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Assessing IoT challenges in supply chain: A comparative study before and during- COVID-19 using interval valued neutrosophic analytical hierarchy process

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ABSTRACT

Although the Internet of Things (IoT) has spawned a new breed of smart factories within supply chains, the latest pandemic has ushered in unparalleled supply chain disturbances. Following the challenges identified in the literature, we interview top experts to evaluate the significance of these challenges. We apply a multi-criteria decision analysis (MCDA) tool, analytical hierarchy process (AHP) in combination with interval-valued neutrosophic numbers (IVN). The critical part of this research is that we also perform a comparative analysis by focusing on before- and during- the pandemic periods individually to better assess the impact of the latest pandemic on the IoT challenges. Our study also includes a comprehensive, systematic literature review to bring the readers up-to-date.

1. Introduction

The world has been going through COVID-19 pandemic, anxiously waiting for vaccination to be completed. As scientists have developed vaccines in record time, the heat is now on for the supply chains for the delivery. The urgency of the production and logistics of billions of jabs to be distributed worldwide has put the supply chain performance under the spotlight. In the wake of the age of digitalization and heavy computer usage, a new era of further-digitized and interconnected large-scale machine-to-machine (M2M) networks have been revolutionized the supply chains (SC). These M2M information exchanges, known as the Internet of Things (IoT), have connoted the fourth industrial revolution, also known as Industry 4.0 (i4.0). The pandemic has disrupted SCs going through this revolutionary transition to i4.0 even further.

There is an echo of recent literature heralding a great wave of disruption taking place. i4.0, also known as Industrial Internet of Things (IIoT) has been spawning a new breed of real-timecapable smart factories (Kiel, Arnold, & Voigt, 2017). The automatic capture of data with sensors, making them accessible to authorized entities both internally and externally, using data analytics for advanced processes securely go beyond digitalization (Ben-Daya, Hassini, & Bahroun, 2019). These capable factories, hallmarked by IoT, laden with the state-of-the art such as smart sensors and big data analytics, buttressed by law and administration are restructuring the traditional ways of manufacturing. While autonomous standalone factories with smart-capabilities are essential, the literature insists that all processes in SCs must be digitalized, integrated, and automated to realize i4.0 (Bauer, Hämmerle, Schlund, & Vocke, 2015; Hofmann & Rüsch, 2017; Tjahjono, Esplugues, Ares, & Pelaez, 2017). Despite the rapid growth of IIoT research, IIoT's merits on supply chains are frequently surmised, and its implications are often misidentified (Müller, Kiel, & Voigt, 2018).

Most manufacturing companies are oblivious to the extent to which their organization will be impacted by IIoT absorption. Even though the research on IIoT technologies consistently underlines their potential benefits (Moeuf et al., 2020; Prause, 2019; Raj, Dwivedi, Sharma, de Sousa Jabbour, & Rajak, 2020; Whitmore, Agarwal, & Da Xu, 2015), the extant literature also posits uncertainties such as, but is not limited

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to, the managerial (Birkel & Hartmann, 2020; Tu, 2018), environmental (Wang & Wang, 2017), or social uncertainties of IIoT (Shah, Bolton, & Menon, 2020). While using real-time, reliable, secure, and timely data processing can help create flexible and resilient supply chains, there is a diverse set of highly complex factors, risks and challenges that must be identified, analyzed, and resolved (Birkel & Hartmann, 2019). The recent COVID-19 pandemic has increased these factors even further in complexity.

Supply Chain Risk Management (SCRM) aims to assess and eliminate the risks to ensure continuity (Heckmann, Comes, & Nickel, 2015). Although the research on SCRM and IIoT is rather limited (Birkel & Hartmann, 2020), addressing the potential benefits of IIoT technologies within supply chains such as agility, flexibility and resilience has gained prominence. To build more capable supply chains, it is particularly important to understand both the issues that supply chains face during the pandemic and the implications of the pandemic on the IIoT use in supply chains. These two matters bolster the importance of managing the challenges of IIoT technologies in supply chains during a pandemic. There have been recent studies to establish a framework for classifying the potential challenges and risks associated with IIoT in supply chains. In IIoT, risks ensue the challenges. Challenges and risks – as the consequent of challenges – impact the realization of the expected gains due to IIoT adoption. To the best of our knowledge, no attempt has been made to quantify the importance of challenges associated with IIoT and supply chains. Furthermore, embedding the impact of the currently ongoing pandemic on studying these challenges could help grasp the future of IIoT in supply chains.

Our research question is: "Given the risk and challenge framework of using IIoT for supply chains, how does the pandemic affect the relative importance of the challenges of IIoT in supply chains". In response to this question, we structure the rest of this article as follows. We offer a comprehensive and systematic literature review, and theoretical background in the next section. We describe our proposed methodology in Section 3. Section 4 is dedicated to the challenge assessment using our proposed methodology. The paper closes with conclusion and discussion section.

2. Literature review and theoretical background

The academic literature on the nascent field of IIoT is rapidly growing. Earlier studies mostly emphasize the positive effects of using IIoT such as better transportation (Harris, Wang, & Wang, 2015), better inventory management (Mathaba, Adigun, Oladosu, & Oki, 2017), higher customer satisfaction (Jie, Subramanian, Ning, & Edwards, 2015), quality improvements in logistics (Gu & Liu, 2013) and expanding the financial benefits (Verdouw, Beulens, & Van Der Vorst, 2013). Studies focusing on the challenges related with IIoT are relatively newer (Radanliev et al., 2020; Raj et al., 2020; Shafique, Khawaja, Sabir, Qazi, & Mustaqim, 2020). Masood and Sonntag (2020) identify three main challenge themes faced by SMEs as financial, knowledge resource and technology awareness limitations. Orzes, Rauch, Bednar, and Poklemba (2018) attempt to determine the latest barriers to IoT implementation in SMEs empirically. Horváth and Szabó (2019) identify and compare IIoT challenges for MNEs and SMEs.

A few studies provide comprehensive, systematic reviews of the IIoT in SC context. Ben-Daya et al. (2019) offer a thorough review of IIoT and SCM literature based on several schemes such as methodology used and industry sector. Birkel and Hartmann (2019) develop a risk framework for i4.0 for manufacturers in sustainability context. In a separate study, same authors, Birkel and Hartmann (2019) develop an extensive review of the risk and challenge related research about IoT in SC. After considering 1936 studies, they review 102 publications related to IIoT risks and challenges within a two-dimensional framework. They adopt three main dimensions for risks and challenges suggested by Jüttner, Peck, and Christopher (2003) as: (i) environmental, (ii) network-related and (iii) organizational. In their study, Birkel and Hartmann (2019) itemize a comprehensive categorization of challenges and consequent risks for the literature. There are several other IoT related literature review studies (Aryal, Liao, Nattuthurai, & Li, 2018; Manavalan & Jayakrishna, 2019; Shafique et al., 2020).

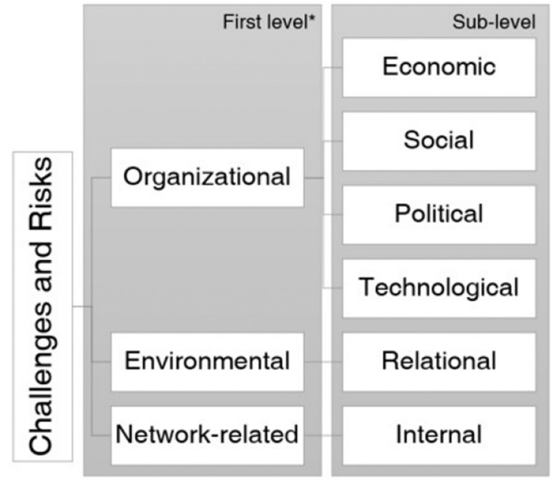

Fig. 1. Birkel and Hartmann's framework of risks and challenges literature. (*) is adopted from Jüttner et al. (2003).

2.1. Systematic literature review of iiot in SCs

In our opinion, Birkel and Hartmann (2019) provide one of the most comprehensive and complete frameworks addressing IoT challenges and risks for SCs (Fig. 1). Although their study is relatively new, there have been a number of newer studies in this emerging area of research. Rather than creating a separate framework for a literature review, we decide to adopt their framework and expand their coverage by appending it with more recent studies. In their paper (Birkel & Hartmann, 2019) label each study with a set of risks and challenges. While their framework looks comprehensive, there are judgment calls to be made in the labeling of newer studies according to the framework. We, therefore, first familiarize ourselves with their method of labeling studies by randomly selecting ten papers from Birkel and Hartmann. We then blindly categorize them according to their risks and challenges template. Finally, we compare our labels against those reported by Birkel and Hartmann (2019) for consistency. As expected, there are gray areas for subjective interpretation, but our labeling of these papers exhibits a high degree of similarity (average Pearson pairwise correlations is found to be > .7).

