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Framework for a sustainable supply chain to overcome risks in transition to a circular economy through Industry 4.0

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ABSTRACT

Transition from a linear to a circular economy (CE) is a challenging process for a sustainable supply chain, and innovative process approaches and technologies are needed to deal with the risks involved. Industry 4.0 principles have great potential to achieve optimal sustainable supply chain solutions and are expected to add value to sustainable supply chain operations by increasing efficiency and resource utilisation. Therefore, Industry 4.0 supports companies transitioning to a CE through improving the efficiency and sustainability of their supply chain management. Thus, the purpose of this paper is to investigate the potential risks of the transition from a linear to a CE, with proposed Industry 4.0-based responses from an operations management perspective within the sustainable supply chain. Implementation of the study was conducted in a logistics company in Turkey. An integrated MCDM (Multi-criteria Decision Making) approach was based on Fuzzy AHP, and TODIM was used to analyse the association between risks and responses. According to the findings, the most important Industry 4.0-based responses are the integrated business processes for cross-functional collaboration, modular processes for simplification and standardisation, and continuous monitoring of the cost and performance throughout the supply chain by big data and analytics. This study may assist managers in managing risks in supply chain operations during the transition from a linear to a CE through Industry 4.0 based responses. The main contribution of this study is a greater understanding of the risks related to the transition from a linear to a circular economy, and proposals for Industry 4.0-based responses as a means of overcoming these risks in a sustainable supply chain context.

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1. Introduction

Increasing environmental, social and economic problems worldwide mean that sustainable development is crucial in a supply chain context. The sustainable supply chains are developed based on economic, environmental and social practices, considering the opinions and expectations of stakeholders, while assuring the flow of material, information and capital throughout the chain (Govindan and Hasanagic 2018).

Similarly, the concept of a circular economy (CE) has been receiving growing attention. With the transition from a linear economy to a CE, companies need to consider sustainability in operations. Sustainable supply chains and CEs have similar aims in terms of increasing the effectiveness of resource use, reducing environmental pollution and advocating eco-design for sustainable production and consumption (Zeng et al. 2017).

The CE concept is adapted as an alternative to the linear economy's 'take, make and dispose' model (Ness 2008) emphasising the usage of renewable materials and technologies. In other words, CE is a regenerative system in which waste emissions and leakage are minimised through reuse, remanufacturing/refurbishing or recycling activities (Geissdoerfer et al. 2017).

Companies should consider the closed-loop production patterns to help the CE accomplish a better balance between sustainability issues. During the transition to a CE, the operational efficiency of resources and processes are expected to increase significantly (Ghisellini, Cialani, and Ulgiati 2016). The transition requires organisations to redesign their supply chain based on a feedback mechanism through the transformation of natural resources (Zhu, Geng, and Lai 2010). However, there are some risks in the adoption of CE principles (de Sousa Jabbour, Jabbour, Godinho Filho, et al. 2018), including lack of advanced technologies (Su et al. 2013) and financial and scheduling issues (de Sousa Jabbour, Jabbour, Godinho Filho, et al. 2018). Moreover, the uncertainties by nature are challenging and therefore considered as risks, which should be minimised with more complete information (Kocabasoglu, Prahinski, and Klassen 2007). For the effective adaptation of CE principles, these risks have to be managed.

Industry 4.0 can be defined as the transition from a machine-oriented industry to digitalisation (Oztemel and Gursev 2020). In a broader definition, Industry 4.0 is a collective term for a range of technologies and concepts including

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Cyber Physical Systems (CPS), Internet of Things (IoT), cloud computing, 3 D printing, Big Data Analytics, augmented reality, smart factory and Blockchain (Lasi et al. 2014; Fatorachian and Kazemi 2018; Xu, Xu, and Li 2018). Internet of Things (IoT) is used to create communication between Cyber Physical Systems (CPS), which monitor and virtualise the processes in order to create value in smart factories (Hermann, Pentek, and Otto 2016).

Within this perspective, with the introduction of Industry 4.0, some responses regarding emerging technologies and smart manufacturing may be proposed to overcome these risks related to the transition from a linear to a circular economy (de Sousa Jabbour, Jabbour, Godinho Filho, et al. 2018). However, as both CEs and Industry 4.0 principles are relatively recent concepts in research, they have generally been analysed separately rather than in an integrated way. Thus, there is a need to (1) analyse how the CE framework may be improved through Industry 4.0 applications; (2) promote the relationship between the CE and Industry 4.0 for sustainable supply chains and (3) develop a roadmap to improve the implementation of CE principles through Industry 4.0 approaches (de Sousa Jabbour, Jabbour, Godinho Filho, et al. 2018).

In this paper, after identifying the risks of the transition from a linear economy to a CE, Industry 4.0 principles-based responses were proposed in order to overcome these risks. The aim of this paper is to link the risks of transition from linearity to a CE with proposed Industry 4.0-based responses from an operations management perspective. The main contribution of this paper is a proposed framework that presents (1) the risks in the process of the transition of a sustainable supply chain from a linear economy to a circular economy and (2) Industry 4.0-based responses to overcome the risks in a sustainable supply chain context. This is achieved with a hybrid decision-making approach, based on the Fuzzy Analytic Hierarchy Process (AHP) and TODIM. Implementation of the study is conducted in a logistics company in Turkey, in which Industry 4.0 adaptation is already in progress. Currently, the company, in transition from a linear economy to a CE, is facing some risks. From this point of view, certain Industry 4.0 based responses are integrated with CE transition risks in the case study.

Following the introduction, Section 2 summarises the theoretical background of this research. Section 3 describes the methodology and Section 4 summarises the application and results. Section 5 proposes the implications and discussions, and finally, Section 6 is the conclusion and future research directions.

2. Theoretical background

The theoretical background of this paper draws on the research areas of sustainable supply chain management and the circular economy, risks related to transition to a CE, Industry 4.0 and the CE and finally Industry 4.0 principles. Before moving to the details of the theoretical background, in Figure 1, the structure of the paper is presented by including the proposed framework as a flowchart, in order to present a clear overview of the research stages.

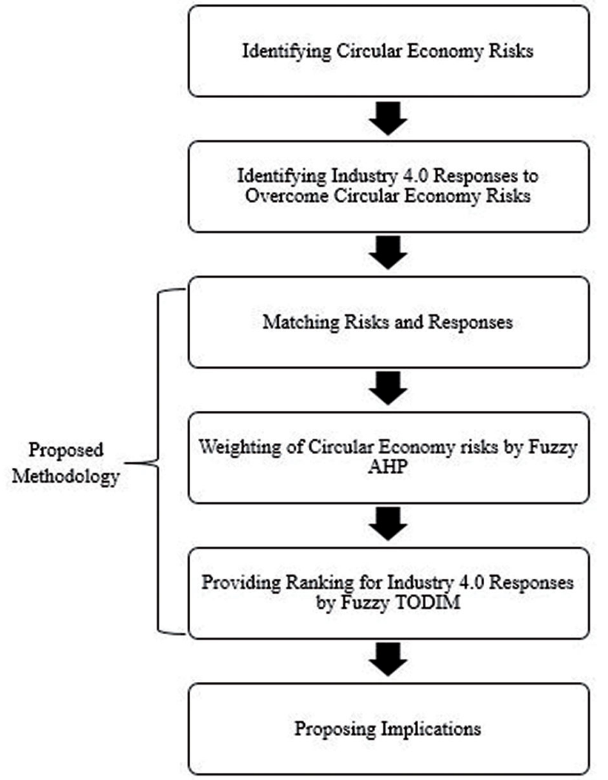

Figure 1. Structural flow of the paper.

