# Investigating potential interventions on disruptive impacts of Industry 4.0 technologies in circular supply chains

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# Investigating potential interventions on disruptive impacts of Industry 4.0 technologies in circular supply chains: Evidence from SMEs of an emerging economy

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## ARTICLE INFO

## ABSTRACT

As a transversal theme, the intertwining of digitalization and sustainability has crossed all Supply Chains (SCs) levels dealing with widespread environmental and societal concerns. This paper investigates the potential interventions and disruptive impacts that Industry 4.0 technologies may have on pharmaceutical Circular *SCs* (*CSCs*). To accomplish this, a novel method involving a literature review and Pythagorean fuzzy-Delphi has initially been employed to identify and screen categorized lists of Industry 4.0 Disruptive Technologies (*IDTs*) and their impacts on pharmaceutical *CSC*. Subsequently, the weight of finalized impacts and the performance score of finalized *IDTs* have simultaneously been measured via a novel version of Pythagorean fuzzy SECA (Simultaneously Evaluation of Criteria and Alternatives). Then, the priority of each intervention for disruptive impacts of Industry 4.0 has been determined via the Hanlon method. This is one of the first papers to provide in-depth insights into advancing the study of the disruptive action of Industry 4.0 technologies cross-fertilizing *CE* throughout pharmaceutical *SCs* in the emerging economy of Iran. The results indicate that digital technologies such as Big Data Analytics, Global Positioning Systems, Enterprise Resource Planning, and Digital Platforms are quite available in the Irans' pharmaceutical industry. These technologies, along with four available interventions, e.g., environmental regulations, subsidy, fine, and reward, would facilitate moving towards a lean, agile, resilient, and sustainable supply chain through the efficient utilization of resources, optimized waste management, and substituting the human workforce by machines.

## 1. Introduction

Traditional business models have been criticized for poor ecological imbalances (i.e., higher resource consumption, waste production, environmental pollution, global warming, and environmental degradation) and various social issues, including poverty, inequality, prosperity, and peace and justice concerns (Bai et al., 2020). These dilemmas have recently highlighted the importance of studying two disruptive concepts in *SC* Management (*SCM*), namely: Industry 4.0 and Circular Economy (*CE*) (Mastos et al., 2021). The fourth industrial revolution, name Industry 4.0, has seen the development of various technological advancements. These technologies have radically altered the traditional *SC*

processes, i.e., strategy & planning, supply & make, deliver & return, and fundamentals & support (Frank et al., 2019). For instance, Goasduff (2020) predicted that drone delivery would decrease transportation costs by 70 % and make the delivery and return process more energy efficient. The MarketsandMarkets report denoted that the drone delivery market will expand from $528 million in 2020 to $39 billion in 2030 (Dunnigan, 2021). Similarly, Dutta (2021) indicated that big data and predictive maintenance technology might decline machine downtime by 50 % and even prolong machine life by 40 %. As a consequence of the broader application of Industry 4.0 Disruptive Technologies (*IDTs*), but massive data in the pharmaceutical industry, IQVIA predicted that the value of this industry will increase from $1.2 trillion in 2018 to $1.5

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trillion in 2023 (Linchpin, 2022). With this in mind, high-tech and new technologies such as big data, cloud computing, the internet of things, etc., are known as *IDTs* (Abdel-Basset et al., 2021).

Similarly, *CE* is a new business mindset that is coupled with the Triple Bottom Line (*TBL*) (i.e., economic, environmental, and societal pillars) towards sustainable development (Lopes de Sousa Jabbour et al., 2018). *CE*-focused *SC*, known as Circular *SC* (*CSC*), offers a new closed-loop production-consumption scheme by implementing restorative systems involving the 5Rs (Repair, Reuse, Refurbishment, Remanufacturing, and Recycling) (Bressanelli et al., 2019). With the aid of the main building blocks (circular product design, servitised business models, reverse logistics, and enablers), *CSCs* aim to improve economic efficiency, optimize resource utilization and waste management, reduce environmental pollution and eventually improve human welfare (Parajuly & Wenzel, 2017). Advanced technologies are required to overcome the obstacles hindering the full adoption of *CSCs*. Generally, *IDTs* have been acknowledged as a capable tool to pave the way for *CE* principles (Lopes de Sousa Jabbour et al., 2018). Practically, several benefits of *SC* 4.0 such as promptly innovation activation, 20 % decrease in time-to-market, 30 % − 50 % growth of anticipation accuracy, 20 % − 50 % decrease in scrap and rework, as well as an 8 % increase in on-time delivery, subsequently result in (i) lower environmental pollution (air, water, and sound), (ii) growing efficiency and effectiveness, (iii) cost reduction, and (iv) high level of both customer and employee satisfaction (Singla, 2019), which are similar to the effects of *CSC*. Recent scholars have theoretically highlighted the relationship between *IDTs* and *CE* principles (Cezarino et al., 2019; Lopes de Sousa Jabbour et al., 2018; Mastos et al., 2021; Nascimento et al., 2019). Moreover, the impacts of *IDTs* on *SC* sustainable development from the *TBL* point of view have recently been emphasized. For instance, Bai et al. (2020) discussed that *SC* production flexibility and operational productivity (efficiency and effectiveness) could be achieved through emergent transmission, information, and intelligent technologies. Machado et al. (2020) asserted that economic efficiency growth, cutback of waste, energy consumption, overproduction, routine jobs, and job opportunities creation would result from Industry 4.0 technologies' implementation. However, some practical concerns such as lack of *IDTs* infrastructure, high investment cost, and vague return, i.e., England's pharmaceutical industry should spend $4.5 Billion on Digital Transformation by 2030 (ABI Research, 2021), resistance towards change, etc., are still impeding the implementation of *CSC* 4.0, particularly in poor emerging economies (Kumar et al., 2020; Mangla et al., 2022). To deal with such concerns, the role of potential interventions is undeniable. For instance, governmental incentives and preventive policies such as giving funds and imposing fines could assist in the transformation of *CSCs* 4.0 (Hinings et al., 2018). Nonetheless, there are still research gaps related to providing a categorized list of *IDTs* based on their relevance to each SC process and a categorized list of potential impacts of *IDTs* in designing innovative *CSCs* through relevant theories such as *TBL*, *CE* principles, etc. Furthermore, some interventions, such as environmental regulations, fine, rewards and subsidies, still incite firms towards *IDTs* and *CSCs*. To the authors' best knowledge, due to the recent emergence of *IDTs* and *CSC*, the investigation of interventions on disruptive impacts of Industry 4.0 technologies on *CSCs* have not yet been addressed.

Moreover, the limited recent research that has connected CSCs and *IDTs* has mainly employed qualitative methodologies. For instance, Cezarino et al. (2019) used literature review and structuralism approaches to propose an original framework to overcome implementation obstacles of *CSCs* through *IDTs*. Mastos et al. (2021) employed a literature review and real-world scenario analysis to evaluate the application of *IDTs* in the sustainability performance of *CSCs*. Nonetheless, quantitative approaches such as hesitant fuzzy VIKOR (Bai et al., 2020) and fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) (Nara et al., 2021) have been applied along with the literature review method to evaluate *IDTs* based on their sustainable performance and application. To the best knowledge of the authors, a mixed-method

of literature review and Pythagorean fuzzy-Delphi has not yet been developed to identify and screen research items. Besides, Pythagorean fuzzy SECA has not yet been proposed to simultaneously measure the weight of criteria and the performance score of alternatives.

Additionally, prioritizing techniques such as the Hanlon method have not been employed in *CSCs* and *IDTs*. With this in mind, this paper aims to (i) propose two categorized list of *IDTs* and their potential impacts on *SCM* via the literature review approach and the extant relevant theories, (ii) conduct the Pythagorean fuzzy-Delphi analysis to screen the two lists through an example of pharmaceutical *CSCs* of Iran's emerging economy, (iii) carry out the Pythagorean fuzzy SECA analysis to simultaneously measure the weight of each impact of IDT on pharmaceutical *CSCs* and the performance score of each IDT, and (iv) employ the Hanlon method to prioritize each intervention for each impact. Thus, this paper addresses the following questions:

- Which IDTs play a role in CSCs, and what are their potential impacts?
- How significant are these impacts in pharmaceutical supply chains?
- What are the essential IDTs in pharmaceutical supply chains?
- What interventions may benefit from the IDTs in the pharmaceutical supply chains of the emerging economy of Iran?

The results of this mixed method would provide practitioners with an effective strategy selection to address the challenge of implementing a pharmaceutical *CSC* 4.0 in emerging economies (Erdogan et al., 2018).

The remainder of this paper is formed as follows. Section 2 presents two categorized lists of IDTs and their impacts on SCM. The research methodology, including the Pythagorean fuzzy-Delphi, Pythagorean fuzzy SECA, and Hanlon methods, are described in Section 3. The results and findings are presented in Section 4, while Section 5 focuses on the discussion and implications derived from the present research. Finally, Section 6 culminates the paper by giving the limitations and future research directions.

## 2. Literature review

Industry 4.0 is a concept coined in 2011 by a German initiative of the federal government with universities and private enterprises. As a strategic scheme, it was developed to enrich production systems by promoting productivity (efficiency and effectiveness) in the manufacturing industry (Frank et al., 2019). According to Weyer et al. (2015), Industry 4.0 contains three paradigms, (i) the *Smart Product*, which deals with objects and machines that are furnished with sensors and actuators, audited by software, and linked to the internet; via which the product can warn the machine-related manufacturing information; (ii) the *Smart Machine*, which refers to devices that machine-to-machine and/or cognitive computing technologies are embedded in them. These machines can reason, problem-solve, and make and launch a decision. Lastly, (iii) the *Augmented Operator* highlights automating system knowledge. It reflects the high-tech knowledge-based support of the employee in the production system with superior flexibility and modularity. Six principles involving *interoperability*, *virtualization*, *decentralization*, *real-time capability*, *service orientation*, and *modularity* are necessary to take action in *Industry 4.0* (Oztemel & Gursev, 2020). Thereupon, Industry 4.0 is defined as "an integrated, consistent, optimized, service-oriented, and interoperable manufacturing process; in which algorithms, big data, and high technologies are embedded" (Lu, 2017). Fig. 1 illustrates the paradigms and principles of Industry 4.0.

Accordingly, Industry 4.0 is chiefly based upon the advent of new communication, information, and intelligent technologies, named *Industry 4.0 Disruptive Technologies (IDTs)*. On the one hand, Bai et al. (2020) divided *IDTs* into *physical* and *digital* technologies. The *physical* category includes manufacturing technologies, e.g., *additive manufacturing, sensors, drones*, etc. The *digital* category mainly covers modern information and transmission technologies, e.g., *cloud computing, blockchain, big data analytics, simulation*, etc. However, it is
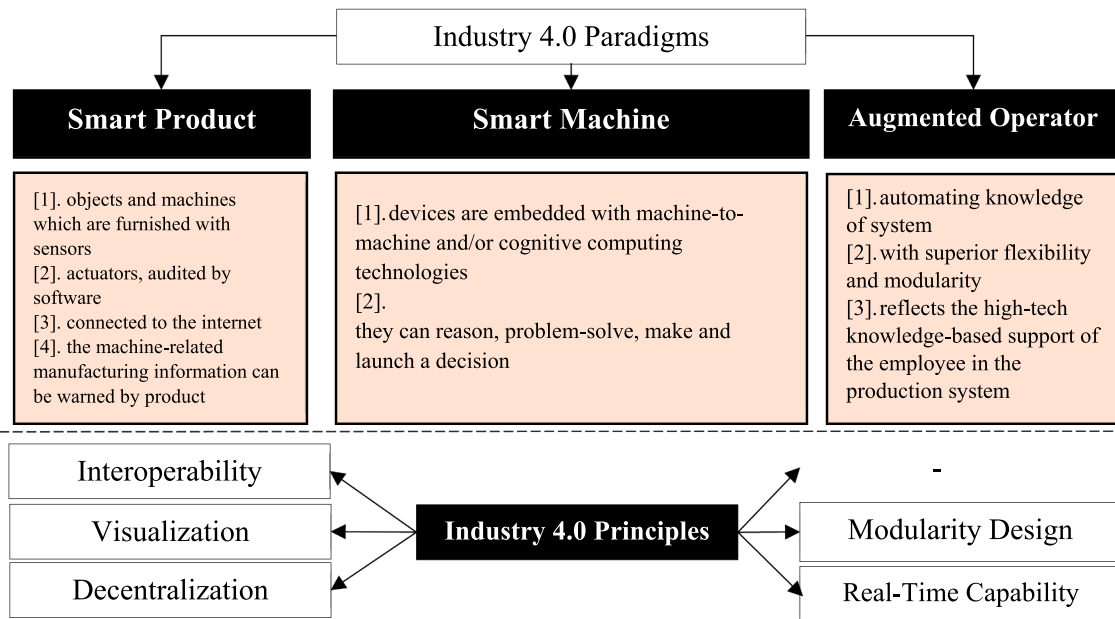
**Fig. 1.** Industry 4.0 paradigms and principles.

criticized that all technological components of Industry 4.0 are somewhat digital and physical. For instance, the *Internet of Things (IoT)* relies on physical devices such as sensors, networking systems, edge computers, and storage systems. Thus, IoT may not be accurately inserted into the digital category.