Locating the studies:. At this stage, we locate newer studies that were published after Birkel and Hartmann (2019) for labeling. The research involving IoT is quite diverse. While searching for relevant studies, we create a generic list of keywords including IoT, IIoT, SCM, challenges, risk, challenges, supply chain, smart supply chain, RFID. Following the footsteps of Birkel and Hartmann we identify 628 studies using Google scholar. After checking for inclusion criteria, relevance and quality, we filter our selection down to 35 studies. Conducting a cross-search on the list of references of the selected 30 studies, and eliminating possible duplicates against Birkel and Hartmann (2019), our final list of studies includes 29 papers. The expanded literature review is provided in Tables A.18 and A.19.

2.2. Background on COVID-19 and its effect on iiot in SCs

COVID-19, a respiratory syndrome that has spread to all countries, started in Wuhan in November 2019. World Health Organization (WHO) declared COVID-19 as a pandemic. The pandemic, especially in its

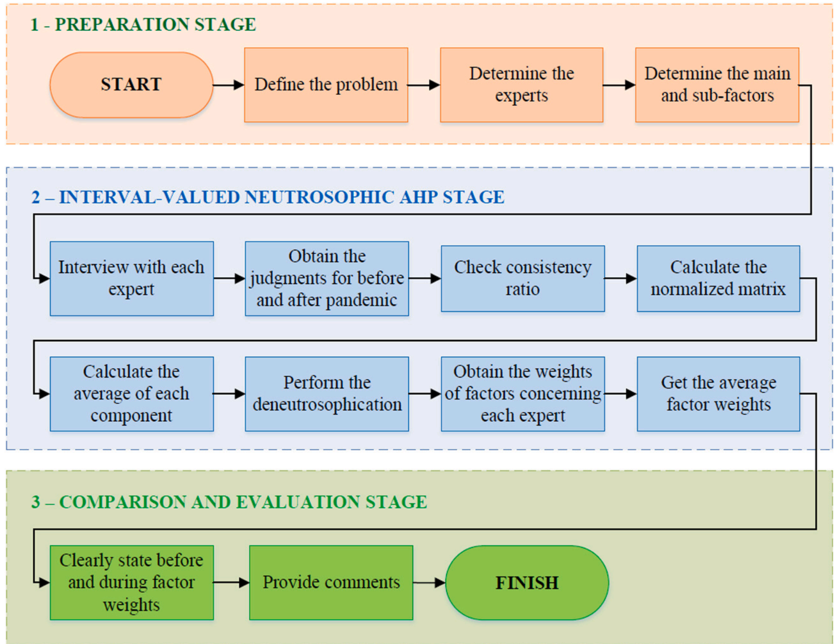

Fig. 2. The stages of the proposed methodology.

Table 1
Linguistic terms for neutrosophic sets due to Bolturk and Kahraman (2018).

Linguistic term (Shortened term)	Neutrosophic sets
Equal Importance (EI)	⟨[0.5, 0.5], [0.5, 0.5], [0.5, 0.5]⟩
Weakly More Importance (WMI)	⟨[0.50, 0.60], [0.35, 0.45], [0.40, 0.50]⟩
Moderate Importance (MI)	⟨[0.55, 0.65], [0.30, 0.40], [0.35, 0.45]⟩
Moderately More Importance (MMI)	⟨[0.60, 0.70], [0.25, 0.35], [0.30, 0.40]⟩
Strong Importance (SIMP)	⟨[0.65, 0.75], [0.20, 0.30], [0.25, 0.35]⟩
Strongly More Importance (SMI)	⟨[0.70, 0.80], [0.15, 0.25], [0.20, 0.30]⟩
Very Strong Importance (VSI)	⟨[0.75, 0.85], [0.10, 0.20], [0.15, 0.25]⟩
Very Strongly More Importance (VSMI)	⟨[0.80, 0.90], [0.05, 0.10], [0.10, 0.20]⟩
Extreme Importance (EXI)	⟨[0.90, 0.95], [0, 0.05], [0.05, 0.15]⟩
Extremely High Importance (EHI)	⟨[0.95, 1.0], [0.0, 0.0], [0.0, 0.10]⟩
Absolutely More Importance (AMI)	⟨[1.0, 1.0], [0.0, 0.0], [0.0, 0.0]⟩

Table 2
Details of the interviewees.

Expert #	Sector	Position
Expert 1	University	Professor of Supply Chain Management
Expert 2	University	Professor of Industrial Engineering
Expert 3	University	Associate Professor of Industrial Engineering
Expert 4	University	Associate Professor of Industrial Engineering
Expert 5	Logistics	CIO in the Ministry of Labor of the Republic of Kazakhstan
Expert 6	Logistics	CIO of IT department of national post company
Expert 7	SCM Consultancy	CEO of consulting company in SCM

earlier days, caused havoc, and a great deal of anxiety among all countries causing shutdown of borders and country-wide lockdowns. At the time of writing, the official number of COVID-19 cases has surpassed 150 million with a death toll of 3+ million individuals. Although unemployment figures are unreliable due to reasons such as government subsidies, it is clear that millions have lost their jobs. An estimate by ILO puts the global working hours lost to an equivalent of 250 million full-time jobs (link, 0000).

COVID-19 spread has poised to disrupt supply chains. The disruption has been so dislocating that most businesses have changed the way they operate. Communication technologies have been proven to be sufficient tools when physical face-to-face are dangerous, enabling a vast spectrum of occupations to be carried out online. The disruption and changes that have come with COVID-19 are so vast and deep that for some businesses it has been difficult to tell the disaster from opportunity. Online business' have soared, along with the technology that go into developing them. Lockdowns have brought local businesses and retail traders to the brink of a moribund economy. Manufacturing firms and supply chains that have been lacking technology, autarky and diversity have found themselves looking into the abyss of annihilation. Some larger companies are reported to be minimally affected by the pandemic, while SMEs are reported to experience intolerable losses and massive dislocations (Bartik et al., 2020). More than half of the SMEs, especially in developing nations, are in arrears (WorldBank, 2022). The supply and demand gap has oscillated frantically, and the magnitude of the hysteresis effect for the post-pandemic era is still unknown.

Governments' COVID-19 containment measures involve a great deal of social distancing in the form of school closures, working from home, and limiting social gatherings. Within manufacturing, IoT and other similar technologies facilitate social distancing. This has promoted the development, improvement, and usage of such technologies in manufacturing firms and supply chains as a whole. It has been clear that on top of their existing risks and challenges regarding IIoT, supply chains are now facing new ones gifted by the pandemic recently. IIoT has been proven to be beneficial in terms of automatization of operations which minimizes human interaction and speeds up processes. However, challenges and risks associated with the integration of IIoT in supply chains are still obstacles on the way. Identification of the challenges and the risks are important in the realization of the expected gains due to IIoT adoption. Risks and challenges are strongly linked, and according to the literature, risks are the subsequent of challenges (Jüttner et al., 2003). We therefore, limit our investigation to the challenges aspect defined by Birkel and Hartmann (2019).

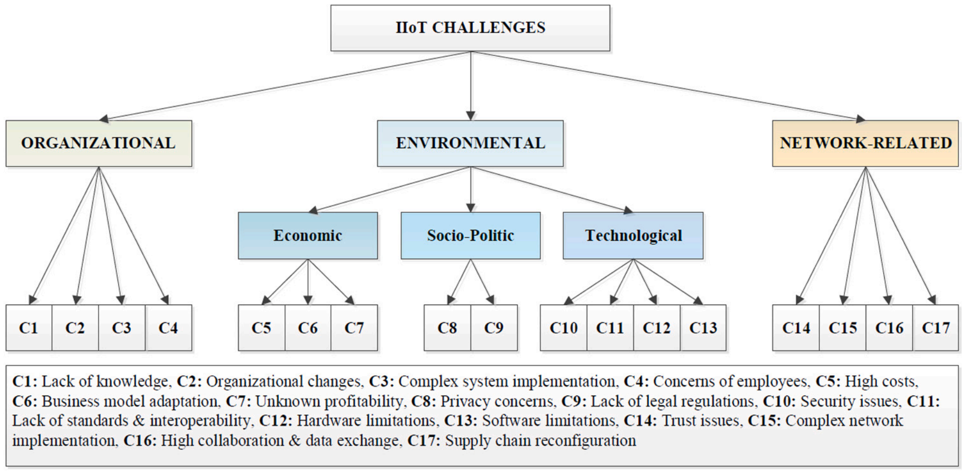

Fig. 3. Hierarchy of challenges (adapted from Birkel & Hartmann).