In the following subsection, firstly, theoretical background related to sustainable supply chains and a circular economy is presented.

2.1. Sustainable supply chains and a circular economy

With the rapid depletion of reserves and increasing importance of social responsibility issues, sustainability has become imperative in the strategies and policies of enterprises (Mangla, Madaan, and Chan 2013; Harangozó and Zilahy 2015; Luthra and Mangla 2018b). Pressures from stakeholders emphasise the need to integrate the concept of sustainability in the supply chain. Adding sustainability edges to supply chains has many advantages in the interaction between stakeholders and material management, sharing information to improve social, economic and environmental performances (Luthra et al. 2018). Sustainable supply chain management is defined as the interaction between organisations to provide environmental and social benefits in a single organisation within the supply chain or the whole supply chain (Seuring and Müller 2008; Taylor and Vachon 2018).

Sustainable supply chain management emphasises a holistic approach to sustainable resource management within the supply chain (Schrödl and Simkin 2014). The scope of sustainable supply chain management is integrated environmental, economic and social benefits of a company as the 'Triple Bottom Line (TBL)' (Carter and Rogers 2008). It aims to reduce the negative environmental consequences, decrease resource use and eliminate waste in production and consumption (Sarkis, Zhu, and Lai 2011; Genovese et al. 2017).

Sustainable supply chain management uses circular approaches similar to circular supply chains which is a closed loop system (Mangla et al. 2018). This involves forward (Seuring and Müller 2008) and more sustainable closed-loop supply chain management, including reverse logistics, remanufacturing and product recovery (Zeng et al. 2017; De Angelis, Howard, and Miemczyk 2018) . Reverse logistics, the main component of the CE, covers not only reverse flow of distribution, but also the repair, remanufacturing, reuse, recycling and refurbishment activities of returned products (Bernon, Tjahjono, and Ripanti 2018).

All these concepts are also related to the CE, which can be defined as an economic concept aimed at long-term sustainability. From this point of view, a CE enables the integration of a sustainable supply chain concept into an economic system (Schrödl and Simkin 2014).

To achieve sustainability goals and strategies, organisations need to promote the CE by focussing on activities such as remanufacturing, recycling, reusing and disposing in sustainable supply chain networks (Winkler 2011). Therefore, a CE indicates the economic and environmental sustainability dimensions by integrating forward flow of the materials in a conventional supply chain with reverse logistics flow, and by closing the loop through waste management, thereby reducing environmental impacts. This leads to establishing a sustainable circular economy, where environmental and economic measures are in the supply chain (Winkler 2011). Moreover, the performance of sustainable supply chains depends on the circular economy capability of the organisations, indicated by levels of pollution and efficiency in the use of resources in the supply chain processes (Zeng et al. 2017).

Aligning sustainable supply chain practices with a CE has become significant, since the CE not only aims to reduce resource utilisation and extend the life cycle of the products, but also creates a system that allows self-sustaining production in the supply chain (Genovese et al. 2017). Similarly, extending the useful life of materials, in other words, circling longer, is the key aspect of transforming from traditional supply chains to sustainable circular supply chains, which can be achieved by the association of a sustainable supply chain and a CE (De Angelis, Howard, and Miemczyk 2018). Furthermore, CE and sustainable supply chain management are mutually supportive in terms of sustainable development (Liu et al. 2018).

From this point of view, our study focuses on a CE under sustainable supply chains. In the following section, risks related to CE transition are presented within the scope of this study.

2.2. Risks related to transition to a circular economy

The transition from a linear economy to a CE requires a change at a strategic level, in business strategies, product design and supply chain strategies (Bocken et al. 2016; Masi et al. 2018).

A CE supports companies in preventing the depletion of natural resources and waste generation, as well as helping companies monitor their products and materials throughout the product life cycle (Bressanelli et al. 2018). It is emphasised that the principles of a CE (reduction, reuse, repair, reconditioning and recycling) must be applied within each node of the supply chain. This new business model affects all the business processes (design, production, distribution, consumption, repairing and remanufacturing), and the infrastructure of the whole supply chain (Batista et al. 2018; Fonseca et al. 2018). For this implementation, all the stakeholders should support its principles. Unfortunately, however, some risks have seriously obstructed the implementation of a CE in sustainable supply chains.

This study identifies nine risks related to the transition to a CE within the sustainable supply chain through a review of the literature:

2.2.1. Risk of management and decision-making

In a sustainable supply chain, the appropriate decisions making is crucial for the effective implementation of the CE. Knowledge and information sharing are essential factors in decision-making within the supply chain. Further, communication among partners is supported by information technology infrastructure (Balasubramanian 2012; Pan et al. 2015; Govindan and Hasanagic 2018).

2.2.2. Risk related to labour

The implementation of a CE requires different types of processes related to repair, reuse, recycling and remanufacturing. There is a need for labour intensity in the implementation of these processes. Van Loon and Van Wassenhove (2018) emphasised that repair and remanufacturing will need higher labour intensity than the recycling process. Compared to new product production, the remanufacturing process is time-consuming, requiring more skilled and experienced labour (Guide et al. 2006; Jiang et al. 2016). The reuse process requires highly qualified labour, while the recycling process only requires low or medium skilled labour (Ellen Macarthur Foundation 2012; Govindan and Hasanagic 2018).

2.2.3. Quality based risks

Another risk that could affect a successful CE is the difficulty in providing and maintaining quality throughout the product lifecycle, and within the returned products in the sustainable supply chains (Govindan and Hasanagic 2018). Singh and Ordoñez (2016) note that there is suspicion surrounding the quality of returned products made from discarded materials. The lack of existence of a specific market for recycled material products means they have to compete in existing markets. High quality standards are essential for the products made from recycled materials because eventually they will be compared to normal products (Sabaghi, Mascle, and Baptiste 2016).

2.2.4. Design related risks

The implementation of a CE aims to decrease the consumption of raw materials, reducing waste via recycling and eco--design. The design of reused/recycled products is problematic (Govindan et al. 2014). Products designed for reuse, recycling and/or recovery are preferred less by companies because of their longer-term returns, such as waste reduction and material efficiency (Fonseca et al. 2018). Therefore, the features to be considered in the product design for reuse, recycle and/or recovery of material, for reducing waste and decreasing consumption of materials should be applied not only in a single company, but also in the whole supply chain (Frohlich and Westbrook 2001; Masi et al. 2018; Govindan and Hasanagic 2018).

2.2.5. Performance related risks

One of the risks for a sustainable supply chain is a standard performance assessment system. As the existing indicators are defined in line with the linear economy, it is necessary to adopt measures, metrics and standards consistent with the principles of the CE (Bressanelli et al. 2018). This system is a significant factor to measure the CE in the supply chain and understand the improvement of performance (Wang et al. 2016). Performance metrics are the basis of integrated work management systems in supply chains. Masi et al. (2018) suggest that organisations should take environmental factors into account within their internal performance evaluation processes. Within the supply chain, firms should not only act in accordance with the CE but must be able to implement its principles in an environmentally friendly manner (Rizos et al. 2016). Each party within the supply chain should have obtained environmental labels and certifications such as ISO 14000 to meet certain standards and to implement the required CE practices. However, a unified standard set of indicators is essential to audit the development of the CE within the supply chain across different parties and different countries .