On the other hand, Frank et al. (2019) separated *IDTs* into two core layers, i.e., (i) *base technologies* that include the *IoT*, *cloud*, *big data*, and *analytics* (e.g., *data mining* and *machine learning*) and (ii) *front-end technologies,* which embrace the rest of the *IDTs*. These are categorized into four sub-streams: *smart manufacturing*, *smart product*, *smart SC*, and *smart working*. To our knowledge, IDTs associated with the SCM context have not yet been categorized based on SC processes. In this regard, a novel integrated view of the SCOR model and the house of process derived from Michael Porter's Value Chain model was employed. Indeed, the concept of SCOR was introduced by the supply chain council in 1996, by which five mega processes, including plan, source, make, and deliver and return, were considered to meet customers' orders. The house of process divides business processes into three main categories; the house's roof contains managerial and strategic processes, the body covers the core processes, and the bottom includes supportive and administrative processes. By combining these two perspectives, a house of SC was hence contextualized. In this line, the roof was assigned to (i) the processes of strategy and plan, whereas the body was divided into two classes, namely (ii) supply & make, as well as (iii) deliver & return processes. Finally, the bottom refers to (iv) the fundamentals and support processes. Accordingly, the house of SC 4.0 can be accomplished by embedding such appropriate *IDTs* in each relevant category. A list of IDTs associated with the SCM context was initially identified through reviewing the contemporary literature. In doing so, the authors carried out a keywords-based search on Google Scholar, Scopus, and ISI Web of Knowledge databases. Keywords such as *"Industry 4.0 Disruptive Technologies employed in SCM"* and *"Industry 4.0 Technologies relevant to the SCM context"* were used. The data source creation step finally collected ten more relevant papers published between 2015 and 2021, resulting in 26 *IDTs*. Most recent scholars have studied base technologies from different perspectives (e.g., Frank et al., 2019). Nevertheless, the authors then categorized the 26 *base* and *front-end* technologies based on their application in each part of the introduced house of SC. As a result, a categorized list of 26 *IDTs*, along with their descriptions, is presented in Table 1.

With this in mind, the strategy & plan category includes the *IDTs* applied in determining extended- and short-term plans for sourcing, manufacturing, delivering, and returning products. For example, *ERP* is a mega coordination technology that holistically links different operations, which assists in real-time data-sharing and prompts decision-making, anticipation, and risk management. Furthermore, remote control and monitoring of sourcing, manufacturing, delivery, and returning activities are essential. For instance, *SCDA* is a kind of control system architecture in this category, via which a considerable amount of data is compiled to facilitate the remote control and monitoring of manufacturing and transportation operations. On the other hand, *MES* warrants the maximum efficiency of manufacturing and logistics plans through tracking and gathering real-time data throughout the product lifecycle and on every piece of equipment embedded in the production process from order to delivery. Moreover, *AI* and *BI* have countless applications in setting plans, such as optimizing stock, lead times, supplier selection, and forecasting demand and supply. Generally, creating a strong linkage between the *IDTs* inserted in the strategy & plan category (*EPR, MES, SCDA, H/VSI, AI, and BI*) would bring the outputs of ideal plans closer to reality.

Considering the House of SC.4.0 scheme, illustrated in Fig. 2, the *IDTs* involved in the functional layer (supply & make, and deliver & return) are distinctly applied in sourcing, manufacturing, delivery, and return operations. For example, *3D printing*, *Nanotechnology*, *FALs*, and *EMSs* have more applications in manufacturing processes. Besides, *SA*, *CPS*, and *M2M* can be employed in supply and manufacturing processes. Moreover, *VT*, *AIDC*, *Drones*, and *GPS* facilitate delivery & return processes. Nevertheless, the rest of the *IDTs* are somewhat essential and can fundamentally be applied in each category mentioned above. In this respect, the authors have proposed a bottom layer, fundamentals & support, covering supportive *IDTs* such as *BDA, CT, IoT, MT, DPs, simulation, Blockchain, and Cybersecurity*.

From a different point of view, Industry 4.0 has radically altered how *SCs* are designed and operated. Albeit, research on the impacts of Industry 4.0 on *SCM* is still scarce. Nevertheless, the significant impacts of *IDTs* on different paradigms of *SCM*, particularly sustainable and circular *SCM*, deserve specific attention. For instance, Ab Rahman et al. (2017) reviewed the application of emerging disruptive technologies to *SCM*. Das et al. (2019) analyzed the impacts of *IDTs* on SC risk management. A year later, Bai et al. (2020) evaluated *IDTs* based on their

**Table 1**

list of Industry 4.0 disruptive technologies.

| Category | Code | IDT | Description | Literature support |
|---|---|---|---|---|
| **Strategy & Plan** | PT1 | Supervisory Control and Data Acquisition (SCDA) | Software and hardware systems allow companies to control processes locally/remotely, gather real-time data, record phenomena into log files, and directly work alongside other devices, e.g., sensors, motors, etc. | (Jeschke et al., 2017) |
| | PT2 | Enterprise Resource Planning (ERP) | Technologies and systems companies that manage and integrate business processes (i.e., scheming, supplying, marketing, financing, human resources, etc.) with resource planning | (Jeschke et al., 2017) |
| | PT3 | Horizontal/Vertical System Integration (H/VSI) | Integrating diverse computing systems and software packages to construct a more comprehensive system. It is well-suited for monitoring and managing systems risk. It is helpful to enhance system value by formulating new functionalities via combining sub-systems and software applications | (Rane et al., 2019) |
| | PT4 | Manufacturing Execution System (MES) | A comprehensive and dynamic software system to monitor, track, document, and control the process of preparing final products from raw materials | (Jeschke et al., 2017; Telukdarie et al., 2018) |
| | PT5 | Artificial Intelligence (AI) | Computer science principles that underline the creation of intelligent devices working and reacting analogous to humans | (Bai et al., 2020) |
| | PT6 | Business Intelligence (BI) | A technological platform is employed to collect, analyze, | (Ghadge et al., 2020) |

**Table 1** (*continued*)

| Category | Code | IDT | Description | Literature support |
|---|---|---|---|---|
| | | | warehouse, and provide business data from several bases. It facilitates the decision-making process by transforming raw data into mature information | |
| **Supply & Make** | MT1 | Additive Manufacturing (3D-printing) | Initiates three-dimensional (3D) solid objects by applying a complex of additive development processes; which aims to untie design alternatives and attain a significant possibility for mass-customization | (Bai et al., 2020) |
| | MT2 | Autonomous and Collaborative Robots or Cobotic Systems (Robotics) | An interdisciplinary branch of computer science and engineering that aims to iterate human actions in manufacturing via Collaborative Robotics, by which employees and machines act in a shared learning setting | (Nara et al., 2021) |
| | MT3 | Nanotechnology (molecular nanotechnology) | The attaint of material on a near-atomic scale to generate new products | (Bai et al., 2020) |
| | MT4 | Sensors and Actuators (SA) | A device that reacts to physical drivers, e.g., sound, light, heat, etc., and transmits impulses to measure or control operations | (Bai et al., 2020) |
| | MT5 | Machine-to-Machine Communication (M2M) | An interoperable wired/wireless communication system, which enables devices to perceive together and facilitates their adjustment in manufacturing lines | (Frank et al., 2019) |
| | MT6 | Cyber-Physical Systems (CPS) | An intelligent system in which workmanship is controlled by computer-based principles such as smart grids, autonomous automobile | (Wang et al., 2015) |

**Table 1** (*continued*)

**Table 1** (*continued*)

| Category | Code | IDT | Description | Literature support |
|---|---|---|---|---|
| | MT7 | Flexible and Autonomous Lines (FALs) | systems, medical monitoring, industrial control systems, robotics systems, etc. A set of technological machines that can recognize products ties in the sensors inserted in them and fulfill required activities to produce | (Frank et al., 2019) |
| | MT8 | Energy Management Systems (EMSs) | Monitoring and improving energy efficiency via intelligent systems | (Frank et al., 2019) |
| **Delivery & Return** | DT1 | Visualization Technology (augmented and virtual reality) (VT) | It is a computer simulation that employs 3D graphics and devices to provide an interactive reality-based experience. Augmented Reality is a complex of innovative Human-Computer Interaction (HCI) techniques that links virtual objects and interacts in the actual setting. Virtual Reality is creating an interactive world that permits a user to monitor the unreal object and whole unreal arena in actual-time | (Zheng et al., 2021) |
| | DT2 | Unmanned aerial vehicles (Drones) | An aircraft without a human pilot on board, namely, a drone used to deliver materials/final products, etc. | (Bai et al., 2020; Garay-Rondero et al., 2020) |
| | DT3 | Automatic Identification and Data Collection (AIDC) | A set of technologies involved in recognizing, ascertaining, filing, conveying, and storing information on discrete and packaged options. Radio Frequency Identification (RFI) is the most popular one. The usual usages include earing and withdrawing, inventory choosing, order completion, | (Garay-Rondero et al., 2020) |

| Category | Code | IDT | Description | Literature support |
|---|---|---|---|---|
| | DT4 | Global Positioning System (GPS) | specifying of weight and volume, as well as tracking quite SC A satellite-based radio-navigation system including a constellation of satellites broadcasting navigation signals and a grid of ground stations and satellite monitor stations to calculate and show exact size, velocity, and time information to the user | (Bai et al., 2020) |
| **Fundamentals & Support** | ST1 | Cybersecurity | Practices of supporting crucial systems and delicate information from the digital menace | (Bai et al., 2020; Garay-Rondero et al., 2020) |
| | ST2 | Blockchain | A circulated database that sustains a perfect, divided, and unshakable ongoing enhancing roster of records employing modern encryption and verification technology and grid-wide harmony workmanship | (Bai et al., 2020) |
| | ST3 | Mobile Technology (MT) | The wireless connection technology grounded on the wireless sets | (Bai et al., 2020) |
| | ST4 | Digital Platforms (DPs) | Employs to link firms to exterior actions. DPs connect SC members and furnish accessible on-demand attain to clouded information | (Frank et al., 2019) |
| | ST5 | Simulation | Employs computer modeling to emulate a concrete process to improve the as-is situation | (Bai et al., 2020) |
| | ST6 | Big Data Analytics (BDA) | The process of analyzing large volumes of data to compensate for the shortage of standard techniques of data mining that cannot discover such sensible fundamental data | (Frank et al., 2019; Garay-Rondero et al., 2020) |

**Table 1** (*continued*)

| Category | Code | IDT | Description | Literature support |
|----------|------|-----|-------------|--------------------|
| | ST7 | Cloud Technologies (CT) | A computing technology with sufficient capacity to warehouse and account for a bulk amount of data; which can retake via distant access | (Bai et al., 2020; Frank et al., 2019) |
| | ST8 | Internet of things (IoT) | Reflects integrating sensors and computing in an internet setting via wireless conveying. It can sense any object and its linkage to a broader grid | (Bai et al., 2020; Frank et al., 2019) |

sustainable performance and application. Similarly, Machado et al. (2020) explored the links between sustainable manufacturing and *IDTs*. Recently, Nara et al. (2021) investigated the impact of *IDTs* on multiple Key Performance Indicators (KPIs) associated with sustainable development. However, there is still an absence of a complete categorized list of potential impacts of *IDTs* on circular *SCM* in the body of literature. This process was initiated by searching keywords such as "*potential impacts of IDTs on SCM*", "*potential impacts of IDTs on sustainable/circular SCM*", "*application of IDTs in SCM*", etc. in the Google Scholar, Scopus, and ISI Web of Knowledge databases. The final data source resulted in about 15 relevant researches between 2017 and 2021. The main contribution, impact extraction approach, employed methodology, data type, and case study/industry of the abovementioned papers are condensed in Table 2.