Table 3
Pairwise comparisons of main challenges with respect to their importance.

First matrix: Comparison of main challenges			
	Organizational	Environmental	Network-related
Organizational	EI	MI^{-1}	EI
Environmental	–	EI	MI
Network-related	–	–	EI

Table 4
Pairwise comparisons of sub-challenges under the organizational main challenge.

Second matrix: Comparison of organizational main challenge's sub-challenges				
	C1	C2	C3	C4
C1-Lack of knowledge	EI	SIMP	MMI	SMI
C2-Organizational changes	–	EI	WMI^{-1}	WMI^{-1}
C3-Complex system implementation	–	–	EI	MI
C4-Concerns of employees	–	–		EI

Table 5
Pairwise comparisons of mid-level challenges under the environmental main challenge.

Third matrix: Comparison of environmental main challenge's challenges			
	Economic	Socio-politic	Technological
Economic	EI	MI	SMI
Socio-politic		EI	MMI
Technological			EI

Table 6
Pairwise comparisons of sub-challenges under the economic mid-level challenge.

Fourth matrix: Comparison of economic challenge's sub-challenges			
	C5	C6	C7
C5-High costs	EI	SIMP	MMI^{-1}
C6-Business model adaptation		EI	$VSMI^{-1}$
C7-Unknown profitability			EI

Table 7
Pairwise comparisons of sub-challenges under the socio-politic mid-level challenge.

Fifth matrix: Comparison of socio-politic challenge's sub-challenges		
	C8	C9
C8-Privacy concerns	EI	MI
C9-Lack of legal regulations		EI

Table 8
Pairwise comparisons of sub-challenges under the technological mid-level challenge.

Sixth matrix: Comparison of technological challenge's sub-challenges				
	C10	C11	C12	C13
C10-Security issues	EI	MI	VSI	SIMP
C11-Lack of standards & interoperability	–	EI	SIMP	MI
C12-Hardware limitations	–	–	EI	MI^{-1}
C13-Software limitations	–	–		EI

Several factors may be used to demonstrate the macroeconomic impact of COVID. For instance, the dramatic reduction in supply brought about by the disruption in Chinese manufacturing and the increase in demand for some manufacturing items had an immediate impact on global trade. Excess demand and shortage of supply capabilities have caused holes in the economy resulting in scarcity of the basic manufactured goods and commodities (Barua, 2020).

The emerging body of literature on the topic of IoT during the COVID-19 pandemic restates the importance of IoT applications in times of crisis and provides examples of IoT usage for; early identification of cases (Otoom, Otoum, Alzubaidi, Etoom, & Banihani, 2020), prevention of the spread of the virus (Dong & Yao, 2021; Kumar, Kumar, & Shah, 2020; Ndiaye et al., 2020), building a transparent treatment process during (Singh, Javaid, Haleem, & Suman, 2020) and post-illness follow-ups (Vedaei et al., 2020). While most of these applications are directly targeting fighting against the pandemic, some studies also point at IoT within supply chain aspects during the pandemic. Rowan and Laffey (2020) propose using smart communication channels in the supply chain, to customize the production, and using sterilization of personal protective equipment. Končar, Grubor, Marić, Vučenović, and Vukmirović (2020) address one of the challenges in IIoT, its implementation. Sarkis (2020) discusses sustainability implications and argues that the pandemic will make us, researchers, revisit the basics of the ontology of the IIoT domain.

3. The proposed methodology

The proposed methodology comprises three stages as shown in Fig. 2. The related stages are preparation, interval-valued neutrosophic AHP, and comparison with evaluation. During the first stage, we first provide a clear definition of the research problem in the first step. We then determine the set of experts. Finally, a systematic literature review and expert discussions are used to determine the key and sub-challenges. In the second stage, IVN-AHP is used to compute the

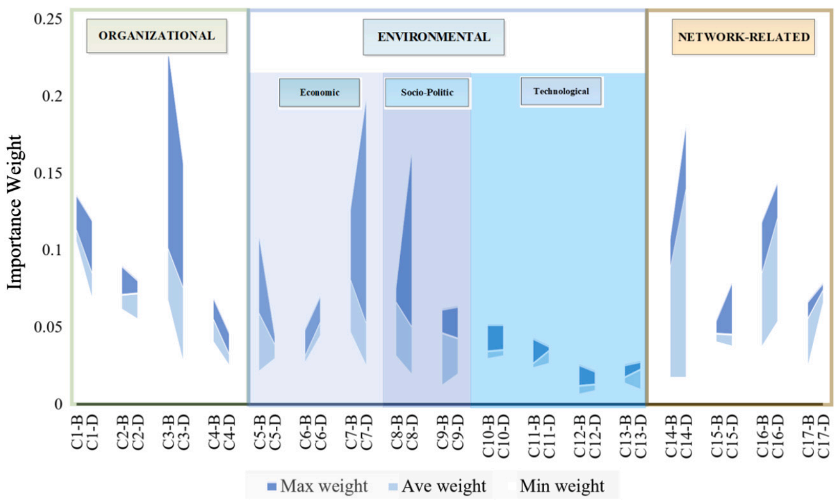

Fig. 4. Visualization of comparative importance weights of sub-challenges before and during the pandemic. Each bar corresponds a sub-challenge represented with six data points (minimum, average, and maximum importance weights for before (left side of the bar) and during (right side of the bar) the pandemic.

Table 9
Pairwise comparisons of sub-challenges under the network-related main challenge.

Seventh matrix: Comparison of network-related main challenge's sub-challenges				
	C14	C15	C16	C17
C14-Trust issues	EI	VSI	MI	SIMP
C15-Complex network implementation	–	EI	$SIMP^{-1}$	MI^{-1}
C16-High collaboration & data exchange	–	–	EI	MI
C17-Supply chain reconfiguration	–	–		EI

Table 10
Consistency values of matrices.

Matrices	Inconsistency (%)
First matrix	0.00
Second matrix	7.38
Third matrix	2.55
Fourth matrix	2.93
Fifth matrix	0.00
Sixth matrix	6.05
Seventh matrix	6.05

importance weights corresponding to each main- and sub-challenges for both before and during the pandemic cases. The last stage provides a comparison of importance weights corresponding to challenges before and during the pandemic is provided with insightful comments. The technical background about IVN-AHP method is provided in the following parts. The preliminaries that give insights to interval-valued neutrosophic numbers, and the IVN-AHP methodology are elaborated.

3.1. Multi-criteria decision analysis and the preliminaries of neutrosophic sets

Multi-criteria decision analysis is described as both a methodology and a group of strategies that offer a total order of choices, ranging from the most favorable to the least favorable option (Crown, 2009). Bonissone, Subbu, and Lizzi (2009) define an overlap of three elements: (i) finding a solution over the space of alternative solutions, (ii) a chosen trade-off mechanism to direct downselection and (iii) an informational presentation to explain the trade-off implications. Many tools can be used in MCDA ranging from the most original analytical hierarchy process (AHP) to analytical network process (ANP), and their derivatives as DEMATEL, TOPSIS, and VIKOR. MCDA is widely used in many industries for specific purposes and on the managerial level as well. The combination of the sets different from crisp numbers as fuzzy and neutrosophic sets with MCDA tools are of common practice. Fuzzy and neutrosophic sets, unlike crisp numbers, provide membership functions for more accurate evaluation, which helps resolve the uncertainty involving decisions for a decision maker. For instance, Büyüközkan, Güleryüz, and Karpak (2017) used an intuitionistic fuzzy ANP with aggregation operator to choose the best CRM operator; Lu, Kuo, Lin, Tzeng, and Huang (2016) designed a framework to develop efficient sustainable development strategies using DEMATEL-based ANP with the VIKOR method on a case study from Taiwan of TFT-LCD industry; Abdel-Basset, Manogaran et al. (2018) suggested implementation of AHP and DEMATEL together for IIoT security system evaluation in a supply chain; Razieh & Ahmad (Keshavarzfard & Makui, 2015) proposed an integrated IF-AHP-DEMATEL for the manager selection problem.