2.2.6. Risk related to human resources

The failure to develop understanding and knowledge about a CE, which considers all the parties within the supply chain, is one of the main risks for its implementation. Difficulty in transition to a CE may be due to a low level of knowledge and lack of familiarity with the CE, and high risk perception in the supply chain (Mudgal et al. 2010). In particular, insufficient skills in the reuse, reproduction, repair and recycling of products may lead to inadequate product design and production in a CE (Pan et al. 2015). Mudgal et al. (2010) argued that environmental knowledge is insufficient due to the fact that the companies are either not aware of, or ignore the benefits of environmental management systems.

2.2.7. Supplier related risks

The main risk of a CE in a sustainable supply chain is the lack of environmental awareness of the suppliers, who do not understand the benefits of the CE (Ravi and Shankar 2005; Govindan et al. 2014; van Buren et al. 2016; Masi et al. 2018). The principles of a CE are related to environmental awareness and behaviour of suppliers. Liu and Bai (2014) mentioned the lack of willingness to adopt CE principles. Once suppliers understand the benefits, then the transition process will be much easier (Rizos et al. 2016).

2.2.8. Risks related to material costs

Companies need to make significant initial investment in order to apply green design, manufacturing and packaging. Apart from the initial cost, there are high indirect costs such as staff and time needed to implement the changes (Rizos et al. 2016). The high costs of environmental-friendly products and the long return time on investments are risks for green business adaptation (van Buren et al. 2016). Bressanelli et al. (2018) stated that the cost of product maintenance and repair are the other challenges. The higher management costs and more complex planning still impede the transition (van Buren et al. 2016).

2.2.9. Risk of supply chain integration

A CE requires information sharing among the different parties of the supply chain. However, suppliers are reluctant to be involved in integration, co-creation and partnership, especially within the product design process, due to the confidentiality, trust and competition among individual parties within the supply chain and through the product life cycle (Fonseca et al. 2018). Partnerships with suppliers are required for a closed loop of materials as partnership affects the performance of the whole supply chain and transition to the CE. Outsourcing new knowledge through collaboration with suppliers is problematic in situations of technology privacy (Govindan et al. 2014) because it could harm their competitiveness (Rizos et al. 2016). Integration with IT systems and planning issues are the other reasons for integration within the supply chain (Bressanelli et al. 2018).

In Table 1, risks of CE transition are presented.

In order to overcome these risks of CE transition, new approaches are needed. From this point of view, responses deriving from the fourth Industrial revolution could be beneficial to overcome these transition risks. With this perspective, in the following section, studies associated with the integration of Industry 4.0 and a CE are presented before the proposed framework is introduced.

2.3. Industry 4.0 and transition to a CE in a sustainable supply chain context

Industry 4.0 can be expressed as the transformation from a machine-dominant to a digital-dominant industry (Oztemel and Gursev 2020). Industry 4.0 provides some operational benefits to the supply chain by decreasing waste and costs, increasing profitability, preventing errors, accelerating production and fasten the value chain (Rüßmann et al. 2015). Moreover, Industry 4.0 leads process innovations related to sustainable manufacturing such as green and lean (Luthra and Mangla 2018a). The main components that shape

Table 1. Risks of CE transition.

Risks	Caused by	Author(s)
Risk of management and decision making (R1)	Lack of management, decision making, information sharing, knowledge	Balasubramanian (2012); Pan et al. (2015); Govindan and Hasanagic (2018)
Risks related to labour (R2)	High labour intensity in CE activities including repair, reuse, recycling and remanufacturing	Van Loon and Van Wassenhove (2018); Guide et al. (2006); Jiang et al. (2016); Ellen Macarthur Foundation (2012); Govindan and Hasanagic (2018)
Quality based risks (R3)	Difficulty to provide and maintain quality through the product lifecycle and within the returned products in sustainable supply chains	Govindan and Hasanagic (2018); Singh and Ordoñez (2016); Sabaghi, Mascle, and Baptiste (2016).
Design related risks (R4)	Difficulties in design of reused/recycled products and not preferable due to long-term returns, such as waste reduction and material efficiency	Govindan et al. (2014); Fonseca et al. (2018); Frohlich and Westbrook (2001); Masi et al. (2018); Govindan and Hasanagic (2018)
Performance related risks (R5)	Lack of standardisation in performance assessment	Bressanelli et al. (2018); Wang et al. (2016); Masi et al. (2018); Rizos et al. (2016)
Risks related to Human Resources (R6)	Low level of knowledge and unfamiliarity with CE and high risk perception in the supply chain.	Pan et al. (2015); Mudgal et al. (2010); Rizos et al. (2016)
Supplier related risks (R7)	Lack of environmental awareness of the suppliers	Ravi and Shankar (2005); Liu et al. (2009); Govindan et al. (2014); van Buren et al. (2016); Masi et al. (2018); Rizos et al. (2016)
Risks related to material cost (R8)	high initial investment in order to apply green design, green manufacturing, green packing	Rizos et al. (2016); van Buren et al. (2016); Bressanelli et al. (2018); van Buren et al. (2016).
Risk of supply chain integration (R9)	Reluctance of suppliers to be involved in integration, co-creation and partnership within the supply chain and through the product life cycle	Fonseca et al. (2018); Govindan et al. (2014); Rizos et al. (2016); Bressanelli et al. (2018)

Industry 4.0 are Cyber Physical Systems (CPS), Internet of Things (IoT), cloud computing, 3D printing, Big Data Analytics, augmented reality, smart factory and Blockchain (Lasi et al. 2014; Fatorachian and Kazemi 2018; Xu, Xu, and Li 2018). Based on these components or enabling technologies, Industry 4.0 was defined by Hermann, Pentek, and Otto (2016) as a collective term covering all the above-mentioned technologies and concepts. The collective structure of Industry 4.0 includes CPS for monitoring and virtualisation of processes. In this case, IoT is used for communication of CPS and people in real time. These activities are conducted in smart factories with an aim of value creation in both internal and external organisational services (Hermann, Pentek, and Otto 2016). All these technological changes reveal the importance for organisations of following principles for Industry 4.0 transformation.

Key principles, design principles, pillars and dimensions are some of the key terms involved in the successful implementation of Industry 4.0. These principles cover areas of interoperability, virtualisation, decentralisation, real time capability, service orientation and modularity (Hermann, Pentek, and Otto 2016; Carvalho et al. 2018; Oztemel and Gursev 2020) and are explained below.

2.3.1. Interoperability

Due to the need for CPS/human connection through IoT, interoperability is one of the most important aspects for Industry 4.0 transformation. The idea behind interoperability is integration, i.e. horizontal, vertical and end-to-end supply chain and it is the key concept behind CPS and IoT (Xu, Xu, and Li 2018). Interoperability refers to the capability of CPS to connect across the entire organisation, including the assembly station, work piece carriers and products, by using open networks and semantic descriptions (Hermann, Pentek, and Otto 2016).

2.3.2. Virtualisation

Another important principle for Industry 4.0 transformation is virtualisation. By using monitoring and machine-to-machine communication, virtual twins can be presented, where data from sensors are linked to virtual and simulation plant models (Carvalho et al. 2018). This allows a virtual copy of the physical system of CPS to be created, and human error can be noticed earlier, safety of working conditions improved and support for technical complexity provided (Hermann, Pentek, and Otto 2016).

2.3.3. Decentralisation

Because increases in the complexity of systems make it more difficult to control processes centrally, decentralisation is essential for Industry 4.0, where individual CPSs make their own decisions based on constant monitoring to avoid quality problems or system failures (Hermann, Pentek, and Otto 2016). In the decentralisation of the plant, devices such as RFID tags inform machines of the stages of production that need to be followed; therefore, decentralised systems have a higher potential to deal with customised products and complex environments, needing no central control mechanism (Brettel et al. 2014).