Considering Table 2, recent scholars have received intense attention for the connection between CE principles implementation and IDTs.

Lopes de Sousa Jabbour et al. (2018) acknowledged that *IDTs* are convenient tools to pave the way for implementing circular *SCM*. Nascimento et al. (2019) argued how rising *IDTs* could be combined with *CE* to propose circular business models. Cezarino et al. (2019) suggested an original model to explore the relationships between *IDTs* and *CE* and overcome its implementation obstacles. Mastos et al. (2021) introduced the applications of *IDTs* in circular *SCM*.

Furthermore, the reviewed papers only employed popular qualitative approaches, i.e., literature review and case study, to identify these impacts. Likewise, the qualitative methodologies, e.g., structuralism approach and interpretive research approach, were applied to evaluate the impacts above. Moreover, SMEs in emerging economies have received extensive attention. However, the pharmaceutical industry of Iran has not yet been studied (see Table 2). These detections provide authors with empirical support to the available literature on the disruptive impact of Industry 4.0 technologies. In doing so, an initial list of 64 impacts was extracted from the extant relevant literature. The impacts with the same concept were merged, resulting in a list of 33 impacts. Afterward, a categorizing process was conducted based upon the theories of manufacturing business process, SC risk management, *TBL*, principles of *CE* such as biological and technical cycles of *CE*, and the framework. Further information on these theories can be found in the studies of (Das et al., 2019; Lopes de Sousa Jabbour et al., 2018; Zheng et al., 2021). Eventually, 33 impacts were grouped into eight categories, see Table 3: *environmental, economic, societal, product lifecycle management, SC configuration, data and knowledge management, SC main functions*, and *risk management*.

This paper employed a literature review to achieve two objectives, i. e. (i) provides a complete list of *IDTs,* including *base* and *front-end technologies*, and (ii) demonstrates a comprehensive categorized list of impacts of *IDTs* on circular *SCM* based upon the extant relevant theories. The literature review is suitable to summarize actual knowledge and survey existing research on a special event to bridge research gaps and fasten the ground of study (Zheng et al., 2021). Moreover, qualitative and quantitative mixed methods are recommended to gain more reliable results (Jafari-Sadeghi et al., 2021). The two lists above were screened with a novel Pythagorean fuzzy-Delphi method based on experts' views
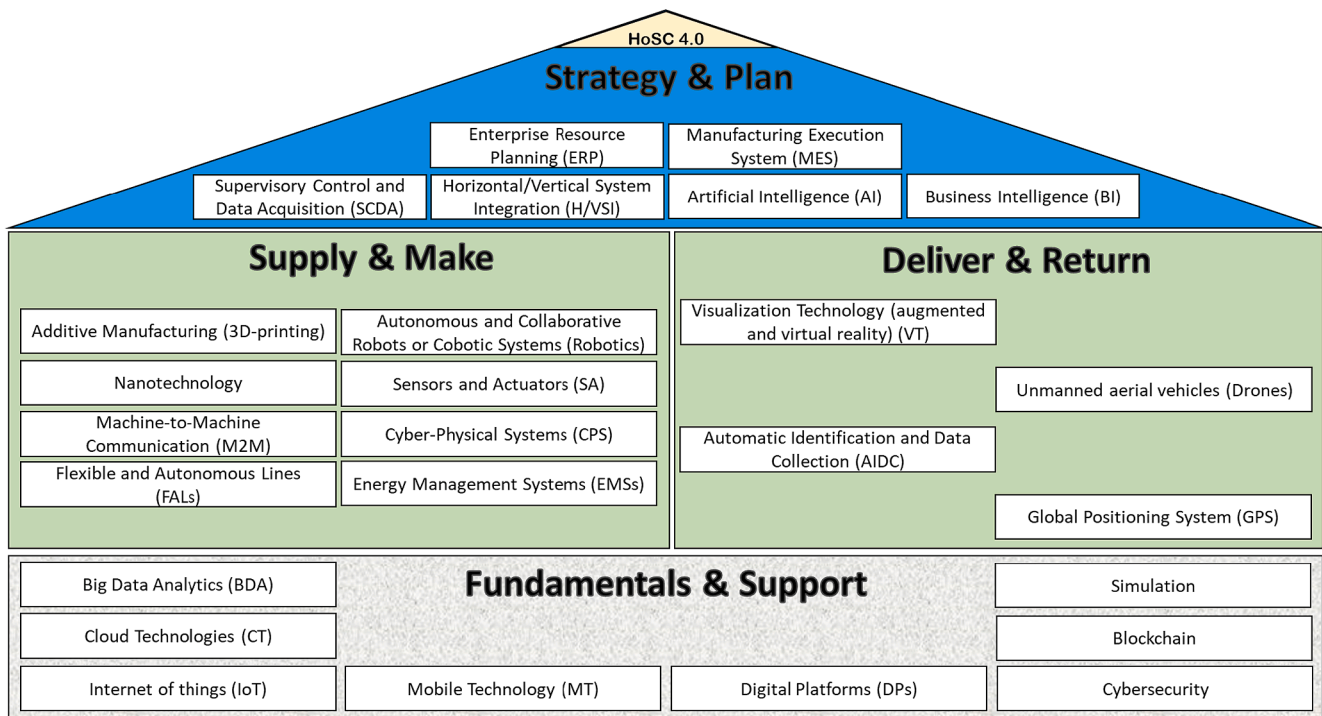


**Fig. 2.** House of SC 4.0.

**Table 2**

Literature overview: potential impacts of *IDTs* on circular *SCM*.

| Scholar (s) | Year | Contribution | Type of Impact Extraction Approach | Type of Methodology | | Data Type | Case Study/ Application |
|---|---|---|---|---|---|---|---|
| | | | | Qualitative | Quantitative | | |
| Ab Rahman et al. | 2017 | Review of the current emerging technologies and their applications | LR | Interpretive research approach | | – | – |
| Lopes de Sousa Jabbour et al. | 2018 | Unveil how various *IDTs* could underpin CE strategies | LR | Interpretive research approach | | – | – |
| Erdogan et al. | 2018 | Select the foremost strategy for implementing industry 4.0 | LR, expert ideas | | AHP-VIKOR | Fuzzy | – |
| Nascimento et al. | 2019 | Explore the relationship between IDTs and CE to reduce wastes | LR | Focus group interviews | | – | |
| Das et al. | 2019 | Study the impacts of IDTs on SC risk management | Multiple case studies | Multiple case studies | | – | Food, Semiconductor, Rail vehicles drive systems, Automotive supplier, Aerospace, automotive, railway, engineering consulting, Automotive, Climate system |
| Cezarino et al. | 2019 | Explore the relationships between IDTs and CE to present an original framework to overcome implementations obstacles | LR | structuralism approach | | – | Emerging economy of Brazil |
| Rane et al. | 2019 | Propose a project risk management model grounded on IDTs | LR | Discussion with experts | | – | Construction project |
| Frank et al. | 2019 | Explore the adoption patterns of IDTs in manufacturing firms | LR | Expert opinion (interview) | Statistics analysis | Crisp | Brazilian Machinery and Equipment Builders' Association |
| Ghadge et al. | 2020 | Analyze the impacts of IDTs on SC and develop an implementation framework for the industry 4.0 paradigm | LR | | System dynamics | | – |
| Machado et al. | 2020 | Explore the links between sustainable manufacturing and industry 4.0 | LR | SLR | | – | – |
| Bai et al. | 2020 | Evaluate IDTs according to their sustainable performance and usage | United Nations Sustainable Development Goals | | Cumulative prospect theory and VIKOR, Sensitivity analysis | Hesitant fuzzy | World Economic Forum project |
| Sriram & Vinodh | 2020 | Analyze the readiness factors for Industry 4.0 deployment | LR | | COPRAS (complex proportionality assessment) | Crisp | SMEs in the Automotive industries of India |
| Zheng et al. | 2021 | Analyze the applications of IDTs in the business processes of manufacturing firms | SLR | SLR | | – | – |
| Mastos et al. | 2021 | Evaluate the application of IDTs in the sustainability performance of circular *SCM* | LR | Real-world scenario analysis | | – | European Connected Factory Platform for Agile Manufacturing |
| Nara et al. | 2021 | Analyze the impact of IDTs on several KPIs associated with sustainable development | LR | | TOPSIS | Fuzzy | The plastics industry in an emerging economy |

LR: Literature Review, SLR: Systematic LR, COPRAS: complex proportionality assessment, AHP: Analytic Hierarchy Process.

of Iran's pharmaceutical industry. Fuzzy-Delphi is a well-suited method to screen research items based on experts' opinions. However, recent scholars have recommended combining new uncertainty approaches such as hesitant, intuitionistic, Pythagorean, etc., with a standard version of fuzzy-Delphi to handle better the error of experts' judgment (Hajiagha et al., 2021). Besides, despite various Multi-Criteria Decision-Making (MCDM) methods, SECA is a unique method that can measure the weight of criteria and score of alternatives (Keshavarz-Ghorabaee et al., 2018). This leads to a minor level of complex computation.

Nonetheless, this MCDM method has not yet been integrated with the abovementioned uncertainty. Regarding the mentioned advantages and limitations, each finalized technology's weight, performance score, and impact were simultaneously measured with a novel Pythagorean fuzzy-SECA approach. The interventions were then prioritized for each finalized impact using the Hanlon method. Excluding healthcare problem prioritization, the Hanlon method is innovatively employed in this area considering four criteria (i.e., size of the problem, the seriousness of the

problem, the effectiveness of the intervention, and feasibility) (Choi et al., 2019). Achieving these aims would provide practitioners with reliable recommendations to enrich pharmaceutical circular *SCM* strategy selection.