A generalization of intuitionistic fuzzy sets – neutrosophic sets were first introduced by Smarandache (2005, 2016). Since it is generally impossible to precisely detect the percentage of truth and falsity, Smarandache proposed that subsets of truth, falsity, and indeterminacy be used instead of numbers. Integration of neutrosophic sets with MCDA tools is a relatively novel method, and is primarily accomplished using AHP. The method with single-valued neutrosophic sets has already been used in several studies (Abdel-Basset, Mohamed et al., 2018; Nabeeh, Abdel-Basset, El-Ghareeb, & Aboelfetouh, 2019; Radwan, Senousy, & Alaa El Din, 2016; Tey et al., 2019). However, a recent approach of using interval-valued neutrosophic sets (IVN) (Wang, Smarandache, Sunderraman, & Zhang, 2005) has not been widely implemented in real-life cases. The studies include using neutrosophic sets with interval-valued parameters to assess solar energy systems (Aydın, Kahraman, & Kabak, 2020) using the IVN-AHP to evaluate the selection of alternative energy sources (Bolturk & Kahraman, 2018) to name a few. This study is the first attempt to use IVN-AHP for the evaluation of IoT challenges. Before we introduce the IVN-AHP steps, we provide the preliminaries of neutrosophic sets following (Smarandache, 2016; Wang et al., 2005) below.

Definition 1. Let X be a space of objects having a universal element referred to as x.

A truth-membership function T_A characterizes a neutrosophic set A in X, similarly, I_A is a function of an indeterminacy-membership and F_A is a falsity-membership. $T_A(x)$, $I_A(x)$ and $F_A(x)$ are real standard or nonstandard subsets of $]\,0^-, 1^+[$.

Which is:

$$T_A : X \rightarrow]\,0^-, 1^+[\tag{1}$$

$$I_A : X \rightarrow]\,0^-, 1^+[\tag{2}$$

Table 11
Normalized matrix of initial interval-valued neutrosophic comparison matrix.

	Organizational						Environmental						Network-related					
	T_l	T_u	I_l	I_u	F_l	F_u	T_l	T_u	I_l	I_u	F_l	F_u	T_l	T_u	I_l	I_u	F_l	F_u
Organizational	.30	.30	.36	.36	.34	.34	.25	.32	.23	.31	.31	.36	.30	.30	.36	.36	.34	.34
Environmental	.33	.39	.21	.29	.24	.31	.36	.36	.38	.38	.28	.28	.33	.39	.21	.29	.24	.31
Network-related	.30	.30	.36	.36	.34	.34	.25	.32	.23	.31	.31	.36	.30	.30	.36	.36	.34	.34

Table 12
The average of components.

	Average of components					
	T_l	T_u	I_l	I_u	F_l	F_u
Organizational	.29	.31	.32	.34	.33	.35
Environmental	.34	.38	.27	.32	.25	.30
Network-related	.29	.31	.32	.34	.33	.35

Table 13
Weights, normalized weights and ranks of main challenges.

	Weight	Normalized weight	Rank
Organizational	.30	.30	2.5
Environmental	.40	.40	1
Network-related	.30	.30	2.5

$$F_A : X \to]\, 0^-, 1^+ [\tag{3}$$

The sum of three is defined as follows: $0^- \leq sum(T_A(x), I_A(x), F_A(x)) \leq 3^+$

Definition 2. $\bar{A}$ denotes the complement of a neutrosophical set A and is defined by:

$$T_{\bar{A}}(x) = \{1^+\} \ominus T_A(x) \tag{4}$$

$$I_{\bar{A}}(x) = \{1^+\} \ominus I_A(x) \tag{5}$$

$$F_{\bar{A}}(x) = \{1^+\} \ominus F_A(x) \tag{6}$$

for all x in X.

Definition 3. Another neutrosophical set B contains a neutrosophic set A, $A \subseteq B$, if and only if:

$$inf T_A(x) \leq inf T_B(x), \quad sup T_A(x) \leq sup T_B(x) \tag{7}$$

$$inf I_A(x) \geq inf I_B(x), \quad sup I_A(x) \geq sup I_B(x) \tag{8}$$

$$inf F_A(x) \geq inf F_B(x), \quad sup F_A(x) \geq sup F_B(x) \tag{9}$$

for all x in X.

Definition 4. Let X be a space of objects having a universal element referred to as x.

An interval neutrosophic set (INS) A in X is defined by IA indeterminacy-membership, TA truth-membership function, and FA falsity-membership function. For each point x in X, $I_A(x)$, $T_A(x)$, $F_A(x) \subseteq [0, 1]$.

Definition 5. For every x in X, A neutrosophic set of interval A is empty if and only if, $inf T_A(x) = sup T_A(x) = 0, inf I_A(x) = sup I_A(x) = 1, inf F_A(x) = sup T_A(x) = 0$.

Definition 6. An interval neutrosophic set B contains another interval neutrosophic A, $A \subseteq B$, if and only if:

$$inf T_A(x) \leq inf T_B(x), sup T_A(x) \leq sup T_B(x) \tag{10}$$

$$inf I_A(x) \geq inf I_B(x), sup I_A(x) \geq sup I_B(x) \tag{11}$$

$$inf F_A(x) \geq inf F_B(x), sup F_A(x) \geq sup F_B(x) \tag{12}$$

for all x in X.

Definition 7. $\bar{A}$ denotes a complement interval of a neutrosophical set A and is defined by:

$$T_{\bar{A}}(x) = F_A(x) \tag{13}$$

$$inf I_{\bar{A}}(x) = 1 - sup I_A(x) \tag{14}$$

$$sup I_{\bar{A}}(x) = 1 - inf I_A(x) \tag{15}$$

$$F_{\bar{A}}(x) = T_A(x) \tag{16}$$

for all x in X.

3.2. IVN-AHP process

Saaty's (1980) AHP is based on factor pairwise comparisons. The method is widely used in a range of fields because it allows for the evaluation of alternatives without the use of direct scoring Kilic, Zaim, and Delen (2014). However, since the traditional AHP is inadequate to resolve uncertainty and ambiguity in real-world decision-making situations, various fuzziness improvements, such as intuitionistic and neutrosophic sets, have been developed. Based on the studies of Bolturk and Kahraman and Nabeeh et al. we use IVN-AHP because of its comprehensive structure and ability to reflect actual decision-making environments through its three parameters. Related steps are explained in brief as follows:

Step 1:. Determine the evaluation scale based on interval-valued neutrosophic sets.

In this study, the scale indicated in Table 1 is used. The three parameters are truth-, indeterminacy- and falsity-memberships. Moreover, for the inverse of these linguistic terms, while the indeterminacy parameter remains the same, the truth-membership and falsity-membership parameters are swapped.

Step 2:. Build a hierarchical structure based on the goal, criteria, sub-criteria, and alternatives.

Step 3:. Using the interval-valued neutrosophic sets given in Eq. (17), calculate the pairwise comparison matrices.

$$A = \begin{bmatrix} [T_{11}^L, T_{11}^U], [I_{11}^L, I_{11}^U], [F_{11}^L, F_{11}^U] & \cdots & [T_{1n}^L, T_{1n}^U], [I_{1n}^L, I_{1n}^U], [F_{1n}^L, F_{1n}^U] \\ \vdots & \ddots & \vdots \\ [T_{n1}^L, T_{n1}^U], [I_{n1}^L, I_{n1}^U], [F_{n1}^L, F_{n1}^U] & \cdots & [T_{nn}^L, T_{nn}^U], [I_{nn}^L, I_{nn}^U], [F_{nn}^L, F_{nn}^U] \end{bmatrix} \tag{17}$$

For checking the consistency of the pairwise comparison matrix, first, each entry of the matrix A is deneutrosophicated via Eq. (18) and the classic consistency process provided in AHP is applied (Saaty, 1980).

$$d = \left(\frac{T^L + T^U}{2}\right) + \left(\left(1 - \frac{(I^L + I^U)}{2}\right) \times I^U\right) - \left(\left(\frac{F^L + F^U}{2}\right) \times (1 - F^U)\right) \tag{18}$$

Table 14
Main challenge: comparative importance weights of main challenges before and during the pandemic.

Main challenge	Consolidated reviews		Expert 1		Expert 2		Expert 3		On Average	
	Before	During	Before	During	Before	During	Before	During	Before	During
Organizational	.304	.262	.392	.308	.308	.215	.477	.308	.342	.269
Environmental	.392	.308	.304	.262	.477	.477	.308	.477	.379	.350
Network-related	.304	.430	.304	.430	.215	.308	.215	.215	.279	.382

Table 15
Mid-level challenge: comparative importance weights of economic, socio-politic, and technological mid-level challenges before and during the pandemic.