2.3.4. Real time capability

Due to the massive amount of data and complex systems, real time capability of organisations is very important in Industry 4.0. In order to optimise resource utilisation and increase the performance of manufacturing processes, real time analysing and integrating data should be conducted (Lu 2017). In general, real time capability refers to the continuous collection and analysis of data in real time (Hermann, Pentek, and Otto 2016).

2.3.5. Service orientation

Internet of Services allows CPS services, human and business, to be available for other participants in order to create product service systems (Carvalho et al. 2018). Service-oriented architectures are important in Industry 4.0 to allow heterogeneous information to be coordinated without problems, enabling information sharing in real time, and improving integration (Xu, Xu, and Li 2018).

2.3.6. Modularity

Flexibility is an important aspect in Industry 4.0 transition due to rapid changes in requirements and the dynamic environment. Therefore, modular systems are needed to facilitate the adding, replacing and removing of expanding processes (Carvalho et al. 2018). By using modular systems, organisations can easily adopt the changes in the product and seasonal fluctuations (Hermann, Pentek, and Otto 2016).

CE and Industry 4.0 are two significant topics in the literature. In general, a CE may be seen as a new sustainability paradigm, that addresses issues of social, economic and environmental sustainability (Geissdoerfer et al. 2017). Industry 4.0, on the other hand, can be defined as a complete digitalisation and connection of production processes starting from the customer's order, throughout the entire life cycle (Jabbour et al. 2017). In this sense, Industry 4.0 has the potential to contribute CE principles (de Sousa Jabbour, Jabbour, Godinho Filho, et al. 2018; Nascimento et al. 2019). For instance, a CE may benefit from large-scale data, such as big data, and therefore, those two concepts can be integrated to improve social and environmental sustainability (Jabbour et al. 2017; Dubey et al. 2019). In order to demonstrate the strong relationship between Industry 4.0 and sustainability, de Sousa Jabbour, Jabbour, Foropon, et al. (2018) argue that '*.while they cannot individually be considered new industrial revolutions, through their overlap and synergy they may together comprise a distinct industrial wave that will change worldwide production systems forever.*' Similarly, Garcia-Muiña et al. (2018) state that '*Industry 4.0 and Circular Economy are the two sides of the same coin*' in order to show the direct relationship between these concepts.

The potential contribution of Industry 4.0 on a CE is an accepted view, and technologies such as cyber physical systems (CPS), Internet of Things (IoT) and cloud computing based data driven analysis can be used to optimise CE practices (Antikainen, Uusitalo, and Kivikytö-Reponen 2018; Tseng et al. 2018); However, so far very few studies integrate these concepts from an operations management perspective.

Integration of Industry 4.0 and the CE was conducted by de Sousa Jabbour, Jabbour, Godinho Filho, et al. (2018), where the ReSOLVE (regenerate, share, optimise, loop, virtualise and exchange) business model for CEs was combined to Industry 4.0 technologies, i.e. IoT, CPS, cloud manufacturing and additive manufacturing.

Moreover, Bressanelli et al. (2018) investigated how two main Industry 4.0 concepts, i.e. IoT and Big Data and Analytics, can reduce CE challenges, including financial risks, loss of ownership, willingness to pay, cannibalisation, technology improvement and return flow uncertainties.

Furthermore, Despeisse et al. (2017) specifically focussed on the benefits of 3 D printing, which are ease of design and mass customisation of the CE, where increased circularity is possible in manufacturing systems by using recycled materials as inputs. Nascimento et al. (2019) also addressed 3 D printing as a means to achieve integration between Industry 4.0 and CE. They aimed to explore sustainable additive manufacturing, derived from Industry 4.0, by using 3 D printing to improve CE practices, and proposing a circular smart production system business model (Nascimento et al. 2019).

Another study conducted by Antikainen, Uusitalo, and Kivikytö-Reponen (2018) also supports the idea of CE benefits from Industry 4.0 technologies. They argue that an increase in transparency and traceability throughout the life cycle of a product by using digital technologies would facilitate the end of life activities, including collection, remanufacturing and recycling, and thus CE activities (Antikainen, Uusitalo, and Kivikytö-Reponen 2018). Similarly, from a micro perspective, Yang et al. (2018) presented the advantages of Industry 4.0 on the remanufacturing industry. Likewise, Lin (2018) suggested a user experience-based product design for smart manufacturing to improve CE in the glass recycling industry by using Industry 4.0 technologies.

Some of the studies that cover integration between Industry 4.0 and a CE are summarised in Table 2.

Industry 4.0 has great potential to contribute to a CE by defusing potential risks. However, in order to apply Industry 4.0, organisations should adopt some key principles, i.e. interoperability, virtualisation, decentralisation, real time capability, service orientation and modularity. Therefore, suggested responses to overcome the risks of a CE transition should reflect Industry 4.0 principles. From this point of view, in this study 14 responses, which are derived from the principles, are suggested based on important Industry 4.0 technologies to overcome CE transition risks.

To start with, changes in organisational structure due to the transition reveal the need to consider dynamic managerial implications and rapid decision making (Prakash and Barua 2015). For organisations to deal with this complexity, increasing top management awareness and support should be the initial step. One of the most important Industry 4.0 dimensions, decentralisation, is a possible solution for this dynamic environment, and decentralised decision making would ease the adaptation of the CE by speeding up reverse logistics activities. From this point of view, first Industry 4.0 response to overcome risks of a CE transition can be demonstrated as: '*Top management awareness and support by decentralised organisation structure*'.

Although environmental concerns are the priority for a CE transition, financial gains are also essential for organisations to stay in the market with a competitive advantage, where a CE can provide this (Lewandowski 2016). Therefore, cost and performance monitoring through the supply chain is necessary. Decentralised structure of the organisations may support the monitoring of cost and general performance in the complex supply chain, and big data and analytics would help to manage this situation. Hence, the second response proposal is: '*Continuous monitoring of the cost and*

Table 2. Integration between Industry 4.0 and Circular Economy.

Author(s)	Objective
Despeisse et al. (2017)	Proposing research questions about how 3 D printing can enable more sustainable modes of production and consumption, and unlock value in the CE.
Pagoropoulos, Pigosso, and McAloone (2017)	Identifying how Big Data and the Internet of Things can support the transition to CE.
Antikainen, Uusitalo, and Kivikytö-Reponen (2018)	Revealing the opportunities of digitalisation in adopting CE based business models.
Bressanelli et al. (2018)	Presenting how the Industry 4.0 technologies, i.e. IoT and Big Data & Analytics, can be used to overcome CE challenges
de Sousa Jabbour, Jabbour, Godinho Filho, et al. (2018)	Revealing the impact of Industry 4.0 technologies on CE strategies and organisation by focussing on those technologies based sustainable operations management decision-making.
Garcia-Muiña et al. (2018)	Presenting a new Circular Business Model by including dimensions of sustainability in the light of Industry 4.0 in manufacturing environment.
Lin (2018)	Proposing smart production approach to empowering industry 4.0 in the CE of the glass recycling industry
Nascimento et al. (2019)	Presenting the integration of Industry 4.0 and CE to create a business model that includes reused and recycled wastes as materials.
Yang et al. (2018)	Presenting the role of Industry 4.0 to overcome challenges in remanufacturing sector.
Martín-Gómez, Aguayo-González, and Luque (2019)	Presenting the necessities to achieve sustainable supply chain from the CE perspective in Industry 4.0

performance through the SC by big data and analytics' for financial benefits and performance management through sustainable supply chain operations.