## 3. Methodology

As ambiguity increases, it is suggested to consider it in solving problems. Hence Zadeh proposed fuzzy sets to deal with uncertainty (Zadeh, 1966). In this regard, each element $x$ is the member of a fuzzy set FS by a particular membership degree $\mu(x)$ (Eq (1)).

$$FS = \{(x, \mu(x)) | x \in X, \mu(x) \in [0,1]\} \tag{1}$$

Since the introduction of fuzzy sets, numerous developments have been offered. A highlighted extension of fuzzy sets called intuitionistic fuzzy sets (IFS) was presented by Atanassov (Atanassov, 1999). On this subject, an element $x$ is a member of the IFS by a membership degree

**Table 3**

List of the potential disruptive impact of Industry 4.0 technology.

| Category | Code | Potential Disruptive Impact of Industry 4.0 Technology | Literature support |
|---|---|---|---|
| Environmental | EI$_1$ | Optimize utilization and efficient allocation of resources, energy, and materials | (Cezarino et al., 2019; Das et al., 2019; Lopes de Sousa Jabbour et al., 2018; Machado et al., 2020; Mastos et al., 2021; Nascimento et al., 2019; Zheng et al., 2021) |
| | EI$_2$ | Resource and material regeneration (i.e., increased material recovery rates) | |
| | EI$_3$ | Improve material supply reliability | |
| | EI$_4$ | Optimize waste management (i.e., reduce (or net-zero) overproduction, expired products, and energy wastes from machines and processes, avoid hazardous materials, etc.) | |
| | EI$_5$ | Reduce environmental (air, water, and sound) pollution and carbon footprint | |
| Economic | CI$_1$ | Improve economic performance (e.g., decrease transaction costs, increase return on investment, etc.) | (Ab Rahman et al., 2017; Ghadge et al., 2020; Machado et al., 2020; Mastos et al., 2021; Nascimento et al., 2019; Zheng et al., 2021) |
| | CI$_2$ | Create a low-budget manufacturing industry | |
| | CI$_3$ | Shorter lead times | |
| | CI$_4$ | Meet multiple demands (meeting consumer needs – mass customization) | |
| Societal | SI$_1$ | Greater accessibility and increased customers satisfaction | (Cezarino et al., 2019; Lopes de Sousa Jabbour et al., 2018; Machado et al., 2020; Nascimento et al., 2019) |
| | SI$_2$ | Improve the quality of the working environment (safe and attractive workplaces) | |
| | SI$_3$ | Increase the possibility of new avenues of communication and entertainment | |
| | SI$_4$ | Modification of current jobs (reduce routine jobs and create job opportunities, especially for disabled and elderly employees) | |
| | SI$_5$ | Substitution of the human workforce by machines | |
| | SI$_6$ | Relocation and outsourcing of jobs (it will result in worse work conditions in emerging economies, inequalities, and social gaps around the world) | |
| Product lifecycle management | PI$_1$ | Improve product/service design | (Cezarino et al., 2019; Lopes de Sousa Jabbour et al., 2018; Zheng et al., 2021) |
| | PI$_2$ | Promotion of product life cycles' optimization (i.e., promote closed-loop life cycles and cradle-to-cradle approaches) | |
| SC configuration | SCI$_1$ | Improves SC productivity and performance (SC's efficiency and effectiveness) | (Das et al., 2019; Ghadge et al., 2020; Lopes de Sousa Jabbour et al., 2018; Nascimento et al., 2019; Zheng et al., 2021) |
| | SCI$_2$ | Improved transparency, collaboration, integration, | |

**Table 3** (*continued*)

| Category | Code | Potential Disruptive Impact of Industry 4.0 Technology | Literature support |
|---|---|---|---|
| | | and communication along with the entire SC | |
| | SCI$_3$ | Facilitate moving towards lean, agile, resilience, and sustainability | |
| Data and knowledge management | DKI$_1$ | Real-time information sharing and synchronization with SC members towards increased trust and better engagement/collaboration | (Ghadge et al., 2020; Machado et al., 2020; Mastos et al., 2021; Nascimento et al., 2019; Zheng et al., 2021) |
| | DKI$_2$ | Improve control of data operations | |
| | DKI$_3$ | Improve customer relationship management | |
| | DKI$_4$ | Workers with the proper knowledge and highly skilled | |
| SC main functions | SNI$_1$ | Improve tracking and traceability of raw material/final products through real-time inventory monitoring | (Cezarino et al., 2019; Ghadge et al., 2020; Machado et al., 2020; Mastos et al., 2021; Nascimento et al., 2019; Zheng et al., 2021) |
| | SNI$_2$ | Intelligent warehousing and vehicle routing systems toward logistics routes and capacity reduction | |
| | SNI$_3$ | Improved availability of personnel and fleet resources | |
| | SNI$_4$ | Optimize other SC functions (i.e., factory layout design, production scheduling and control, quality, maintenance, after-sales management, etc.) | |
| Risk management | RI$_1$ | Improve production capacity reliability | (Cezarino et al., 2019; Das et al., 2019; Ghadge et al., 2020) |
| | RI$_2$ | Support ripple effect control | |
| | RI$_3$ | Better demand forecasting | |
| | RI$_4$ | Regularly auditing suppliers toward a reliable supplier selection process | |
| | RI$_5$ | Joint responsibility of entire stakeholders in combating both digitization's risks and challenges | |

($\mu(x)$) and is not a member of the IFS by a non-membership degree $\nu(x)$ (Eq. (2)).

$$IFS = \{(x, \mu(x), \nu(x)) \,|\, x \in X, 0 \leq \mu(x) + \nu(x) \leq 1 \} \qquad (2)$$

The intuitionistic index of the element $x$ is defined by Eq. (3), demonstrating the non-determinacy (Lin et al. 2007).

$$\pi(x) = 1 - \mu(x) - \nu(x) \qquad (3)$$

As illustrated in Eqs. (2) and (3), there is a limit that indicates that the sum of membership and non-membership degrees must be less than one. However, the vagueness of real cases can make the sum of membership and non-membership more than one (Peng & Selvachandran, 2019). Thus, Pythagorean fuzzy sets (PFS) were proposed by Yager to solve this limitation (Yager, 2013). Assume that X presents a universe of discourse, and the PFS is presented via Eq. (4).

$$PFS = \{(x, \mu(x), \nu(x)) \,|\, x \in X, 0 \leq \mu(x)^2 + \nu(x)^2 \leq 1 \} \qquad (4)$$

The non-determinacy degree of a PFS is computed via Eq. (5) (Peng

et al. 2017).

$$\pi(x) = \sqrt{1 - \mu(x)^2 - \nu(x)^2} \qquad (5)$$

As elaborated in Eq. (4) and (5), PFSs place fewer fuzzy constraints than IFSs. Consider the P= $(\mu(x), \nu(x))$ as a Pythagorean fuzzy number (PFN). The P score is calculated by Eq. (6) (Peng et al. 2017). This research applies a Pythagorean fuzzy approach to deal with uncertainty.

$$S(P) = \mu(x)^2 - \nu(x)^2 \qquad (6)$$

This research followed a mixed method containing three phases. In phase I, a literature review was conducted in two streams to study and recognize the Industry 4.0 disruptive technologies and their potential impact on circular *SCM*. Next, a novel Pythagorean Delphi-SECA analysis was performed in phase II to evaluate and prioritize the highlighted IDTs and their consequences. Finally, in phase III and based on the Hanlon method, the intervention toward benefiting from Industry 4.0 technologies in pharmaceutical supply chains of the emerging economy of Iran was presented. Fig. 3 illustrates the methodology followed by the present research. The details of each step are elaborated further.

**Step1. Literature review.** First, the literature was reviewed in two main streams, including Industrial 4.0 disruptive technologies and their potential impact on circular *SCM*. Hence, two lists were obtained to be applied in the quantitative stage of the research. The results of this stage are provided in Tables 1-3 and Figs. 1-3.

**Step 2. Screening lists via Pythagorean Fuzzy Delphi (PFD).** Delphi is a structured method to obtain and aggregate experts' opinions (Goodman, 1987). In this method, (i) the opinions are gathered, and (i) the consensus is analyzed. If an agreement is reached, then Delphi is stopped. Otherwise, (iii) the average and standard deviation of opinions are informed to the experts to adjust their opinion (Rezaei et al., 2021). The rounds continue to reach a consensus. Numerous extensions of the Delphi have been proposed, e.g., fuzzy Delphi (Shahbahrami et al., 2020) and hesitant fuzzy Delphi (Mahdiraji et al., 2021). In this research, a new development of the Delphi has been developed by applying Pythagorean fuzzy numbers to screen the list of the IDTs and their impacts. In this regard, three panels of experts were invited. These panels included a government official, a university professor, and three pharmaceutical supply chain activists. Each panel was coordinated by a university professor, who was responsible for planning and managing the meetings on behalf of the research team. To qualify, a minimum age of 30 years, at least ten years of related work experience, and a master's degree or equivalent were considered. The experts' profile is illustrated in Table 4.

In the first meeting, which was held for each panel for one hour, it was asked to determine the score of each IDTs as well as each impact using the Pythagorean linguistic terms described in Table 5. In this

**Table 4**
Experts' profiles.

| Panel | Expert | Age (yrs.) | Experience (yrs.) | Education | Academia (A)/ Industry(I)/Officials (O) |
|---|---|---|---|---|---|
| A | E1 | 45 | 15 | PHD | A |
|   | E2 | 50 | 20 | MD | I |
|   | E3 | 55 | 25 | MD | I |
|   | E4 | 50 | 30 | MD | I |
|   | E5 | 45 | 20 | PHD | O |
| B | E6 | 45 | 15 | DBA | O |
|   | E7 | 40 | 15 | MD | I |
|   | E8 | 35 | 10 | MD | I |
|   | E9 | 55 | 25 | PHD | I |
|   | E10 | 45 | 10 | PHD | A |
| C | E11 | 40 | 10 | PHD | A |
|   | E12 | 50 | 20 | PHD | I |
|   | E13 | 35 | 10 | MD | I |
|   | E14 | 40 | 15 | MD | I |
|   | E15 | 45 | 20 | MBA | O |

regard, the availability and unavailability of each alternative were attained.

To analyze the Delphi, first, the score of each panel was computed via Eq. (6). Then, the standard deviation (SD) of each panel's score for each alternative was measured. If the average of the SDs was less than 1, then consensus was obtained. Otherwise, another round of Delphi was required. After reaching an agreement, the elements with an average score above the threshold were selected for the next step.

**Step 3. Analyzing the impact of IDTs applying Pythagorean SECA (P-FSECA).** SECA is an MCDM tool that can extract the weights of criteria and the prioritization of alternatives simultaneously (Keshavarz-Ghorabaee et al., 2018). In this research, a Pythagorean fuzzy SECA was

**Table 5**
Linguistic pythagorean terms.

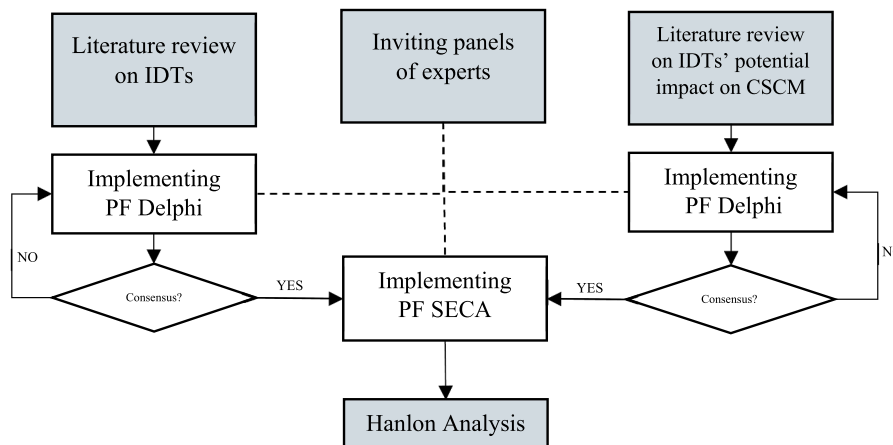| Linguistic Term | Membership | Linguistic Term | Non-membership | Value | Triangular Fuzzy Number |
|---|---|---|---|---|---|
| $S_0$ | No | $\overset{\Lambda}{S_0}$ | No | 0 | (0, 0, 0.25) |
| $S_1$ | Nearly | $\overset{\Lambda}{S_1}$ | Nearly | 1 | (0, 0.25, 0.5) |
| $S_2$ | Pretty | $\overset{\Lambda}{S_2}$ | Pretty | 2 | (0.25. 0.5, 0.75) |
| $S_3$ | Very | $\overset{\Lambda}{S_3}$ | Very | 3 | (0.5, 0.75. 1) |
| $S_4$ | Absolutely | $\overset{\Lambda}{S_4}$ | Absolutely | 4 | (0.75, 1, 1) |



**Fig. 3.** The research framework.

proposed. In this regard, the second meeting of the panels was held for 2 h. Experts were asked to determine how each IDTs was causing an impact by applying the terms of Table 5. These terms were then translated into fuzzy triangular numbers (TFNs). Hence, two models contacting a maximum model for membership degrees and a minimum model for non-membership degrees were constructed. The following steps were designed and employed in this regard.