Mid-level challenge	Consolidated reviews		Expert 1		Expert 2		Expert 3		On Average	
	Before	During	Before	During	Before	During	Before	During	Before	During
Organizational	.434	.391	.392	.438	.477	.308	.599	.599	.458	.415
Environmental	.352	.259	.304	.167	.215	.477	.146	.146	.296	.261
Network-related	.214	.351	.304	.395	.308	.215	.255	.255	.246	.324

Step 4:. After checking the consistency of the matrix A, the normalized matrix (B*) is obtained by dividing each entry in matrix A by the sum of the corresponding upper parameter column following Eqs. (19) and (20).

$$B^*_{ij} = [[\frac{T^L_{ij}}{\Sigma^n_{k=1}T^U_{kj}}, \frac{T^U_{ij}}{\Sigma^n_{k=1}T^U_{kj}}], [\frac{I^L_{ij}}{\Sigma^n_{k=1}I^U_{kj}}, \frac{I^U_{ij}}{\Sigma^n_{k=1}I^U_{kj}}], [\frac{F^L_{ij}}{\Sigma^n_{k=1}F^U_{kj}}, \frac{F^U_{ij}}{\Sigma^n_{k=1}F^U_{kj}}]]; \forall i, j \tag{19}$$

$$B^*_{ij} = [[T^{*L}_{ij}, T^{*U}_{ij}], [I^{*L}_{ij}, I^{*U}_{ij}], [F^{*L}_{ij}, F^{*U}_{ij}]]; \forall i, j \tag{20}$$

Step 5:. Compute the row average of each parameter in B^* indicated in Eq. (21) and obtain C^{**} as in Eq. (22).

$$B^* = \begin{bmatrix} [T^{*L}_{11}, T^{*U}_{11}], [I^{*L}_{11}, I^{*U}_{11}], [F^{*L}_{11}, F^{*U}_{11}] & \cdots & [T^{*L}_{1n}, T^{*U}_{1n}], [I^{*L}_{1n}, I^{*U}_{1n}], [F^{*L}_{1n}, F^{*U}_{1n}] \\ \vdots & \ddots & \vdots \\ [T^{*L}_{n1}, T^{*U}_{n1}], [I^{*L}_{n1}, I^{*U}_{n1}], [F^{*L}_{n1}, F^{*U}_{n1}] & \cdots & [T^{*L}_{nn}, T^{*U}_{nn}], [I^{*L}_{nn}, I^{*U}_{nn}], [F^{*L}_{nn}, F^{*U}_{nn}] \end{bmatrix} \tag{21}$$

$$C^{**} = \begin{bmatrix} [\frac{\Sigma_j T^{*L}_{1j}}{n}, \frac{\Sigma_j T^{*U}_{1j}}{n}] & [\frac{\Sigma_j I^{*L}_{1j}}{n}, \frac{\Sigma_j I^{*U}_{1j}}{n}] & [\frac{\Sigma_j F^{*L}_{1j}}{n}, \frac{\Sigma_j F^{*U}_{1j}}{n}] \\ & \cdots & \\ & \cdots & \\ & \cdots & \\ [\frac{\Sigma_j T^{*L}_{nj}}{n}, \frac{\Sigma_j T^{*U}_{nj}}{n}] & [\frac{\Sigma_j I^{*L}_{nj}}{n}, \frac{\Sigma_j I^{*U}_{nj}}{n}] & [\frac{\Sigma_j F^{*L}_{nj}}{n}, \frac{\Sigma_j F^{*U}_{nj}}{n}] \end{bmatrix} = \begin{bmatrix} [T^{**L}_1, T^{**U}_1], & [I^{**L}_1, I^{**U}_1], & [F^{**L}_1, F^{**U}_1] \\ & \cdots & \\ & \cdots & \\ & \cdots & \\ [T^{**L}_n, T^{**U}_n], & [I^{**L}_n, I^{**U}_n], & [F^{**L}_n, F^{**U}_n] \end{bmatrix} \tag{22}$$

Step 6:. Deneutrosophicate matrix C^{**} via Eq. (23) and obtain the crisp values for criteria weights.

$$d_x = (\frac{(T^{**L}_x + T^{**U}_x)}{2}) + ((1 - \frac{(I^{**L}_x + I^{**U}_x)}{2}) * I^{**U}_x) - ((\frac{F^{**L}_x + F^{**U}_x}{2}) * (1 - F^{**U}_x)) \quad x = 1, \dots, n \tag{23}$$

Step 7:. Normalize the crisp values found in the previous step and compute the importance weights following Eq. (24).

$$w_x = \frac{d_x}{\Sigma^n_{i=1} d_i} \quad \forall x \tag{24}$$

4. Assessment of challenges via the application of the proposed methodology

We implement the suggested methodology in three stages, with the findings presented in the sections below.

4.1. Preparation stage

We aim to identify the importance weights of IIoT challenges before and during the pandemic to make informed decisions about supply chain redesign. To this end, we recruit seven experts from universities and the industry, as stated in Table 2.

Following lengthy discussions with the experts and a comprehensive review of the IIoT challenges in the literature, the main and sub-challenges of IIoT are determined based on the study (Birkel & Hartmann, 2019). In this study, we use content analysis approach inspired by earlier works (Birkel & Hartmann, 2019; Ho, Zheng, Yildiz, & Talluri, 2015; Jüttner et al., 2003; Seuring & Gold, 2012). Birkel and Hartmann (2019) propose a hierarchy of challenges and risks based on the intersection of IIoT and supply chain literature, with risks as subsequent of challenges. The hierarchy of challenges is indicated in Fig. 3 with a minor change (merging of social and political challenges).

In the following, we provide brief definitions of each of the main- and sub-challenges.

Challenges at the organizational level:. The research on the organizational level focuses on a lack of expertise and the complexity of IIoT implementation. The organizational challenges of IIoT within an organization includes, (C1) the shortage of expertise among existing staff or lack of them thereof, (C2) being compelled to adapt their structure, culture, and practices, (C3) implementation complexities stemming from harmonization of corporate procedures and integration of physical assets and services, (C4) concerns emerging from the privacy and trust issues of the employees.

Challenges at the environmental level:. Environment, in our context, refers to the standalone challenges throughout the entire supply-chain ecosystem regarding economic, socio-politic, and technological aspects. Economic challenges include, (C5) high costs associated with hardware (such as RFID sensors), and software (off-the shelf or in-house developed), (C6) IIoT business model adaptation to be able to handle new lines product Haaker, Ly, Nguyen-Thanh, and Nguyen (2021), (C7) complex assessment of both total ownership cost and profitability of IIoT. The economic challenges are coupled with socio-politic and technological challenges. The socio-politic challenges refer to (C8) privacy concerns that cover the continuum ranging from individual-organization aspect to SC and society as a whole, (C9) lack of legal regulations due to unclear data ownership, complex governance of security and resources. The extant literature is laden with studies on technological challenges regarding IIoT. These challenges can be grouped as: (C10) security related involving encryption, establishment of secure interfaces and sufficient authorization, (C11) lack of standards and interoperability to ensure compatibility and reliability, (C12) hardware limitations such as battery capacity, computation resource needs, and (C13) software limitation challenges related to processing large chunks of data instantly.

Table 16
Comparative importance weights of sub-challenges before and during the pandemic.

Sub-challenge	Consolidated reviews		Expert 1		Expert 2		Expert 3		On Average	
	Before	During	Before	During	Before	During	Before	During	Before	During
C1	.106	.084	.136	.120	.109	.076	.127	.070	.114	.086
C2	.062	.077	.086	.081	.090	.063	.079	.056	.072	.072
C3	.078	.067	.100	.081	.068	.029	.230	.157	.101	.076
C4	.059	.034	.069	.026	.041	.047	.042	.026	.055	.034
C5	.061	.042	.042	.030	.108	.045	.022	.035	.059	.040
C6	.028	.052	.031	.045	.049	.070	.034	.053	.032	.054
C7	.081	.026	.047	.040	.070	.032	.127	.197	.081	.053
C8	.076	.031	.056	.020	.074	.163	.032	.050	.066	.051
C9	.062	.049	.037	.024	.029	.064	.013	.020	.047	.043
C10	.030	.032	.040	.036	.052	.036	.034	.052	.035	.036
C11	.025	.038	.024	.027	.043	.030	.024	.037	.027	.035
C12	.011	.009	.012	.018	.026	.018	.007	.022	.013	.014
C13	.018	.028	.016	.023	.026	.018	.014	.010	.019	.023
C14	.107	.169	.108	.180	.075	.107	.018	.018	.090	.140
C15	.041	.038	.054	.052	.055	.079	.052	.039	.046	.046
C16	.089	.144	.089	.126	.038	.054	.119	.093	.086	.121
C17	.067	.079	.054	.072	.047	.068	.026	.066	.056	.074

Table 17
Rate of change in percentage.