Standardisation and simplification of the processes are important for the improvement of circularity. The modularisation dimension of Industry 4.0 would benefit from this suggestion by increasing the flexibility and adoptability of the system. Therefore, another Industry 4.0 response proposal can be posed as: '*Modular processes for simplification and standardisation'*. Moreover, modularity also supports the capacity for collaboration. Collaboratively, all the parties in the supply chain for the transition (Prakash and Barua 2015) and integrated business processes could meet the needs of this dynamic environment. Therefore, '*Integrated business processes for cross-functional collaboration'* could be presented as another Industry 4.0 response.

In order to reduce risks related to stakeholders in the reverse logistics supply chain, it is important to have strategic collaboration with reverse chain partners for circular goals. Decentralised organisation structure combined with the amount of data would be beneficial for this collaboration if it is used properly. From this point of view, '*Using big data for strategic collaboration with reverse chain partners'* can be a response to decrease CE transition risks.

Aligning policies and processes to optimise circularity of the organisation, including human collaboration is an important aspect. With advanced technological developments, human-machine interaction has become an essential feature for organisations (Lasi et al. 2014). Consequently, interoperability is an important dimension of Industry 4.0, where human-machine interaction is conducted through CPS and IoT across the entire organisation. To align the policies and processes, the interoperability dimension can be adopted as a response as: '*Advanced human-machine interaction for aligned policies and processes'*. Furthermore, '*Utilisation of CPS to develop supply chain technology for interoperability'* can also be suggested for improved waste collection and effective recycling operations where environmental and economic factors would benefit the organisation.

Industry 4.0 technologies can be employed to track products in the life cycle for improving CE principles (de Sousa Jabbour, Jabbour, Godinho Filho, et al. 2018). With the same view, the dimension of real time capabilities could be beneficial for organisations to monitor the supply chain from the beginning of the life cycle to the reverse logistics activities. From this point of view, IoT based technologies can be used to monitor the supply chain activities to reduce risks. As a result, an Industry 4.0 response related to the real time capability dimension can be presented as: '*IoT technologies for monitoring and tracking supply chain activities for sustainable goals'*. Similarly, real time capabilities could also be useful to manage turnaround times through standardisation of the necessary activities for circularity and the control of each process. From this point of view, another response related to real time capabilities can be: *'Real time data management to control turnaround times.'* Moreover, coordination between supply chain members is also crucial to overcome CE transition risks, and it is possible with the following proposed response: '*Real time capability making a fast and effective coordination among supply chain members'*.

Infrastructure and facility design are important for the CE goals due to the high costs and environmental impacts. The virtualisation dimension of Industry 4.0 could be beneficial to simulate risks related to design by giving the opportunity to imitate the infrastructure and facility design before the investment. From this point of view, '*Virtualisation for developing infrastructure support and facility'* is another Industry 4.0 response.

One of the main goals of a CE is minimising waste, while maximising the reuse of resources. Therefore, the product design phase is the determinant of the end of life phase. 3 D printing enables closed loop circulation of materials and the use of recycled materials during the design phase (Despeisse et al. 2017). To deal with the risks related to quality problems during the design phase, and to eliminate defects, the following Industry 4.0 response is proposed: '*3 D printing and virtualisation to be used during product design for minimising waste and providing easily recycled products'*.

The closed-loop supply chain is an important aspect of the CE, where an output of one process can be an input for another, making resource saving possible (Winkler 2011). Greater decentralisation of decision-making could be beneficial to close the loop of sustainable supply chains, hence, another Industry 4.0 response can be presented as: '*Closing the loop of the SC by decentralised decision making.*'

Collection and recovery of the products at the end of their lifecycle is crucial for circularity (Winkler 2011). Therefore, outsourcing can be used for these activities as a part of the reverse chain. Both technologies and human resources are available within the organisation and through the entire supply chain via the service orientation dimension of Industry 4.0. Therefore, service orientation allows information and service sharing between different partners. From this point of view, '*Service orientation for developing an outsourcing strategy to recover and collect end of life products*' can reduce the risks related to these activities.

In the following section, the suggested methodology is explained.

3. Methodology

In this work, an association between risks and the responses is provided by using integrated MCDM methods, namely fuzzy AHP and TODIM, where fuzzy AHP is used for calculating the weights of risks, and TODIM, a useful method to evaluate risks, is used for revealing the ranking of Industry 4.0-based responses. As shown in Figure 1, the proposed framework for Industry 4.0-based responses to overcome the risks of CE transitions is presented by including the key Industry 4.0 dimensions as the root of responses and the methods to link the risks and responses. The reason to hire fuzzy logic is its ability to overcome the subjectivity and vagueness of human judgement when dealing with uncertainties in the decision-making process. The advantage of using fuzzy AHP is its ability to calculate the weights of the respective criteria within a hierarchy, whereas Fuzzy TODIM is used due to its ability to rank the alternatives in a risky environment, in this case, responses for the risk-based problems.

3.1. Fuzzy AHP

The AHP proposed by Saaty (1980) is one of the most commonly used MCDM techniques; it is known for its capacity to manage the qualitative and quantitative criteria (Chung, Lee, and Pearn 2005).

AHP has limited applicability in uncertain and vague decision-making processes (Önüt, Kara, and Işik 2009). Zadeh (1965) introduced the fuzzy set theory in order to reveal the usage of linguistic terms to overcome the subjectivity and vagueness of human judgement. A class of objects with a continuum of membership grades is called a fuzzy set. A tilde (~) is placed above when a fuzzy set is represented (Zadeh 1965).

There are various fuzzy membership functions. In this paper, triangular fuzzy numbers were used, which are indicated as (l_{ij}, m_{ij}, r_{ij}) referring to the smallest possible, the most likely and the largest possible values respectively (Kahraman, Ruan, and Doğ an 2003, Önüt, Kara, and Işik 2009).

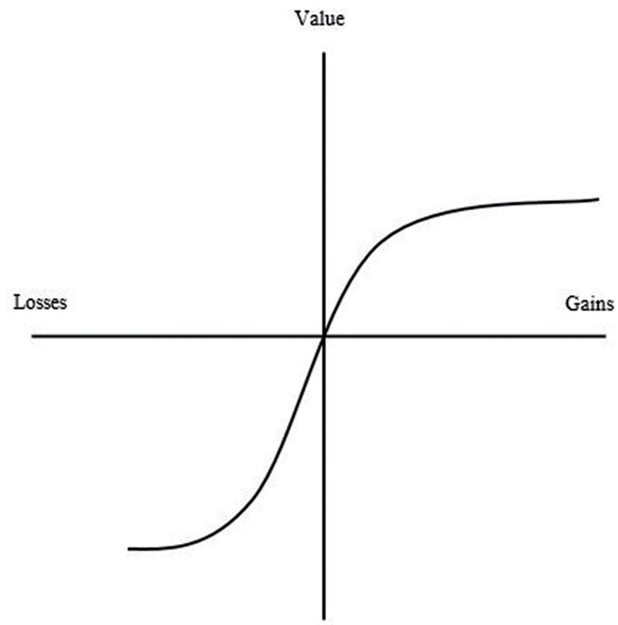

Figure 2. Value function of TODIM.

Fuzzy extension of AHP methodology differs from Saaty's (1980) approach because it incorporates fuzzy set theory (Duran and Aguilo 2008; Kilincci and Onal 2011). Fuzzy numbers are used to build the pairwise comparison matrices in fuzzy AHP. The fuzzy judgement vector is attained for each criterion using pairwise comparisons. Although Saaty's (1980) scale of 1–9 has advantages including simplicity and ease of use, the usage of linguistic terms to overcome the subjectivity and vagueness of human judgement is recommended.