1. The decision matrix was formed.

$$\widetilde{X} = \begin{bmatrix} \widetilde{x}_{11} \cdots \widetilde{x}_{1m} \vdots \ddots \vdots \widetilde{x}_{n1} \cdots \widetilde{x}_{nm} \end{bmatrix} = \begin{bmatrix} \left(x_{11}^l, x_{11}^m, x_{11}^u\right) & \cdots & \left(x_{1m}^l, x_{1m}^m, x_{1m}^u\right) \\ \vdots & \ddots & \vdots \\ \left(x_{n1}^l, x_{n1}^m, x_{n1}^u\right) & \cdots & \left(x_{nm}^l, x_{nm}^m, x_{nm}^u\right) \end{bmatrix} \tag{7}$$

In Eq. (7), TFN $\widetilde{x}_{ij}$ is the fuzzy performance value of the $i$th ($i \in \{1, 2, \cdots, n\}$) alternative on the $j$th ($j \in \{1, 2, \cdots, m\}$) criteria.

2. The decision matrix was normalized as Eq. (8).

$$\widetilde{X}^N = \begin{bmatrix} \widetilde{x}_{11}^N \cdots \widetilde{x}_{1m}^N \vdots \ddots \vdots \widetilde{x}_{n1}^N \cdots \widetilde{x}_{nm}^N \end{bmatrix}$$

$$= \begin{bmatrix} \left(x_{11}^{l\,N}, x_{11}^{m\,N}, x_{11}^{u\,N}\right) & \cdots & \left(x_{1m}^{l\,N}, x_{1m}^{m\,N}, x_{1m}^{u\,N}\right) \\ \vdots & \ddots & \vdots \\ \left(x_{n1}^{l\,N}, x_{n1}^{m\,N}, x_{n1}^{u\,N}\right) & \cdots & \left(x_{nm}^{l\,N}, x_{nm}^{m\,N}, x_{nm}^{u\,N}\right) \end{bmatrix} \tag{8}$$

Note that TFN $\widetilde{x}_{ij}^N$ is the normalized fuzzy performance value of the $i$th ($i \in \{1, 2, \cdots, n\}$) which is obtained via Eq. (9).

$$\widetilde{x}_{ij}^N = \begin{cases} \left(\dfrac{x_{ij}^l}{x_j^{u+}}, \dfrac{x_{ij}^m}{x_j^{u+}}, \dfrac{x_{ij}^u}{x_j^{u+}}\right) and x_j^{u+} = max_i x_{ij}^u, if j \in BC \\ \left(\dfrac{x_j^{l-}}{X_{ij}^l}, \dfrac{x_j^{l-}}{x_{ij}^m}, \dfrac{x_j^{l-}}{x_{ij}^u}\right) and x_j^{l-} = max_i x_{ij}^l, if j \in NC \end{cases} \tag{9}$$

Notice that $BC$ and $NC$ represent the sets of beneficial and non-beneficial criteria.

3. The fuzzy reference points for criteria weights were determined. In this regard, let $\widetilde{V}_j = \begin{bmatrix} \widetilde{x}^N \end{bmatrix}_{ij_{n\times 1}}$ is the fuzzy vector of the $j$th ($j \in \{1, 2, \cdots, m\}$) criteria. The fuzzy value of the standard deviation of the elements of each vector $\widetilde{\sigma}_j$ was obtained from fuzzy changes. Variation between fuzzy criteria was attained by measuring the fuzzy correlation between each pair of criterion vectors. Thus, the degree of fuzzy contrast between criteria j and other criteria $\widetilde{\pi}_j$ arises as Eq. (10).

$$\widetilde{\pi}_j = \sum_{l=1}^m \left(1 - \widetilde{r}_{jl}\right) \tag{10}$$

It is notable that in Eq. (10), $\widetilde{r}_{jl}$ denotes the correlation between the $j$th and $l$th vectors ($j and l \in \{1, 2, \cdots, m\}$). Accordingly, $\widetilde{\sigma}_j$ and $\widetilde{\pi}_j$ were normalized via (11) and (12).

$$\widetilde{\sigma}_j^N = \frac{\widetilde{\sigma}_j}{\sum_{j=1}^m \widetilde{\sigma}_j} \tag{11}$$

$$\widetilde{\pi}_j^N = \frac{\widetilde{\pi}_j}{\sum_{j=1}^m \widetilde{\pi}_j} \tag{12}$$

4. A fuzzy multi-objective non-linear programming model was shaped as Eqs. (13–1) to (13–6).

$$max\widetilde{s}_i = \sum_{j=1}^m \widetilde{w}_j \widetilde{x}_{ij}^N, \forall i \in \{1, 2, \cdots, n\}, \tag{13-1}$$

$$min\widetilde{\lambda}_b = \sum_{j=1}^m \left(\widetilde{w}_j - \widetilde{\sigma}_j^N\right)^2, \tag{13-2}$$

$$min\widetilde{\lambda}_c = \sum_{j=1}^m \left(\widetilde{w}_j - \widetilde{\pi}_j^N\right)^2, \tag{13-3}$$

$s.t.$

$$\sum_{j=1}^m \widetilde{w}_j = (1, 1, 1), \tag{13-4}$$

$$\widetilde{w}_j \leq (1, 1, 1), \forall j \in \{1, 2, \cdots, m\}, \tag{13-5}$$

$$\widetilde{w}_j \geq (\varepsilon, \varepsilon, \varepsilon), \forall j \in \{1, 2, \cdots, m\}. \tag{13-6}$$

It can be seen that in the model (13), the overall performance of each alternative was maximized by the objective (13–1), and the deviation of criteria weights from the reference point was minimized by the objectives (13–2) and (13–3). Constraint (13–4) illustrates that the sum of weights equals 1. Constraints (13–5) and (13–6) attempt to justify the criteria weights to some values in the interval $[\varepsilon, 1]$. Notice that $\varepsilon$ is a small positive parameter considered as $10^{-3}$ in this research (Keshavarz-Ghorabaee et al., 2019). In the following, the model was transferred from Eqs (14–1) to (14–8) (Keshavarz-Ghorabaee et al., 2018).

$$maxz = \widetilde{\lambda}_a - \beta(\widetilde{\lambda}_b + \widetilde{\lambda}_c) \tag{14-1}$$

$$s.t. \widetilde{\lambda}_a \leq \widetilde{s}_i, \forall i \in \{1, 2, \cdots, n\}, \tag{14-2}$$

$$\widetilde{s}_i = \sum_{j=1}^m \widetilde{w}_j \widetilde{x}_{ij}^N, \forall i \in \{1, 2, \cdots, n\}, \tag{14-3}$$

$$\widetilde{\lambda}_b = \sum_{j=1}^m \left(\widetilde{w}_j - \widetilde{\sigma}_j^N\right)^2, \tag{14-4}$$

$$\widetilde{\lambda}_c = \sum_{j=1}^m \left(\widetilde{w}_j - \widetilde{\pi}_j^N\right)^2, \tag{14-5}$$

$$\sum_{j=1}^m \widetilde{w}_j = (1, 1, 1), \tag{14-6}$$

$$\widetilde{w}_j \leq (1, 1, 1), \forall j \in \{1, 2, \cdots, m\}, \tag{14-7}$$

$$\widetilde{w}_j \geq (\varepsilon, \varepsilon, \varepsilon), \forall j \in \{1, 2, \cdots, m\}. \tag{14-8}$$

In the model of Eq. (14), the minimum of the fuzzy overall performance score of alternatives $(\widetilde{\lambda}_a)$ was maximized, and the summation of $\widetilde{\lambda}_b$ and $\widetilde{\lambda}_c$ which was subtracted from the objective function with a coefficient $\beta$ ($\beta \geq 0$) was minimized. The coefficient influence the significance of reaching the fuzzy reference points of criteria weights. It is notable that the overall performance score of each alternative ($s_i$) and the objective weight of each criterion ($w_j$) were computed by solving this model.

5. To solve the model of Eq. (14), the fuzzy ranking method proposed by Jiménez et al. (2007) was applied. This method was found on two ideas of *expected interval (EI)* and *expected value (EV)* of a fuzzy number to deal with the fuzzy equality/inequality constraints and fuzzy objective values. Hence, the *EI* of a fuzzy number $\widetilde{a}$ was obtained using Eq. (15) (Heilpern, 1992).

$$EI(\widetilde{a}) = \left[E_1^a, E_2^a\right] = \left[\int_0^1 f_a^{-1}(r)dr, \int_0^1 g_a^{-1}(r)dr\right]. \tag{15}$$

The *EV* of a fuzzy number $\widetilde{a}$, noted $EV(\widetilde{a})$, is the halfway point of $EI(\widetilde{a})$, which was computed via Eq. (16) (Heilpern, 1992).

$$EV(\widetilde{a}) = \frac{E_1^a + E_2^a}{2}. \tag{16}$$

For any TFN $\widetilde{a} = (a_l, a_m, a_u)$, $EI(\widetilde{a})$ and $EV(\widetilde{a})$ were measured via Eq. (17).

$$EI(\widetilde{a}) = \left[\frac{1}{2}(a_l + a_m), \frac{1}{2}(a_m + a_u)\right]; EV(\widetilde{a}) = \frac{1}{3}(a_l + a_m + a_u) \tag{17}$$

For any pair of fuzzy numbers $\widetilde{a}$ and $\widetilde{b}$, the degree to which $\widetilde{a}$ is higher than $\widetilde{b}$ was presented in Eq. (18) (Jiménez & Verdegay, 1999).

$$\mu_M\left(\widetilde{a}, \widetilde{b}\right) = \begin{cases} 0 \, if \, E_2^a - E_1^b < 0, \\ \dfrac{E_2^a - E_1^b}{E_2^a - E_1^b - \left(E_1^a - E_2^b\right)} \, if \, 0 \in \left[E_1^a - E_2^b, E_2^a - E_1^b\right], \\ 1 \, if \, E_1^a - E_2^b > 0. \end{cases} \tag{18}$$

If $\mu_M\left(\widetilde{a}, \widetilde{b}\right) \geq \alpha$, then $\widetilde{a}$ is greater than, or equal, to $\widetilde{b}$ at least in a degree $\alpha$, noted $\widetilde{a} \geq_\alpha \widetilde{b}$. Considering a constraint of the type $\widetilde{a}_i.x \geq \widetilde{b}_i$, it is noticeable that $\widetilde{a}_i.x \geq_\alpha \widetilde{b}_i$ is equivalent to Eq. (19).

$$[(1 - \alpha)E_2^{a_i} + \alpha E_1^{a_i}]x \geq \alpha E_2^{b_i} + (1 - \alpha)E_1^{b_i} \tag{19}$$

Similarly, for any equality type constraint, the "=" sign was substituted with/by $\geq$ in equation (19) (Amoozad Mahdiraji et al., 2018). Finally, the model of Eq. (20) was constructed as follows.