Sub-challenge	Consolidated	Reviewer 1	Reviewer 2	Reviewer 3	In Average
C1	−20.75%	−11.76%	−30.28%	−44.88%	−24.56%
C2	24.19%	−5.81%	−30.00%	−29.11%	0.00%
C3	−14.10%	−19.00%	−57.35%	−31.74%	−24.75%
C4	−42.37%	−62.32%	14.63%	−38.10%	−38.18%
C5	−31.15%	−28.57%	−58.33%	59.09%	−32.20%
C6	85.71%	45.16%	42.86%	55.88%	68.75%
C7	−67.90%	−14.89%	−54.29%	55.12%	−34.57%
C8	−59.21%	−64.29%	120.27%	56.25%	−22.73%
C9	−20.97%	−35.14%	120.69%	53.85%	−8.51%
C10	6.67%	−10.00%	−30.77%	52.94%	2.86%
C11	52.00%	12.50%	−30.23%	54.17%	29.63%
C12	−18.18%	50.00%	−30.77%	214.29%	7.69%
C13	55.56%	43.75%	−30.77%	−28.57%	21.05%
C14	57.94%	66.67%	42.67%	0.00%	55.56%
C15	−7.32%	−3.70%	43.64%	−25.00%	0.00%
C16	61.80%	41.57%	42.11%	−21.85%	40.70%
C17	17.91%	33.33%	44.68%	153.85%	32.14%

Challenges at the network level:. These challenges arise as a result of the interactions between organizations as well as the complexities that come with implementing IIoT across the supply chain. (C14) A plethora of studies address challenges pertaining trust issues stemming from the interaction between collaborating SC entities. (C15) complex network implementation challenges arise when annexing the already complex existing network structure with IIoT. (C16) high collaboration and data exchange challenges which stem from IIoT's ubiquity and may impede its implementation. (C17) supply chain reconfiguration may be needed to accommodate a reconfiguration of the supply chain due to IIoT implementation.

4.2. IVN-AHP stage

Following the hierarchy of challenges (Fig. 3), we design our interviews with seven experts. A consensus is reached among the (four) experts from the universities. Hence, a total of four analyses are performed via IVN-AHP. While we report all final results, we explicitly include the analysis steps for the judgments of the experts in consensus for the before pandemic period only. We omit steps 1–2, as the evaluation scale step (Table 1) was determined and the hierarchy was already built (Fig. 2).

Step 3:. Regarding the hierarchy, there are 7 pairwise comparison matrices. The judgments in each of the matrices are provided as in Tables 3–9 below:

Step 4:. The consistency of each pairwise comparison matrix is computed, and the level of each pairwise inconsistency was verified to be under 10%, as shown in Table 10.

The following steps (Steps 5–8) explicitly were applied considering the First matrix that includes organizational, environmental, and network-related key challenges. We omit applications for other matrices and include the results only for the sake of brevity.

Step 5:. The normalized matrix is obtained by applying Eq. (19), as indicated in Table 11.

Table A.18
Systematic review of the literature (*) from Birkel and Hartmann (2019) — Part A.

	Environmental																		
	Economic					Social					Technological							Politic	
	C			R		C		R			C				R			C	R
	High costs	Business model adaptation	Unknown profitability	Creation of zero-sum competition	Further economic risks	Privacy concerns	further social challenges	uncertain technology adoption	surveillance and distrust	further social risks	security issues	lack of standards & interoperability	hardware limitations	software limitations	attack-related risks	low data quality	further technological risks	lack of legal regulations	generic political risks
Ahmed et al. (2017)*						X		X		X	X	X		X				X	X
Alaba et al. (2017)*						X					X	X	X	X	X			X	
Badia-Melis et al. (2018)*	X										X	X	X	X					
Bardaki et al. (2012)*	X					X	X						X	X					
Bauk et al. (2017)*	X		X			X					X	X	X	X				X	
Bisaga et al. (2017)*	X					X												X	
Bogataj et al. (2017)*			X																
Bogle (2017)*											X	X		X					
Boos et al. (2013)*						X					X			X					
Borgia (2014)*						X					X	X	X	X	X				
Cavalcante et al. (2016)*						X					X	X	X	X	X				
Chong et al. (2015)*																			
Conti et al. (2018)*						X					X				X				
Dar et al. (2015)*												X			X				
DeCremer et al. (2017)*					X					X	X								
Del Giudice (2016)*			X																
Diaz et al. (2016)*						X					X	X	X	X	X				
Dixit (2016)*											X		X	X	X				
Docherty et al. (2018)*																		X	
Dutton (2014)*						X			X	X									
Dweekat et al. (2018)*						X				X									
Elng and Schnell (2016)*											X				X			X	
Eurich et al. (2010)*																			
Falkenreck and Wagner (2017)*						X			X									X	
Friedewald and Raabe (2011)*						X		X	X	X	X	X			X			X	
Galinina et al. (2017)*												X	X						
Geerts and O'Leary (2014)*												X							
Ghanbari et al. (2017)*		X																	
Grieco et al. (2014)*						X					X	X			X				
Gu et al. (2017)*	X					X		X											
Gubbi et al. (2013)*												X							
Haddud et al. (2017)*	X	X									X	X	X	X					
Harris et al. (2015)*	X		X									X	X	X				X	
Harwood and Garry (2017)*						X													
Hofmann and Bosshard (2017)*			X																
Jin et al. (2017)*		X										X							
Jing et al. (2014)*						X					X	X	X	X	X	X		X	
Kache and Seuring (2017)*	X										X	X	X		X				
Karkouch et al. (2016)*											X	X	X	X	X	X			
Khan and Salah (2018)*						X					X	X	X	X	X			X	
Kiel et al. (2017)*	X	X	X									X	X					X	
Kong et al. (2015)*											X		X						
Kshetri (2017b)*						X					X	X	X		X			X	X
Kshetri (2017a)*	X										X			X	X				
Kumar et al. (2016)*													X	X					
Lee and Lee (2015)*	X		X			X		X			X	X	X	X	X				
Leone (2017)*						X	X			X		X						X	X
Li et al. (2012)*												X							
Li et al. (2015)*						X					X	X	X	X	X		X		
Li et al. (2015)*	X	X																	
Li et al. (2016)*						X					X	X	X	X	X				
Lindqvist and Neumann (2017)*							X	X	X		X				X			X	
Liu et al. (2017)*											X	X							
Lowry et al. (2017)*						X			X	X	X	X			X			X	
Luo et al. (2017)*	X																		
Mehrjerdi (2011)*						X			X		X								

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Table A.18 (*continued*).

	Environmental																		
	Economic					Social					Technological							Politic	
	C			R		C		R			C				R			C	R
	High costs	Business model adaptation	Unknown profitability	Creation of zero-sum competition	Further economic risks	Privacy concerns	further social challenges	uncertain technology adoption	surveillance and distrust	further social risks	security issues	lack of standards & interoperability	hardware limitations	software limitations	attack-related risks	low data quality	further technological risks	lack of legal regulations	generic political risks
Miorandi et al. (2012)*						X					X	X	X	X	X				
Neirotti et al. (2018)*					X					X							X		
Neumann (2016)*						X					X				X				
Ng et al. (2015)*				X															
Ochoa et al. (2017)*														X		X			
Orsino et al. (2017)*																			
Ouaddah et al. (2017)*		X				X		X			X	X	X	X					
Pang et al. (2015)*	X												X	X				X	
Papert et al. (2016)*												X		X					
Parry et al. (2016)*						X													
Pease et al. (2017)*											X		X	X					
Preuveneers et al. (2017)*											X				X				
Prince et al. (2014)*						X						X							
Qiu et al. (2015)*		X										X	X	X	X				
Roman et al. (2013)*		X									X	X		X	X			X	
Rymaszewska et al. (2017)*	X	X		X		X					X	X	X	X	X				
Seol et al. (2017)*	X																		
Shamsuzzoha et al. (2016)*																			
Shin (2014)*						X					X	X		X				X	
Shin and Park (2017)*	X	X				X		X	X	X	X	X	X	X				X	
Skwarek (2017)*											X		X		X				
Srai et al. (2016)*	X	X										X	X	X				X	
Strange and Zucehella (2017)*											X				X			X	
Talavera et al. (2017)*											X	X	X	X					
Tu et al. (2018a)*												X							
Tu et al. (2018b)*												X							
Vanderroost et al. (2017)*													X	X	X				
Verdouw et al. (2013)*		X				X					X	X		X		X			
Wang and Yue (2017)*																			
Wang et al. (2017)*											X		X						
Weber (2010)*						X					X				X			X	
Weinberg et al. (2015)*						X					X	X		X					
Whitmore et al. (2015)*		X				X					X							X	
Wu and Li(2017)*											X								
Wu et al. (2017)*		X																	
Wu et al. (2016)*											X				X				
Xu et al. (2014)*						X					X	X		X				X	
Yan (2017)*			X																
Yan et al. (2016)*						X		X	X		X	X	X	X				X	
Yan et al. (2014)*	X																		
Yan et al. (2017)*					X					X	X	X	X		X			X	X
Yang et al. (2016)*											X		X		X		X		
Yu et al. (2017)*	X																		
Zancul et al. (2016)*																			
Zheng and Wu (2017)*																			
Zhong et al. (2017)*	X																		
Abdul-Hamid et al. (2020)	X		X								X	X	X					X	
Agostini and Filippini (2019)																			
Birkel and Hartman (2020)																X			
Birkel et al. (2019)				X	X	X									X	X	X		X
Bujari et al. (2018)		X	X			X			X		X				X				
Chhetri et al. (2018)											X	X			X		X		
Colicciha et al. (2019)									X		X								
Cui et al. (2020)																			
Omitola and Wills (2018)	X										X		X	X	X				
Ghadge et al. (2020)			X								X					X		X	
Hafdi et al. (2019)							X				X	X	X	X					
Horvath and Szabo (2019)	X										X	X							
Luthra and Mangla (2018)	X		X								X	X	X			X		X	