The consistency ratio has to be computed to check whether the results of any AHP analysis are consistent.

3.2. Todim (tomada de decisão iterativa multicritério)

TODIM is an acronym in Portuguese of Interactive and multi criteria Decision Making (Gomes, Rangel, and Maranhao 2009; Ren, Xu, and Gou 2016). In contrast to discrete multi criteria methods, which direct the decision-makers to search for the maximum global measures, TODIM uses the global measures of values by the implementation of the Prospect Theory (Gomes, Rangel, and Maranhao 2009).

Figure 2 shows the value function of TODIM, which is the same as the gains/losses function of the Cumulative Prospect Theory, where gains and losses are identified regarding a reference point (Pereira, Gomes, and Paredes 2014). The TODIM method also allows the usage of a verbal scale using a criteria hierarchy, fuzzy value judgements and the interdependence relationships for the judgements of values (Tseng et al. 2014).

The main aim of the TODIM method is to determine the dominance degree of each alternative compared to others, using the prospect theory based utility function (Qin, Liu, and Pedrycz 2017). Pairwise comparisons are made to compute the relative dominance of one alternative to other (Gomes and Rangel 2009).

Normalisation of the values in the matrix is done by the division of the value of one alternative by the sum of all the alternatives for each organisation. In a given matrix where $A_1, A_2, \ldots, A_m$ are m alternatives, $C_1, C_2, \ldots, C_n$ are n criteria, P_{ij} is the rating of the alternative A_i regarding criterion C_j, and $\omega = (\omega_1, \omega_2, \ldots, \omega_n)$. T is the weight vector related to the set of criteria $C = \{C_1, C_2, \ldots, C_n\}$, which fulfils the below conditions $\omega_j \in [0, 1]$ and $\sum_{j=1}^{n} \omega_j = 1$.

Mathematical formulations are summarised systematically as follows (Gomes, Rangel, and Maranhao 2009; Qin, Liu, and Pedrycz 2017):

- ***Step 1:*** Calculation of the relative weight ω_{ir} of the criterion C_j to the reference criterion C_r that is shown below:

$$\omega_{jr} = \omega_j / \omega_r (j = 1, 2, \ldots, n) \quad (1)$$

  where ω_j indicates the weight of the criterion C_j and $\omega_r = \max\{\omega_j\}$
- ***Step 2:*** Calculation of the dominance degree of each alternative A_i over each alternative A_k with regard to criterion C_j by using Equation (2).

$$\Phi_c(A_i, A_k) = \begin{cases} \sqrt{\dfrac{w_{jk}(P_{ij} - P_{kj})}{\sum_{j=1}^{m} w_{jk}}} & \text{if } P\ ij - P\ kj > 0 \\ 0 \text{ if } P\ ij - P\ kj = 0 & \\ \dfrac{-1}{\theta} \sqrt{\dfrac{(\sum_{j=1}^{n} w_{jk})(P_{kj} - P_{ij})}{w_{jk}}} & \text{if } P\ ij - P\ kj < 0 \end{cases} \quad (2)$$

  In Equation (2), θ represents the attenuation factor of the losses. When the θ is changed, shapes of the prospect theoretical value function change in the negative quadrant. The range of the values of this parameter is $\theta > 0$; if $0 < \theta < 1$, then the effect of loss will increase; if $\theta > 1$, then the effect of loss will reduce.
- ***Step 3:*** Calculation of the overall dominance degree of each alternative A_i over A_k with regard to criterion C_j as shown below:

$$\delta(A_i, A_k) = \sum_{j=1}^{n} \Phi_j(A_i, A_k) \quad (3)$$

- ***Step 4:*** Calculation of the global prospect value of the alternative A_i ($i = 1, 2, \ldots, m$) by using the following equation:

$$\xi_i = \frac{\sum_{k=1}^{m} \delta(A_i, A_k) - \min \sum_{k=1}^{m} \delta(A_i, A_k)}{\max \sum_{k=1}^{m} \delta(A_i, A_k) - \min \sum_{k=1}^{m} \delta(A_i, A_k)}. \quad (4)$$

- ***Step 5.*** Based on the global prospect values of the alternatives, ranking should be completed. Increase in the value represents the better alternative A_i.

4. Case study

4.1. Background information

The application was conducted in a leading transport and logistics service company in Turkey; the leading 3rd party logistics (3PL) firm and a significant cross dock operator (CDO) with ten distribution centres. The company offers warehousing, road freight, Ro-Ro, Ro-Ro port, sea and air trade customs clearance and international commerce services in 15 countries. The consumer profile is from a wide range of sectors such as retailing apparel and home products, pharmaceuticals, home electronics, international mass retailing and sportswear retailing.

The case company is in the process of a transition from a linear to a circular economy and seeks to develop sustainability in its supply chain operations. Thus, it has become involved in 'Reverse Logistics and REsolve framework for CE'. The company is facing several risks in this transition, and due to the important role of reverse logistics in CE transition, it is essential for management to focus on that area.

Reverse logistics is the main component of the CE that covers not only reverse flow of distribution, but also the repair, remanufacturing, reuse, recycling and refurbishment activities of returned products (Bernon, Tjahjono, and Ripanti 2018). Reverse logistics activities are divided into two different distribution models in the company; firstly, intercity partial transportation, which is hub to hub distribution using large vehicles, and secondly, a model which covers city logistics activities with partial distribution activities using smaller vehicles. The company is actively involved in logistics 4.0 applications, involving process integration through the internet and mobile applications and creating a network among objects. It also aims to utilise communication technologies and cloud computing, simulation and robotic systems. This digitalisation on their reverse logistics activities brings advantages, such as direct delivery of transport orders to the operational units, continuous tracking of loads, the ability to monitor track packaging relations, automatic information and alerts in real time, and advanced statistics and reporting by the developed data management.

The managers of company are seeking to apply Industry 4.0 based technologies responses to overcome the risks of transition from linear to circular economy in an operations management context.

4.2. Data analysis and results

The proposed research framework in this study, shown in Figure 3, focuses on the linkage between 9 risks and 14 Industry 4.0-based responses. The framework may be generalised; in other words, it may be used for different applications, because it was formed based on past studies. However, the application is specific to the company, which make the results unique to the organisation. This is in line with Hervani, Helms, and Sarkis (2005) statement that there is no perfect tool for performance measurement systems and that their usage is greatly dependent on acceptance by organisations. The application and the scales are specific to the organisations; therefore, there is no generally applicable tool or approach for generalising the results.