$$Min(-Z) = \left[\beta.\left(\frac{\lambda_b^{\,l} + \lambda_b^{\,m} + \lambda_b^{\,u}}{3}\right) + \beta.\left(\frac{\lambda_c^{\,l} + \lambda_c^{\,m} + \lambda_c^{\,u}}{3}\right) - \left(\frac{\lambda_a^{\,l} + \lambda_a^{\,m} + \lambda_a^{\,u}}{3}\right)\right], \tag{20-1}$$

$$s.t. \left[\alpha.\left(\frac{-\lambda_a^{\,l} - \lambda_a^{\,m}}{2}\right) + (1 - \alpha).\left(\frac{-\lambda_a^{\,m} - \lambda_a^{\,u}}{2}\right)\right] \geq -s_i, \forall i \in \{1, 2, \cdots, n\}, \tag{20-2}$$

$$s_i = \sum_{j=1}^m \left[\alpha.\left(\frac{w_j.x_{ij}^{mN} + w_j.x_{ij}^{uN}}{2}\right) + (1 - \alpha).\left(\frac{w_j.x_{ij}^{l\,N} + w_j.x_{ij}^{mN}}{2}\right)\right] \forall i \in \{1, 2, \cdots, n\}, \tag{20-3}$$

$$\left[\alpha.\left(\frac{\lambda_b^{\,l} + \lambda_b^{\,m}}{2}\right) + (1 - \alpha).\left(\frac{\lambda_b^{\,m} + \lambda_b^{\,u}}{2}\right)\right]$$
$$= \left[\alpha.\left(\sum_{j=1}^m w_j^2 - \sum_{j=1}^m \left(w_j.\sigma_j^m + w_j.\sigma_j^u\right)\right.\right.$$
$$\left. + \sum_{j=1}^m \left(\frac{(\sigma_j^m)^2 + (\sigma_j^u)^2}{2}\right)\right) + (1 - \alpha).\left(\sum_{j=1}^m w_j^2 - \sum_{j=1}^m \left(w_j.\sigma_j^l\right.\right.$$
$$\left.\left. + w_j.\sigma_j^m\right) + \sum_{j=1}^m \left(\frac{(\sigma_j^l)^2 + (\sigma_j^m)^2}{2}\right)\right)\right], \tag{20-4}$$

$$\left[\alpha.\left(\frac{\lambda_c^{\,l} + \lambda_c^{\,m}}{2}\right) + (1 - \alpha).\left(\frac{\lambda_c^{\,m} + \lambda_c^{\,u}}{2}\right)\right]$$
$$= \left[\alpha.\left(\sum_{j=1}^m w_j^2 - \sum_{j=1}^m \left(w_j.\pi_j^m + w_j.\pi_j^u\right)\right.\right.$$
$$\left. + \sum_{j=1}^m \left(\frac{(\pi_j^m)^2 + (\pi_j^u)^2}{2}\right)\right) + (1 - \alpha).\left(\sum_{j=1}^m w_j^2 - \sum_{j=1}^m \left(w_j.\pi_j^l\right.\right.$$
$$\left.\left. + w_j.\pi_j^m\right) + \sum_{j=1}^m \left(\frac{(\pi_j^l)^2 + (\pi_j^m)^2}{2}\right)\right)\right], \tag{20-5}$$

$$\sum_{j=1}^m w_j = 1, \tag{20-6}$$

$$w_j \leq 1 \forall j \in \{1, 2, \cdots, m\}, \tag{20-7}$$

$$w_j \geq \epsilon \forall j \in \{1, 2, \cdots, m\}. \tag{20-8}$$

In Eq. (20), for the minimum model of the non-membership degrees, the objective function was replaced with Eq. (20-9).

$$Min(Z) = \left[\beta.\left(\frac{\lambda_b^{\,l} + \lambda_b^{\,m} + \lambda_b^{\,u}}{3}\right) + \beta.\left(\frac{\lambda_c^{\,l} + \lambda_c^{\,m} + \lambda_c^{\,u}}{3}\right) - \left(\frac{\lambda_a^{\,l} + \lambda_a^{\,m} + \lambda_a^{\,u}}{3}\right)\right], \tag{20-9}$$

**Step 4. Prioritization of each intervention by Hanlon's Basic Priority Rating (BPR).** The third meeting for each panel was held for an hour, and panels were asked to analyze the interventions for each impact by determining the scores based on Hanlon's BPR model. Numerous models have been proposed for priority setting, considering its importance. Hanlon first proposed the priority rating process to rank health problems in developing countries and then revised it in 1984 in collaboration with Pickett (Pickett & Hanlon, 1990). BPR 2.0 is comprised of four elements, namely: the size of the problem (A: 0–10 points), the seriousness of the problem (B: 0–20 Points), Effectiveness (C: 0–10 Points), and PEARL indicators (D: 0 or 1). The score is computed via Eq. (21) (Neiger et al. 2011).

$$BPR = \frac{(A + B)C}{3} \times D \tag{21}$$

Notice that In Eq. (21), D is the PEARL indicator, including propriety, economics, acceptability, resources, and legality. These indicators can be 0 or 1. Accordingly, for any 0 value of the indicators, the total score will be 0 (Neiger et al., 2011). In the following section, the results are presented.

## 4. Results and findings

As described in Section 3, the literature was first reviewed on IDTs and their potential impact on *CSCM*. The results are presented in Tables 1 and 2. Next, in the first meeting, experts were asked to assess the availability and unavailability of each list by the terms included in Table 5. To analyze the Delphi analysis results, each panel's score was obtained via Eq. (6), and the average and standard deviation of the panel's scores were computed. The IDTs results are presented in Table 6.

The average SDs in Table 6 is 0.42, less than 1. Hence, a consensus was reached, and Delphi stopped. The threshold for electing the IDTs was 5 ($\pm 0.1$). Moreover, the results of the impacts were determined in Table 7.

The average SDs in Table 7 is 0.47, which was also less than 1. Thus, a consensus was reached, and the Delphi stopped. Following, the decision matrix was constructed and found on 9 highlighted IDTs as alternatives and 14 major impacts as criteria. Then the second meeting was held, and the panels evaluated how each IDT was causing an impact by the Pythagorean fuzzy linguistic terms. Next, the terms were translated into TFNs according to Table 5. Hence, a maximum model found on memberships and a minimum model based on non-membership TFNs were constructed and solved via Eqs (7) to (20). The resulted were attained 100 times (via GAMS software) for each panels for $\alpha$ and $\beta = \{$ 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1$\}$. And the optimal point was obtained by sensitivity analysis. The trend of sensitivity analysis of weights and scores in maximum and minimum models is depicted in Figs. 4a–4d.

As illustrated in Figs. 4a–4d, the $\alpha = 0.1$ and $\beta = 0.1$ models have more distinctive responses. Thus, the weights of IDTs impacts and scores of Industry 4.0 technologies were in the order illustrated in Tables 8 and 9. A discussion regarding these tables and graphs is presented in Section 5.

As illustrated in Table 8, SNI1 has the most weight in the minimum model, and in the maximum model, SCI$_3$ is the most highlighted impact. Moreover, as demonstrated in Table 9, the minimum model leads to greater scores. The results are discussed in the next section.

**Table 6**
Pythagorean Delphi results for IDTs.

| Category | Code | Panel 1 Score 1 | Panel 2 Score 2 | Panel 3 Score 3 | Score | S.D |
|---|---|---|---|---|---|---|
| Strategy and Plan | PT1 | 4.58 | 3.32 | 4.00 | 3.97 | 0.52 |
| | **PT2** | 4.90 | 5.66 | 5.66 | **5.40** | 0.36 |
| | **PT3** | 4.58 | 5.66 | 5.66 | **5.30** | 0.51 |
| | PT4 | 4.58 | 3.32 | 4.58 | 4.16 | 0.60 |
| | PT5 | 4.90 | 4.58 | 4.00 | 4.49 | 0.37 |
| | PT6 | 4.90 | 4.00 | 4.00 | 4.30 | 0.42 |
| Purchase and Make | MT1 | 2.83 | 2.83 | 3.32 | 2.99 | 0.23 |
| | MT2 | 3.32 | 4.58 | 2.83 | 3.58 | 0.74 |
| | **MT3** | 4.90 | 5.66 | 4.90 | **5.15** | 0.36 |
| | **MT4** | 4.90 | 5.66 | 4.90 | **5.15** | 0.36 |
| | MT5 | 4.58 | 4.58 | 4.58 | 4.58 | 0.00 |
| | MT6 | 5.66 | 4.00 | 4.58 | 4.75 | 0.69 |
| | MT7 | 4.90 | 4.58 | 3.32 | 4.27 | 0.68 |
| | MT8 | 2.83 | 2.83 | 3.32 | 2.99 | 0.23 |
| Delivery and Return | DT1 | 2.83 | 2.83 | 3.32 | 2.99 | 0.23 |
| | DT2 | 2.83 | 0.00 | 2.83 | 1.89 | 1.33 |
| | DT3 | 4.90 | 4.00 | 3.32 | 4.07 | 0.65 |
| | **DT4** | 5.66 | 5.66 | 5.66 | **5.66** | 0.00 |
| Support and admin | ST1 | 4.90 | 4.58 | 4.58 | 4.69 | 0.15 |
| | ST2 | 3.32 | 4.58 | 4.90 | 4.27 | 0.68 |
| | **ST3** | 5.66 | 5.66 | 5.00 | **5.44** | 0.31 |
| | **ST4** | 4.90 | 4.90 | 5.66 | **5.15** | 0.36 |
| | **ST5** | 4.58 | 5.66 | 5.00 | **5.08** | 0.44 |
| | **ST6** | 4.90 | 5.66 | 5.00 | **5.19** | 0.34 |
| | ST7 | 4.90 | 4.58 | 5.00 | 4.83 | 0.18 |
| | ST8 | 3.32 | 4.00 | 3.32 | 3.54 | 0.32 |

## 5. Discussion and implications

***Theoretical implications***. Widespread concerns associated with environmental and societal issues have been emphasized in *SCM* literature (Bai et al., 2020). The intertwining of digitalization and sustainability is a transversal theme crossing all levels of *SCs* (Machado et al., 2020). Considering this, the synergies between *CE* and *IDTs* have recently been proposed as an effective strategy to enhance sustainable operations management (Lopes de Sousa Jabbour et al., 2018; Mastos et al., 2021). This study engenders multiple advanced theoretical implications for the community of practitioners and academics. **(I)** It unveiled the House of SC 4.0, demonstrating a novel categorization of *IDTs* associated with the *SCM* context. To this end, an original integrated fashion of SCOR and house of process has been employed. **(II)** This research provided a categorized list of potential disruptive impacts of the *IDTs* in designing innovative *CSC*. **(III)** An in-depth insight into measuring the interventions on the impacts of *IDTs* on pharmaceutical *CSCs* has also been provided. **(IV)** A novel version of the Pythagorean fuzzy-Delphi method was initially proposed to screen the research items (i.e., IDTs and their impacts on pharmaceutical *CSCs*), considering the

hesitation and intuition of industry experts. **(V)** A novel Pythagorean fuzzy set, SECA, and fuzzy ranking solution method by Jiménez et al. (2007) was developed in this research to simultaneously measure the weight of the impacts of *IDTs* in pharmaceutical *CSCs* and the performance score of the finalized *IDTs*. Finally, **(VI)** The Hanlon method was innovatively applied to prioritize each intervention for each impact of *IDTs* in pharmaceutical *CSCs*.