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Table A.18 (*continued*).

	Environmental																		
	Economic					Social					Technological							Politic	
	C			R		C		R			C				R			C	R
	High costs	Business model adaptation	Unknown profitability	Creation of zero-sum competition	Further economic risks	Privacy concerns	further social challenges	uncertain technology adoption	surveillance and distrust	further social risks	security issues	lack of standards & interoperability	hardware limitations	software limitations	attack-related risks	low data quality	further technological risks	lack of legal regulations	generic political risks
Masood and Sonntag (2020)	X																		
Moeuf et al. (2020)									X										
Moktadir et al. (2018)	X										X		X	X					
Müller, Kiel, 2018											X						X		
Olsen & Tomlin (2020)	X												X	X		X			
Orzes et al. (2019)	X		X				X				X	X	X	X				X	
Prause (2019)	X		X								X	X							
Raj et al. (2020)	X		X					X			X	X	X			X			
Rodanliev et al. (2019)									X		X		X	X			X	X	
Rodanliev et al. (2020)											X								
Schneider (2018)		X	X				X				X			X			X		
Shafique et al. (2020)											X		X				X		
Shah et al. (2020)					X					X									X
Singh et al. (2019)																			
Sony and Naik (2019)		X												X					
Zangiacomi et al. (2020)		X	X								X								
Zhou and Piramuthu (2018)											X		X						

Step 6:. The averages for each component are computed using Eq. (22) for each main challenge Table 12.

7-8. The deneutrosophication is performed applying Eq. (23). After the deneutrosophication, normalization and ranking procedures are employed and indicated in Table 13.

4.3. Comparison and evaluation stage

All the judgments of experts corresponding to before- and during-the pandemic periods are processed following the steps of IVN-AHP, and the comparative importance weights are computed for different hierarchical levels. Comparative importance weights for the main challenge level (first matrix) are computed and presented in Table 14.

For the main challenge level, the average importance weights corresponding to the periods before and during the pandemic are found as (0.342. 0.379, 0.279) and (0.269, 0.350, 0.382), respectively. To calculate the average of weights, we used the following formula stated in Eq. (23). Table 14 reveals substantial changes e.g., "Environmental" criterion the main challenge ranked first for the before period lost its position to "Network-related" criterion during pandemic period.

$$Average = \frac{4\times C1 + C2 + C3 + C4}{7} \tag{25}$$

Because our consolidated responses include the opinions of four experts, three additional experts are interviewed individually. The comparative importance weights corresponding to environmental main challenge, economic, socio-politic, and technological mid-level challenges are obtained as indicated in Table 15.

The rankings of the sub-challenges within the "Environmental" category of challenges have also changed. For instance, the socio-political sub-challenge fell from the second most important position before the pandemic to the lowest position during the pandemic. Nonetheless, economic challenges continue to be the most influential, according to experts. Finally, the nominal and percentage comparative importance weights of sub-challenges are computed for before and during the pandemic and given in Tables 16 and 17, and depicted in Fig. 4.

The comparative importance weights for sub-challenges reveal notable changes. Fig. 4 visually summarizes Table 16. We summarize some of the observations as follows: prior to the pandemic, at the aggregate level, organizational and environmental challenges are perceived as more important than the network-related challenges (Table 14). According to the experts, the pandemic reverses the ranking and places network-related challenges first. Whereas technological challenges are not perceived as important. This could be due to recent technological advancements regarding IIoT technology. The pandemic has also altered the perceived importance of the challenges by the experts. During the pandemic period, the importance of all organizational and socio-political sub-challenges decreased, while the importance of all network-related challenges increased. Technological challenges, however, remained relatively unaffected during the pandemic period. While two of the economic challenges (business model adaptation, and unknown profitability) became more pressing, the high costs have become less of an issue, possibly because of other relentless pandemic-related issues. Above, the changes are shown in nominal terms. We also include Table 17 to depict changes in relative terms (percentages).

Table 17 shows that experts unanimously reduce the importance weights for lack of knowledge (C1) and complex system implementation (C3), and increase the importance weights for Business model adaptation (C6). This consensus of all experts reveals that while organizations have gained more knowledge about IIoT and its implementation, the challenge during pandemic times is in how to adapt IIoT according to their business models.

5. Conclusion and discussion

Without a doubt, the COVID-19 pandemic has disrupted nearly every aspect of our lives, including business organizations and supply chains. Traditional supply chains have had issues that lead to supply shortages and flow interruptions. IIoT, with its underutilized potential, and available features are being used to address these issues. However, its implementation involves a set of challenges that have been itemized in prior research. The key purpose of this study is to quantify

Table A.19
Systematic review of the literature (*) from Birkel and Hartmann (2019) — Part B.

	Network-related										Organizational								
	Relational										Internal								
	C				R						C				R				
	trust issues	complex network implementation	high collaboration & data exchange	supply chain reconfiguration	complex network coordination	asymmetry of information	opportunism	dependency	distrust & trust management	competition	lack of knowledge	organizational changes	complex system implementation	concerns of employees	strategic management	operational management	financial-related	complex data management	human esources
Ahmed et al. (2017)*								X				X			X	X		X	
Alaba et al. (2017)*	X																		
Badia-Melis et al. (2018)*												X	X				X	X	
Bardaki et al. (2012)*														X			X	X	
Bauk et al. (2017)*	X					X		X			X		X		X			X	
Bisaga et al. (2017)*	X										X						X		
Bogataj et al. (2017)*																			
Bogle (2017)*				X	X						X		X						
Boos et al. (2013)*															X				
Borgia (2014)*																			
Cavalcante et al. (2016)*		X					X						X			X	X		
Chong et al. (2015)*					X						X			X					X
Conti et al. (2018)*																			
Dar et al. (2015)*																		X	
DeCremer et al. (2017)*							X		X								X		X
Del Giudice (2016)*											X								
Diaz et al. (2016)*									X										
Dixit (2016)*																			
Docherty et al. (2018)*						X	X												
Dutton (2014)*																			
Dweekat et al. (2018)*																			
EIing and Schnell (2016)*								X									X		
Eurich et al. (2010)*	X					X													
Falkenreck and Wagner (2017)*					X	X		X	X		X								
Friedewald and Raabe (2011)*						X	X	X			X		X						
Galinina et al. (2017)*																			
Geerts and O'Leary (2014)*					X	X													
Ghanbari et al. (2017)*								X		X	X								
Grieco et al. (2014)*	X																		
Gu et al. (2017)*		X														X	X	X	
Gubbi et al. (2013)*		X																	
Haddud et al. (2017)*		X									X		X				X		X
Harris et al. (2015)*	X								X		X		X				X		X
Harwood and Garry (2017)*	X			X							X								
Hofmann and Bosshard (2017)*																			
Jin et al. (2017)*															X				
Jing et al. (2014)*	X				X	X			X	X									
Kache and Seuring (2017)*	X		X								X	X	X						
Karkouch et al. (2016)*	X				X				X						X				
Khan and Salah (2018)*	X												X						
Kiel et al. (2017)*	X						X			X		X	X			X			X
Kong et al. (2015)*												X							
Kshetri (2017b)*							X				X								
Kshetri (2017a)*					X														
Kumar et al. (2016)*				X								X							
Lee and Lee (2015)*					X						X			X					X
Leone (2017)*	X						X												
Li et al. (2012)*					X					X	X				X				
Li et al. (2015)*	X	X			X						X								
Li et al. (2015)*		X			X														

(*continued on next page*)

the importance weights associated with the set of IIoT challenges to help IIoT decision makers, and to analyze how pandemic has changed these weights. We used the interval neutrosophic AHP to assess the significance of the IIoT challenges. In total, we organized our model with respect to three main challenge categories, three intermediate challenges, and seventeen sub-challenges. We also included the steps to derive the importance weights in the experimental part of this paper.