Data collection processes were conducted with the consent of the Board of Directors. Since it is a case study, with no aim to generalise the results, there is no need to justify the statistical process. Five authorities carried out the

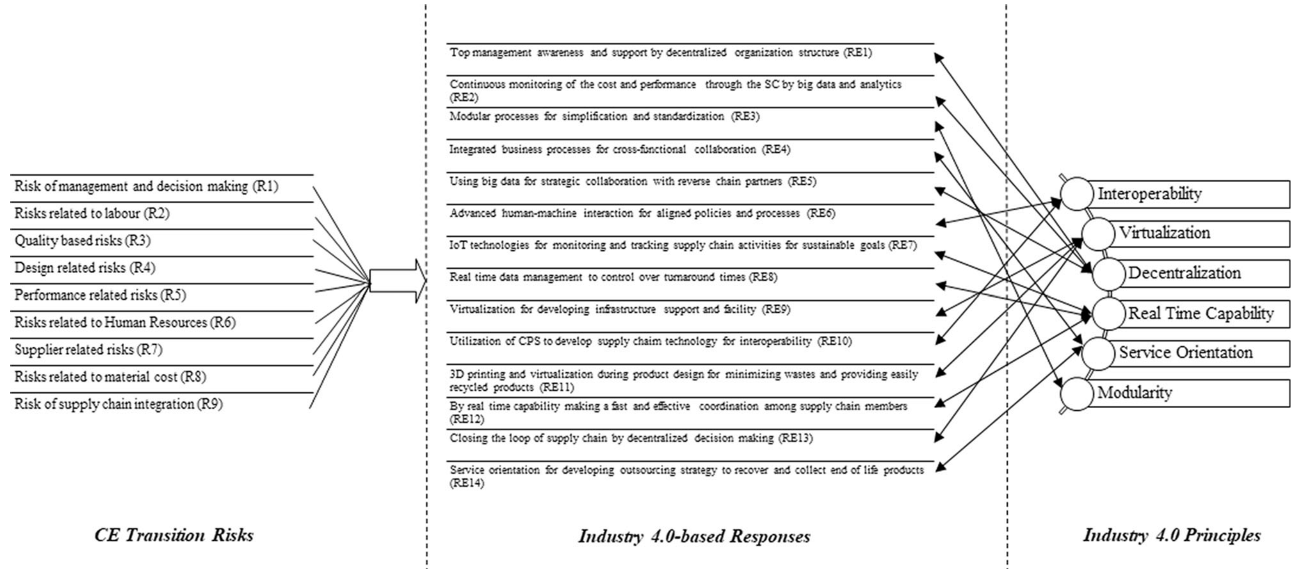

Figure 3. Proposed framework to overcome CE risks by Industry 4.0-based responses.

Table 3. Information about participants.

Expertise	Position in the company	Department	Year of experience in the company	Total work experience in years	Gender
Industrial Management	Manager	Strategic Sustainability Centre	3	6	Male
Operations	Manager	Customer Sustainability Centre	1	15	Male
Supply chain operations management	Manager	Corporate Quality Centre	12	14	Male
Supply chain management	Engineer	Process Sustainability Centre	1	1	Female
IT expert	Engineer	Strategic Sustainability Centre	2	2	Male

Table 4. Linguistic variables for fuzzy AHP.

Linguistic variables	Scale of fuzzy number	Scale of reciprocal fuzzy number
Equally important (E)	(1, 1, 1)	(1/1, 1/1, 1/1)
Equally to moderately more important (EM)	(1, 2, 3)	(1/3, 1/2, 1/1)
Moderately more important (MM)	(2, 3, 4)	(1/4, 1/3, 1/2)
Moderately to strongly more important (MS)	(3, 4, 5)	(1/5, 1/4, 1/3)
Strongly more important (SM)	(4, 5, 6)	(1/6, 1/5, 1/4)
Strongly to very strongly more important (SVM)	(5, 6, 7)	(1/7, 1/6, 1/5)
Very strongly more important (VSM)	(6, 7, 8)	(1/8, 1/7, 1/6)
Very strongly to extremely more important (VSEM)	(7, 8, 9)	(1/9, 1/8, 1/7)
Extremely more important (EM)	(8, 9, 9)	(1/9, 1/9, 1/8)

pairwise comparisons; managers and engineers were responsible for sustainable supply chain activities within the company. Sample size for the study is adequate since it is a specified case study, where other researchers also followed the similar procedure like Luthra et al. (2016), Luthra et al. (2017). Due to the context of the problem covered in the case study, where both knowledge of Industry 4.0 technologies and CE principles are essential, these authorities have been considered as experts. In Table 3, information about the participants is presented.

The weight associations of the 9 risks were found using the fuzzy AHP technique, and prioritisation of the responses was found through Fuzzy TODIM.

Firstly, for the fuzzy AHP application, each expert made the pairwise comparisons using the linguistic variables shown in Table 4.

Table 5 shows the pairwise comparisons of one of the experts.

Table 6 shows the weights of the barriers during the transition from a linear to a CE for sustainable development.

According to the fuzzy AHP result, the most important problem to be overcome is the lack of management and decision-making, with a weight of 24.6%. The other important problems are labour intensiveness (15.3%), quality problems of the product during the entire life cycle (13.5%) and difficulties in the performance assessment of the CE (11.1%).

Next, we applied Fuzzy TODIM, and for this, each expert made the pairwise comparisons among identified Industry 4.0 based responses using the linguistic variables shown in Table 7. The attenuation factor θ is taken as 1 since the generally acceptable value of it is 1.

Table 5. Pairwise comparison of one of the experts.

	Risk of management and decision making (R1)	Risks related to labour (R2)	Quality based risks (R3)	Design related risks (R4)	Performance related risks (R5)	Risks related to Human Resources (R6)	Supplier related risks (R7)	Risks related to material cost (R8)	Risk of supply chain integration (R9)
Risk of management and decision making (R1)	E	MM	SM	VSM	E	1/MM	SM	1/MM	SM
Risks related to labour (R2)		E	MM	MM	1/SM	SM	MM	1/MM	MM
Quality based risks (R3)			E	SM	1/MM	MM	E	1/SM	MM
Design related risks (R4)				E	1/VSM	E	E	1/VSM	MM
Performance related risks (R5)					E	VSM	VSM	E	MM
Risks related to Human Resources (R6)						E	1/MM	1/VSM	MM
Supplier related risks (R7)							E	MM	MM
Risks related to material cost (R8)								E	E
Risk of supply chain integration (R9)									E

Table 6. The weights of risks.

Risks	Weights
Risk of management and decision making (R1)	0.2463
Risks related to labour (R2)	0.1531
Quality based risks (R3)	0.1357
Design related risks (R4)	0.1120
Performance related risks (R5)	0.0849
Risks related to human resources (R6)	0.0732
Supplier related risks (R7)	0.0730
Risks related to material cost (R8)	0.0632
Risk of supply chain integration (R9)	0.0587

Table 7. Linguistic variables for fuzzy TODIM.

Linguistic terms	Triangular fuzzy numbers		
VG	0.75	1	1
G	0.50	0.75	1
M	0.25	0.50	0.75
B	0	0.25	0.50
VB	0	0	0.25

Table 8 shows the overall dominance degrees of each Industry 4.0-based response.

Table 9 shows the rankings of the Industry 4.0-based responses in order to overcome the barriers associated with a CE.

Table 9 shows that the most important response for overcoming the problems of a CE is the integrated business processes for cross-functional collaboration. The other most important responses are modular processes for simplification and standardisation (S2), continuous monitoring of the cost and performance through the supply chain by big data and analytics (S3) and IoT technologies for monitoring and tracking reverse logistics activities for sustainable goals (S4).

5. Implications and discussions

The transition to a CE requires managerial actions. This transition process is not an ordinary type of process, because of the nature of the transition from a linear to a CE. Since all the current processes are rooted in the linear economy, significant managerial initiatives are essential. The steps taken should take into consideration both the internal and external environments of the company. In the first part of this section, the results of the study are further developed with managerial implications, supported by the literature.

The first ranked proposed response is 'Integrated business processes for cross-functional collaboration'. This result signals the need for a *systems theory*, highlighting the need to establish integration among all business functions, which is a precondition for efficient and effective transition to circularity, because of its importance in managing the flow of people, materials and information. Liu and Bai (2014) stated that the structure of the firm affects its behaviour in the transition to a CE. In addition, the hierarchical organisational structure prevents flexibility and innovation. Therefore, from a managerial perspective, the proposed structure is *matrix organisational structure*. The matrix organisational structure will enable integration and collaboration among the departments of the company. This structure will contribute not only to the internal management, but also support the

Table 8. Overall dominance degrees of each Industry 4.0 response.

