optimisation can positively affect the sustainability of these systems. This research fits amongst the few studies intending to evaluate the potential challenges of I4.0 adoption for moving toward a more sustainable future. The identified challenges for adopting I4.0 are specified by reviewing the most recent studies and interviews with determined experts to select the ones with the highest compatibility to the conditions of the problem. After applying the research methodology, the four most significant challenges that could hinder the efficient adoption of I4.0 initiatives integrated with sustainable steel RLs systems would be determined. They are the absence of experts in I4.0, the lack of clear comprehension of I4.0 concepts, training programs, and governmental policies and support. The results showed that more than half of the total weights of challenges are associated with these four, meaning that adequately addressing them can significantly alleviate the pressure on managers for efficient integration of I4.0 and steel RLs. These challenges were explored in the discussion section, and some strategies were presented for addressing them. The limitation of this study is in evaluating the results of using I4.0 based technologies to observe the exact influence of the changes caused by this process on the sustainability of the steel RLs system.

In future research, the application process of adopting I4.0 technologies can be considered in the SC planning stage. A potential future study can be evaluating the conditions of the system before and after adopting I4.0 for a better evaluation of its effects on the processes of the logistics system and sustainability. Moreover, considering other industries similar to the steel industry and integrating data from different sources or even similar countries can provide more generic results.

CRediT authorship contribution statement

Mohammad Pourmehdi: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft. **Mohammad Mahdi Paydar:** Supervision, Conceptualization, Methodology, Validation, Writing – review & editing. **Pezhman Ghadimi:** Conceptualization, Methodology, Writing – review & editing. **Amir Hossein Azadnia:** Supervision, Conceptualization, Methodology, Validation, Writing – review & editing.

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.

Appendix A

See Tables A1–A3.

Table A1
Characteristics of the selected experts.

Number	Position and expertise	Gender	Years of experience
1	Production manager in steel manufacturer 1	Male	7
2	Production manager in steel manufacturer 1	Male	5
3	Production manager in steel manufacturer 1	Female	5
4	Senior manager in steel manufacturer 1	Male	6
5	Senior manager scrap provider company 1	Female	5
6	Senior manager scrap provider company 1	Male	6
7	Production manager in steel manufacturer 2	Female	5
8	Production manager in steel manufacturer 2	Male	6
9	Senior manager in steel manufacturer 2	Female	6
10	Senior manager scrap provider company 2	Female	5
11	Senior manager scrap provider company 2	Male	5
12	Production manager in steel manufacturer 3	Female	5
13	Production manager in steel manufacturer 3	Male	7
14	Senior manager in steel manufacturer 3	Male	7
15	Senior manager scrap provider company 3	Male	6
16	Senior manager scrap provider company 3	Female	5
17	Associate professor Industrial engineering	Male	8
18	Assistant professor Industrial engineering	Male	6
19	Associate professor Management science	Male	7
20	Associate professor Management science	Female	5

Table A2
Levels of challenges.

Level	Challenge
1	T1
2	E2, E5
3	C1, C2, C3, E1, E3, E4, E7, E8, T1, T3, T4, R1, R2, R4, R5
4	E6, E9, R3

Table A3
Unweighted supermatrix.

		Category				Challenges																				
	G	C	E	T	R	C1	C2	C3	E1	E2	E3	E4	E5	E6	E7	E8	E9	T1	T2	T3	T4	R1	R2	R3	R4	R5
C	0.283																									
E	0.331																									
T	0.165																									
R	0.218																									
C1		0.529										0.233					0.653							0.289		
C2		0.354										0.152				0.408							0.251		0.331	
C3		0.116											0.341					0.079						0.098		
E1			0.172					0.265		0.251	0.251			0.204				0.234								
E2			0.056					0.051	0.346																	
E3			0.002												0.079						0.098					
E4			0.231			0.644	0.321		0.653	0.289			0.408	0.289					0.408				0.289		0.283	
E5			0.083					0.194			0.155				0.192		0.346							0.204		
E6			0.204			0.355	0.279					0.265														
E7			0.096					0.152			0.098	0.103		0.098												
E8			0.015												0.079								0.098		0.162	
E9			0.136					0.233			0.204	0.051		0.155	0.234					0.257	0.251			0.251		
T1				0.162									0.249													
T2				0.222			0.226	0.103		0.204											0.204		0.204		0.222	
T3				0.331											0.146			0.192								
T4				0.283														0.146		0.205						
R1					0.251															0.245						
R2					0.204					0.155						0.341			0.341							
R3					0.289						0.289	0.194		0.251	0.268			0.268		0.127	0.289					
R4					0.155		0.172			0.098						0.249			0.249				0.155			
R5					0.098													0.079		0.163	0.155			0.155		

G: Goal.
C: Conceptual.
E: Executive.
T: Technical.
R: Regulatory.

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