***Practical implications***. The customized House of pharmaceutical *CSC* 4.0 for emerging economies like Iran includes nine *IDTs* embedded in four categories that are strategy & plan (*ERP, H/VSI*), supply & make (*Nanotechnology, SA*), deliver & return (*GPS*), and fundamentals & support (*MT, DPs, Simulation, and BDA*). In this vein, technologies associated with processes of fundamentals & support, delivery & return, as well as strategy & plan, respectively, have been reasonably available. However, *IDTs* of supply & make processes have the lowest accessible priority. Besides, according to the maximum availability vein, *BDA, GPS, ERP, DPs, MT, nanotechnology, H/VSI, SA, and simulation* would launch the House of pharmaceutical *CSCs* 4.0. Although *ERP* and *H/VSI* in strategy & plan are available, *IDTs* of the functional layer of supply & make processes are not. Hence, the technologies that assist in ideal

**Table 7**
Results of pythagorean Delphi for potential impacts of IDTs on *CSCM*.

| Code | Panel 1 Score 1 | Panel 2 Score 2 | Panel 3 Score 3 | Score | S.D |
|---|---|---|---|---|---|
| $EI_1$ | 4.90 | 5.66 | 4.90 | **5.15** | 0.36 |
| $EI_2$ | 4.00 | 5.00 | 4.58 | 4.53 | 0.41 |
| $EI_3$ | 4.58 | 4.58 | 4.90 | 4.69 | 0.15 |
| $EI_4$ | 4.90 | 4.90 | 5.00 | **4.93** | 0.05 |
| $EI_5$ | 5.66 | 4.58 | 5.00 | **5.08** | 0.44 |
| $CI_1$ | 4.90 | 4.90 | 5.66 | **5.15** | 0.36 |
| $CI_2$ | 4.58 | 3.32 | 2.83 | 3.58 | 0.74 |
| $CI_3$ | 4.90 | 4.90 | 4.58 | 4.79 | 0.15 |
| $CI_4$ | 4.00 | 3.61 | 4.36 | 3.99 | 0.31 |
| $SI_1$ | 4.00 | 2.83 | 5.66 | 4.16 | 1.16 |
| $SI_2$ | 4.90 | 3.32 | 4.90 | 4.37 | 0.75 |
| $SI_3$ | 2.83 | 3.32 | 4.47 | 3.54 | 0.69 |
| $SI_4$ | 2.83 | 4.00 | 5.66 | 4.16 | 1.16 |
| $SI_5$ | 5.66 | 5.66 | 4.90 | **5.40** | 0.36 |
| $SI_6$ | 5.66 | 4.58 | 4.58 | **4.94** | 0.51 |
| $PI_1$ | 4.90 | 4.90 | 4.90 | **4.91** | 0.00 |
| $PI_2$ | 4.00 | 3.61 | 5.66 | 4.42 | 0.89 |
| $SCI_1$ | 4.58 | 4.90 | 5.66 | **5.05** | 0.45 |
| $SCI_2$ | 5.66 | 4.58 | 5.66 | **5.30** | 0.51 |
| $SCI_3$ | 4.90 | 4.90 | 4.90 | **4.91** | 0.00 |
| $DKI_1$ | 4.90 | 4.90 | 5.66 | **5.15** | 0.36 |
| $DKI_2$ | 4.90 | 4.90 | 4.90 | **4.91** | 0.00 |
| $DKI_3$ | 4.90 | 4.58 | 4.90 | 4.79 | 0.15 |
| $DKI_4$ | 2.83 | 2.83 | 4.90 | 3.52 | 0.98 |
| $SNI_1$ | 4.90 | 4.90 | 5.66 | **5.15** | 0.36 |
| $SNI_2$ | 4.90 | 3.32 | 5.66 | 4.62 | 0.97 |
| $SNI_3$ | 4.00 | 3.32 | 3.32 | 3.54 | 0.32 |
| $SNI_4$ | 3.32 | 4.36 | 4.58 | 4.09 | 0.55 |
| $RI_1$ | 3.32 | 4.36 | 4.58 | 4.09 | 0.55 |
| $RI_2$ | 4.90 | 4.90 | 4.90 | **4.91** | 0.00 |
| $RI_3$ | 4.58 | 3.32 | 4.90 | 4.27 | 0.68 |
| $RI_4$ | 3.32 | 2.83 | 4.90 | 3.68 | 0.88 |
| $RI_5$ | 4.90 | 4.00 | 4.90 | 4.60 | 0.42 |

decisions and plans are accessible to Iran's pharmaceutical industry towards *CSC*.

Nevertheless, the technologies that help practitioners improve sourcing and manufacturing processes are hardly utilized. In comparison, Nanotechnology and *SA* can significantly reduce environmental pollution (water, air, and sound) emitted from manufacturing raw chemical materials and end-used products of toxic nature. Fortunately, *GPS* is an available technology in the delivery & return layer. Therefore, Iran's pharmaceutical industry could apply *GPS* to profoundly decrease contamination emissions of the drug distribution system, a great crisis in this country. Moreover, such supportive technologies as *BDA*, *MT*, and *DPs* have the potential to facilitate the three abovementioned processes.
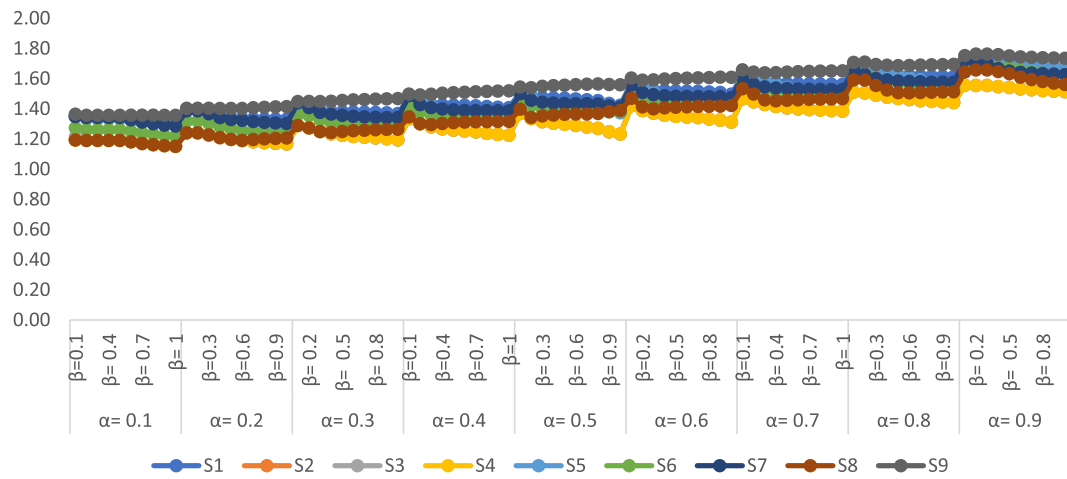
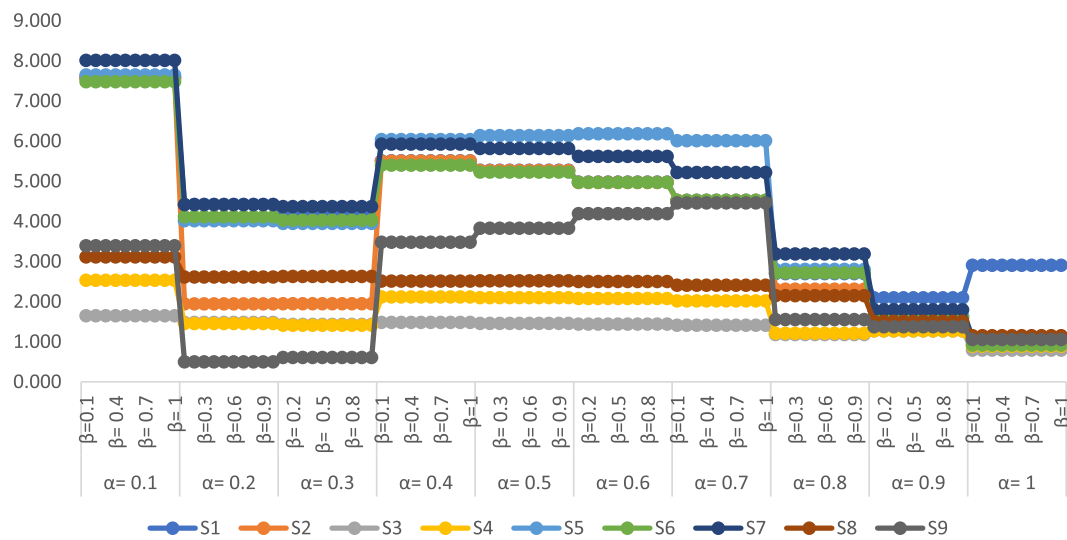**Fig. 4a.** Score trends in the maximum model.
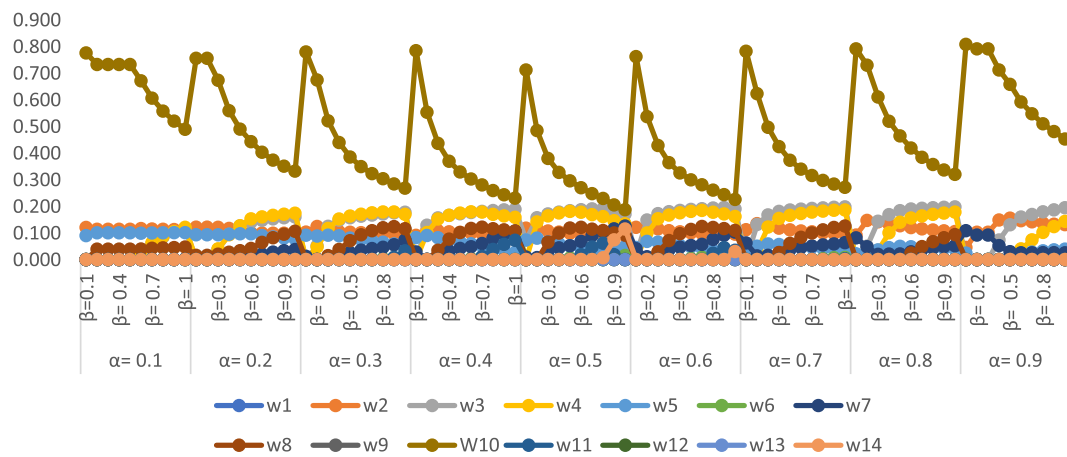


**Fig. 4b.** Score trends in the minimum model.
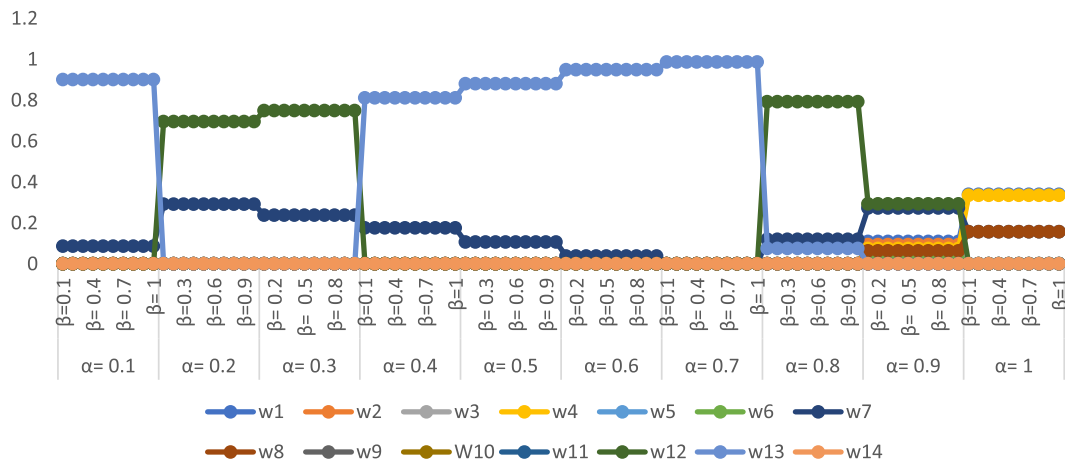


**Fig. 4c.** Weights trends in maximum model.

**Fig. 4d.** Weights trends in minimum model.

**Table 8**
Weights of potential impacts.

|  | EI$_1$ w$_1$ | EI$_4$ w$_2$ | EI$_5$ w$_3$ | CI$_1$ w$_4$ | SI$_5$ w$_5$ | SI$_6$ w$_6$ | PI$_1$ w$_7$ | SCI$_1$ w$_8$ | SCI$_2$ w$_9$ | SCI$_3$ W$_{10}$ | DK$_1$ w$_{11}$ | DK$_2$ w$_{12}$ | SNI$_1$ w$_{13}$ | RI$_2$ w$_{14}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.087 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.901 | 0.001 |
| Max | 0.001 | 0.121 | 0.001 | 0.001 | 0.091 | 0.001 | 0.001 | 0.001 | 0.001 | 0.777 | 0.001 | 0.001 | 0.001 | 0.001 |

Albeit, *Simulation* technology has been relatively utilized to do so. While simulating a real-world process/system would warrant the promoted 'as-is' situation.