5.1. Discussion

IIoT, like any other new technology, brings about benefits, risks and challenges. Although the risks and challenges have been extensively researched and outlined in previous studies, managers must also understand how to prioritize each of these challenges in order to best prepare their organizations for IIoT endeavors. However, the

Table A.19 (*continued*).

	Network-related										Organizational								
	Relational										Internal								
	C				R						C				R				
	trust issues	complex network implementation	high collaboration & data exchange	supply chain reconfiguration	complex network coordination	asymmetry of information	opportunism	dependency	distrust & trust management	competition	lack of knowledge	organizational changes	complex system implementation	concerns of employees	strategic management	operational management	financial-related	complex data management	human esources
Li et al. (2016)*					X				X										
Lindqvist and Neumann (2017)*									X							X			
Liu et al. (2017)*													X						
Lowry et al. (2017)*							X							X					
Luo et al. (2017)*																			
Mehrjerdi (2011)*											X			X		X			
Miorandi et al. (2012)*	X		X				X				X							X	
Neirotti et al. (2018)*											X								
Neumann (2016)*																			
Ng et al. (2015)*						X				X									
Ochoa et al. (2017)*					X													X	
Orsino et al. (2017)*												X							
Ouaddah et al. (2017)*	X	X			X								X		X		X		
Pang et al. (2015)*																			
Papert et al. (2016)*		X																	
Parry et al. (2016)*											X							X	
Pease et al. (2017)*																			
Preuveneers et al. (2017)*	X																		
Prince et al. (2014)*		X			X														
Qiu et al. (2015)*		X	X					X					X		X				
Roman et al. (2013)*		X						X										X	
Rymaszewska et al. (2017)*							X	X							X	X			
Seol et al. (2017)*																		X	
Shamsuzzoha et al. (2016)*									X										
Shin (2014)*		X	X																
Shin and Park (2017)*	X	X							X		X								
Skwarek (2017)*																			
Srai et al. (2016)*											X						X		
Strange and Zucehella (2017)*																			
Talavera et al. (2017)*			X															X	
Tu et al. (2018a)*													X						
Tu et al. (2018b)*													X						
Vanderroost et al. (2017)*		X																X	
Verdouw et al. (2013)*						X							X						
Wang and Yue (2017)*																X		X	
Wang et al. (2017)*																			
Weber (2010)*																			
Weinberg et al. (2015)*																			
Whitmore et al. (2015)*																			
Wu and Li (2017)*	X																		
Wu et al. (2017)*												X		X	X				
Wu et al. (2016)*																			
Xu et al. (2014)*					X														
Yan (2017)*																			
Yan et al. (2016)*	X					X	X							X		X	X		
Yan et al. (2014)*																			
Yan et al. (2017)*						X			X	X					X	X			
Yang et al. (2016)*	X																		
Yu et al. (2017)*															X				
Zancul et al. (2016)*											X		X			X			
Zheng and Wu (2017)*											X								
Zhong et al. (2017)*				X															
Abdul-Hamid et al. (2020)				X							X			X					
Agostini and Filippini (2019)															X	X			
Birkel and Hartman (2020)					X	X	X	X		X									
Birkel et al. (2019)								X		X					X	X	X		X
Bujari et al. (2018)																			
Chhetri et al. (2018)																			
Colicciha et al. (2019)	X					X			X		X	X	X		X				X

(*continued on next page*)

Table A.19 (*continued*).

	Network-related										Organizational								
	Relational										Internal								
	C				R						C				R				
	trust issues	complex network implementation	high collaboration & data exchange	supply chain reconfiguration	complex network coordination	asymmetry of information	opportunism	dependency	distrust & trust management	competition	lack of knowledge	organizational changes	complex system implementation	concerns of employees	strategic management	operational management	financial-related	complex data management	human esources
Cui et al. (2020)			X													X			
Omitola and Wills (2018)																			
Ghadge et al. (2020)	X	X													X		X		
Hafdi et al. (2019)		X	X		X														
Horvath and Szabo (2019)											X			X					
Luthra and Mangla (2018)											X	X							
Masood and Sonntag (2020)											X								
Moeuf et al. (2020)											X				X		X		
Moktadir et al. (2018)		X											X	X					X
Müller, Kiel, 2018										X	X	X	X						
Olsen & Tomlin (2020)													X					X	
Orzes et al. (2019)											X		X						
Prause (2019)												X	X						
Raj et al. (2020)	X	X									X	X		X					
Rodanliev et al. (2019)																			
Rodanliev et al. (2020)		X			X														
Schneider (2018)	X		X								X	X			X				
Shafique et al. (2020)																			
Shah et al. (2020)	X			X											X				
Singh et al. (2019)		X									X					X			
Sony and Naik (2019)											X		X		X				
Zangiacomi et al. (2020)											X	X					X		X
Zhou and Piramuthu (2018)																			

priority ranking of these challenges can be altered by disruptions such as the currently ongoing COVID-19 that has brought an unprecedented disruption. Our results can assist in identification of weak points of the organization to meet the IIoT challenges, while taking the pandemic into account. Before pandemics, the three main challenge categories were ranked as "Environmental", "Organizational", and "Network-related", (Table 14). After pandemics, the rankings were updated to "Network-related", "Environmental", and "Organizational", respectively. This shows that, according to the experts, the pandemic has caused organizations prioritize external challenges over the internal ones. Some of our experts indicated this will change in the future as the operations will adopt the new normal and challenges regarding the organizational structure will have to be prioritized.

Environmental challenges correspond to standalone challenges across the entire supply-chain landscape. Within the "Environmental" challenges category, "Economic" challenges, high costs, business model adaptation, and unknown profitability have the highest associated weights regardless of COVID-19. According to our experts, all organizational sub-challenges were associated with a non-positive average importance weights. This indicates that companies are more willing to accept and resolve problems arising from lack of expertise (C1), are more willing to change their organizational structure (C2), and incorporate complex IIoT structures (C3), and are less concerned with employee issues that they were during pre-pandemic period (C4). The pandemic also increased the need to launch new or modified products. Hence, IIoT adaptation to handle new product lines (C6) reflects immediate needs to accommodate the launch of such product lines within IIoT-powered facilities. The pandemic has put a lot of strain on supplier cooperation. SCs across the globe have experienced intermittences or even have come to a complete halt. Emulating this, the experts weigh managing trust issues within SC participants (C14) consistently higher corresponding to the pandemic period. Some sub-challenges, on the other hand, remained relatively the same across periods, such as, organizational changes (C2), security issues (C10), lack of standards and interoperability (C12) and complex network implementation (C15). These are the challenges that are independent of the pandemic and pertain to tasks that are inherently related to IIoT implementations.

5.2. Limitations and future research

The interviews in this study have revealed some important information in how experts view IIoT challenges for supply chains before and during the pandemic periods. Our study aims at shedding light on IIoT-related challenges faced by decision makers. However, the pandemic is still ongoing with no visible finish on the horizon. Therefore, it is possible for some of these challenges gain or lose importance by the end of the spread of the disease. Thus, our study is limited to during-pandemic period, and a post-pandemic study is recommended as a future study. Another limitation of this research is that the challenge hierarchy is based on Birkel and Hartmann (2019), hence a different hierarchy includes challenges that arose as a result of the pandemic could produce different results. Drilling down into these challenges and populating them into more specific components can improve the usefulness of the obtained results. Our board of experts included prominent scholars on supply chain and IoT, and high-level decision-makers. To account for diverse viewpoints, it is advised to include other decision-makers at various levels of management. Finally, owing to its novelty, AHP of interval-valued neutrosophic numbers has not been extensively used as an analysis method. Other alternative techniques such as Pythagorean fuzzy AHP or neutrosophic DEMATEL could be applied to measure IIoT challenges and their importance.

CRediT authorship contribution statement

Enes Eryarsoy: Investigation, Writing – original draft, Writing – review & editing. **Huseyin Selcuk Kilic:** Methodology, Investigation, Formal analysis. **Selim Zaim:** Conceptualization, Methodology, Supervision. **Marzhan Doszhanova:** Data curation.

Appendix

See Tables A.18 and A.19.

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