On the other hand, the impacts of *IDTs* in designing pharmaceutical *CSCs* in emerging economies like Iran cover **(I)** the *TBL* pillars along with **(II)** product lifecycle management, **(III)** *SC* configuration, **(IV)** data and knowledge management, **(V)** *SC* main functions, and **(VI)** risk management categories. More precisely, based upon the mood of minimum unavailability of *IDTs*, optimized utilization and efficient allocation of resources, improved tracking and traceability of raw material/final products through real-time inventory monitoring, and improved product/service design, respectively, have been sorted as the first three impacts of *IDTs* in pharmaceutical *CSCs*.

From the environmental perspective, applying *IDTs* results in optimizing the utilization and efficient allocation of resources, energy, and materials, reducing (or net-zero) overproduction, expired products, and energy wastes from machines and processes, avoiding hazardous materials, and decreasing environmental (air, water, and sound) pollutions as well (Mastos et al., 2021). Contemplating the economic perspective, employing *IDTs* improves economic performance by decreasing total and transaction costs, growing return on investment, etc. (Ab Rahman et al., 2017). From the societal point of view, implementing Industry 4.0 in pharmaceutical *CSCs* could have both positive and negative impacts. As a positive point, substituting the human workforce with machines would prevent complex routine jobs and create soft job opportunities (Nascimento et al., 2019). However, the relocation and outsourcing of jobs could result in worse work conditions in emerging economies, inequalities, and social gaps around the world (Cezarino et al., 2019).

Furthermore, employing *IDTs* would improve product/service design. Generally, the life cycle of products would be optimized

considering the closed-loop issue (Zheng et al., 2021). Accordingly, *SC* configuration would move towards a lean, agile, resilient, and sustainable *SC*. In this theme, *SC* productivity and performance (*SC*'s efficiency and effectiveness), transparency, collaboration, integration, and communication, along with the entire *SC,* would be improved (Cezarino et al., 2019). In this context, the improved control of data operations leads to real-time information sharing and synchronization with SC members, resulting in trust and better engagement/collaboration.

Furthermore, real-time inventory monitoring would enhance the tracking and traceability of raw material/final products (Mastos et al., 2021). From the risk management point of view, implementing Industry 4.0 would support ripple effect control by improving production capacity reliability and demand forecasting (Ghadge et al., 2020). More precisely, based upon the minimum unavailability of *IDTs*, optimized utilization and efficient allocation of resources, improved tracking and traceability of raw material/final products through real-time inventory monitoring, and improved product/service design, respectively, have been sorted as the first three impacts of *IDTs* in pharmaceutical *CSCs*. Besides, upon maximum availability of *IDTs*, moving towards a lean, agile, resilient, and sustainable supply chain, optimizing waste management, and substituting the human workforce with machines, were considered the most critical impacts in the pharmaceutical industry of emerging economies, which are more limited in *TBL* pillars of sustainability than developed countries.

Furthermore, a survey of both the extant literature and authentic international documents revealed environmental regulations, fines, rewards, subsidies, and a strong culture of ecological/societal preference among customers as effective interventions in *CSC* 4.0 (Jiang et al., 2018; Li et al., 2019; Science for Environment Policy, 2020; Tian et al., 2014). However, an additional survey of experts' views specified

**Table 9**
Scores of IDTs.

|  | PT$_2$ S$_1$ | PT$_3$ S$_2$ | MT$_3$ S$_3$ | MT$_4$ S$_4$ | DT$_4$ S$_5$ | ST$_3$ S$_6$ | ST$_4$ S$_7$ | ST$_5$ S$_8$ | ST$_6$ S$_9$ |
|---|---|---|---|---|---|---|---|---|---|
| Min | 7.58 | 7.57 | 1.64 | 2.52 | 7.64 | 7.47 | 8.01 | 3.11 | 3.39 |
| Max | 1.35 | 1.19 | 1.21 | 1.19 | 1.36 | 1.27 | 1.35 | 1.19 | 1.36 |

environmental regulations, fines, rewards, and subsidies as the four most influential interventions in Iran's pharmaceutical *CSCs* 4.0. Considering Iran's situation, the environmental regulations are associated with the determination of, for example, the site of the company (the maximum distance between the site of the company and the residential area), waste disposal site and method, water consumption, environmental (air, sound, water) pollution, as well as expired products per month. Regulatory enterprises impose fines for failure to comply with environmental regulations. Regulatory enterprises give a reward for each job creation per month. The subsidy is provided by regulatory enterprises to establish a new business considering sustainable development. These interventions would affect the impacts of *IDTs* in designing pharmaceutical *CSCs*. To prioritize these interventions, the Basic Priority Rating (BPR), Hanlon method, was employed using the accumulation of experts' views. (Choi et al., 2019).

As illustrated in Fig. 5, moving toward a lean, agile, resilient, and sustainable supply chain impacts *IDTs* in pharmaceutical *CSC*. This *CSC* would be affected by all four interventions with a priority of subsidy, fine, environmental regulations, and reward. On the other hand, relocation and outsourcing of jobs, improving SC's efficiency and effectiveness, improving transparency, collaboration, integration, and communication along with the entire *SC*, real-time information sharing, and control of data operations are such impacts that would be affected by none of the four particular interventions. Besides, the results associated with *SC*'s primary function and risk management categories would be affected only by subsidy and environmental regulations. Moreover, the impacts related to the ecological category were mostly impacted by fines, environmental regulations, and subsidies. Subsidy (51.3) and environmental regulations (21) could impress the impact related to product life cycle management. Improve economic performance would indeed be affected by subsidy (87), reward (58.3), and fine (36.7). The positive impact associated with the societal perspective could be affected by reward (93.3) and subsidy (37.3).

Similarly, rewards and subsidies are effective global interventions to enhance *CSCs* 4.0 in the perspective of *TBL* pillars (Jiang et al., 2018; Li et al., 2019; Tian et al., 2014). However, the efficiency and effectiveness of *CSCs* 4.0 in developed countries have been more considerable. In this respect, systems of imposed fine and given reward and subsidy needs to be reorganized and optimized in emerging economies like Iran.

***Managerial implications.*** Iran's pharmaceutical industry needs to improve all layers of its house of *CSC*. Indeed, senior managers need to apply *MES, SCAD, AI,* and *BI* to improve the processes associated with setting long- and short-term strategies and plans. Middle managers must employ EMSs, FALs, Robotics, CPS, Drones, etc., to enhance the sourcing, manufacturing, distributing, returning, etc. Moreover, fundamental technologies like *CT, IoT, and Blockchain* are required to support *CSC* processes. Hence, **(I)** the regulatory enterprises should initially edit regulations and reorganize the reward and punishment system; more

impacts of *IDTs* would be supported toward lean, agile, resilience, and sustainability. For instance, environmental regulations and fines should expand on societal rules to enrich the positive societal impacts, e.g., enhance job opportunities and avoid adverse effects such as worse work conditions in emerging economies, inequalities, and social gaps worldwide. **(II)** Financial support is additionally required from the government to enrich the House of pharmaceutical *CSC* 4.0 with more useful *IDTs* such as *Robotics, SA, Nanotechnology, and Drones*, which are essential for implementing well-adjusted plans. **(III)** Senior managers should increase investors to boost their technology portfolio with entirely unavailable ones (e.g., *CT, IoT, AI, MES, SCAD, etc.*) to deal with the low level of sustainability of pharmaceutical *CSCs* 4.0 resulting from various stakeholders with distinct aims, high level of expired products, pollution, unemployment, etc. Moreover, **(IV)** middle and operational managers should accurately employ technologies like *BDA* and *GPS* to promote leverage of high-ranked impacts towards a lean, agile, resilient, and sustainable supply chain.

## 6. Conclusion and future research recommendations

This paper advances the study of the disruptive action of Industry 4.0 technologies cross-fertilizing CE throughout pharmaceutical *SCs*. The paper has been enriched by employing the intuition and hesitation of industry experts of an emerging economy, which was integrated with contemporary and relevant literature. To accomplish the research's aim, the novel *House of SC 4.0*, including 26 SC process-based *IDTs*, along with a categorized list of the impacts of *IDTs* in *CSCs*, was initially provided through two streams of the literature review process. These two categorized lists were then screened considering the pharmaceutical industry of Iran's emerging economy. To do so, a novel Pythagorean fuzzy-Delphi was developed. Next, the weight of finalized impacts and the finalized IDTs' performance score were simultaneously measured via a novel Pythagorean fuzzy SECA. Eventually, the Hanlon method was innovatively applied to prioritize each identified intervention for each finalized impact. This paper hence provides practitioners with the best strategy selection to address the fundamental challenges associated when implementing *CSCs* 4.0 in the pharmaceutical sector of emerging economies.

Future developments of this work can be accomplished in five main directions: (i) Due to the importance of this sector in developed nations, in the post-Covid19 era, the pharmaceutical CSC of a developed country could also be considered in the future. Then, the results could be benchmarked and compared against those obtained from this study. Hence, the results could be applied in emerging economies to promote the performance of pharmaceutical *CSCs* 4.0; (ii) the qualitative approach of extracting the impacts of *IDTs* in *SCM* could also be complemented with other methodological approaches, such as multiple case studies. This can help to determine and examine these effects more precisely and extract the impacts that have not been considered in the literature so far; (iii) from the methodological perspective, the results of the proposed Pythagorean fuzzy SECA could be compared with the R-number SECA developed by Seiti et al. (2021). Moreover, the solving approach could be compared with other methods such as bi-level and goal programming (Dong & Wan, 2018). Examining different proposed methodologies can help ensure the stability of the results; (iv) this research methodology could be applied in other industries and emerging economies, and (v) future scholars could develop a mathematical model to optimize the reward and punishment system of sustainable pharmaceutical *SCs* in emerging economies like Iran.

### CRediT authorship contribution statement

**Hannan Amoozad Mahdiraji:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Visualization. **Fatemeh Yaftiyan:** Conceptualization, Formal analysis, Writing – original draft, Writing –
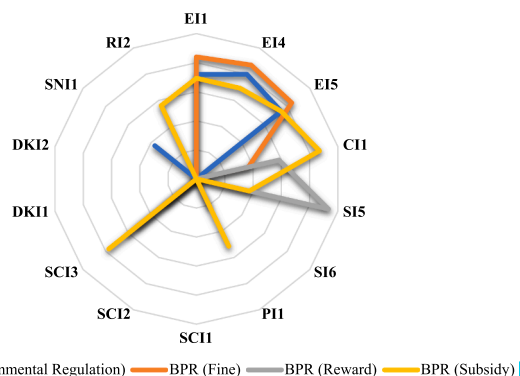


**Fig. 5.** Impact of potential interventions on impacts of *IDTs* in pharmaceutical *CSC*.

review & editing, Visualization, Investigation. **Aliasghar Abbasi-Kamardi:** Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Investigation. **Jose Arturo Garza-Reyes:** Conceptualization, Validation, Writing – original draft, Writing – review & editing, Supervision.

## 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

No data was used for the research described in the article.

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