	RE1	RE2	RE3	RE4	RE5	RE6	RE7	RE8	RE9	RE10	RE11	RE12	RE13	RE14
RE1	0	−1.28	−0.57	−0.82	−1.80	−1.83	−1.25	−2.82	−2.76	−1.22	−1.27	−1.95	−2.14	−2.18
RE2	−1.80	0	−0.81	−0.93	−1.12	−1.65	−1.61	−2.76	−2.99	−1.95	−2.10	−2.37	−2.48	−2.46
RE3	−2.13	−1.85	0	−1.09	−2.60	−2.10	−1.63	−3.54	−3.50	−2.10	−1.83	−2.61	−3.04	−2.50
RE4	−2.27	−1.63	−1.13	0	−2.32	−1.88	−1.67	−3.18	−3.34	−2.39	−2.01	−2.42	−2.52	−2.06
RE5	−1.38	−0.93	−0.95	−0.64	0	−1.26	−1.66	−2.55	−2.61	−1.67	−1.79	−1.86	−2.05	−2.03
RE6	−1.38	−1.16	−0.33	−0.33	−1.67	0	−1.58	−2.40	−2.41	−1.39	−1.58	−1.89	−2.01	−1.83
RE7	−1.98	−1.81	−1.41	−1.49	−2.23	−2.19	0	−2.77	−2.95	−2.14	−1.24	−2.40	−2.99	−1.78
RE8	−0.65	−0.07	−0.42	−0.30	−0.13	−0.67	−0.82	0	−1.45	−1.16	−1.20	−1.10	−1.25	−1.16
RE9	−0.33	0.05	−0.19	0.04	0.24	−0.54	−0.48	−0.87	0	−0.59	−0.61	−0.85	−1.07	−0.66
RE10	−0.48	−0.96	0.25	−0.10	−1.27	−1.11	−0.63	−2.13	−2.35	0	−0.70	−1.42	−1.60	−1.37
RE11	−2.10	−1.76	−1.61	−1.71	−2.31	−2.14	−0.95	−2.70	−2.76	−2.20	0	−2.37	−2.99	−1.84
RE12	−0.98	−1.26	−0.51	−0.24	−1.17	−1.23	−1.36	−1.89	−2.14	−1.35	−1.42	0	−1.65	−1.52
RE13	−0.47	−0.85	−0.13	0.25	−0.86	−1.22	−0.91	−1.61	−1.76	−0.83	−0.98	−0.23	0	−0.83
RE14	−0.98	−1.11	−0.65	−0.20	−1.31	−1.08	−0.34	−1.64	−1.97	−0.86	−0.33	−1.10	−1.59	0

Table 9. Rankings of Industry 4.0-based responses.

Industry 4.0-based responses	Global values
Integrated business processes for cross-functional collaboration (RE4)	1.0000
Modular processes for simplification and standardisation (RE3)	0.9646
Continuous monitoring of the cost and performance through the supply chain by big data and analytics (RE2)	0.7226
IoT technologies for monitoring and tracking supply chain activities for sustainable goals (RE7)	0.7113
Top management awareness and support by decentralised organisation structure (RE1)	0.6310
3D printing and virtualisation during product design for minimising waste and providing easily recycled products (RE11)	0.6258
Using big data for strategic collaboration with reverse chain partners (RE5)	0.5669
Advanced human-machine interaction for aligned policies and processes (RE6)	0.5538
Utilisation of Cyber Physical Systems to develop supply chain technology for interoperability (RE10)	0.5158
Service orientation for developing an outsourcing strategy to recover and collect end of life products (RE14)	0.4226
Real time capability making a fast and effective coordination among supply chain members (RE12)	0.4090
Closing the loop of the supply chain by centralised decision making (RE13)	0.2207
Real time data management to control turnaround times (RE8)	0.0828
Virtualisation for developing infrastructure support and facility (RE9)	0

company in the external environment throughout the supply chain. In addition, the matrix organisational structure that is given as the managerial implication is in line with the fifth proposed response: 'Top management awareness and decentralised organisational structure'. The proposed matrix organisational structure can close the gap, as it is asserted in Liu and Bai (2014) that a gap exists between a firm's awareness and its behaviour; the hierarchical structure of the firm is an important element of this gap.

The second-ranked proposed response is 'Modular processes for simplification and standardisation'. The simplification and standardisation of processes are critical because the current processes in a linear economy transform to a circular economy in which the way of flow and sub-processes are changing. As stated by Romero and Rossi (2017), Circular Lean Product-Service Systems can enhance the dematerialisation via reducing waste in manufacturing and services operations, and the use of virgin materials, by using a restorative and regenerative operational system. Therefore, as suggested by Gaustad et al. (2018), the lean approach can be useful to simplify and standardise the processes through the elimination of waste, continuous improvement (kaizen) and improved efficiency. The lean tools, such as value stream mapping, autonomation (jidoka) and establishing quality circles, may be helpful tools in this context. On the other hand, due to the nature of the transition from a linear to a CE, the internal crosswise task management should be revised as the longitudinal tasks of process management in the trans-functional departments (Ying and Li-Jun 2012). Thus, it is also possible that the simplification may not be adequate so that *business process reengineering* can be used to redesign the linear processes to adopt the CE.

The third ranked proposed response is 'Continuous monitoring of the cost and performance through the supply chain by big data and analytics' and the fourth-ranked proposed response is 'IoT technologies for monitoring and tracking supply chain activities for sustainable goals'. Performance assessment is essential in all stages of management. Thus, to achieve circular objectives, the integration of all business operations is essential as mentioned in the first implication. However, it is becoming much more complex and difficult to make an evaluation as processes become more interdependent and are affected by a wide range of stakeholders. Hence, a holistic assessment is required regarding CEs to evaluate the performance of the circular processes. The same phenomenon is seen in Green Supply Chain Management. Similar models can be deployed and adopted to circular processes and reverse logistics. As depicted by Kazancoglu, Kazancoglu, and Sagnak (2018) the *GSCM performance assessment* model should be in line with the first managerial implication in that it should stand on a systems approach, it should include all the processes, cover all the business functions and have a detailed structure with predetermined metrics to achieve a scorecard that is analytic and traceable. The results should be compared with predetermined sustainable goals of the management. The data analytics may significantly contribute to achieve this aim so long as the performance assessment system with appropriate metrics is stated.

The sixth-ranked proposed response is '3 D printing and virtualisation during product design for minimising waste and providing easily recycled products'. The design is a key issue in CEs to minimise waste and enable the circular flow. As mentioned in Despeisse et al. (2017) the features of 3 D printing are in line with sustainability and circularity and have potential for the transition to a more sustainable society. Its importance is because all potential concerns can be reflected in the product design and may have a preventative feature. Due to the shrinkage of the product life cycle, the design process needs to be much faster than before. The *3 D printing* can be a useful tool for managers to make the design process faster. On the other hand, the design concept should be managed in such a way that it encompasses all the current and possible circular activities that may be considered during the product life cycle. Thus, the *Design for Everything (DfX)* concept may possess CE principles. This would be a step in line with the first implication of integration among the business operations and supply chain.

It is clear that the Industry 4.0 technologies can be used and deployed for the transition from a linear to a CE, but the managerial point of view and skills should not be ignored. The success of the transformation is based on the company's managerial performance. As indicated by Khanna et al. (2004) the management should handle the transformation by considering the market scenarios and managing the transition phases within a systems dynamics approach. This means that the required management knowledge, expertise and analytical skills for using the Industry 4.0 technologies to increase the efficiency and effectiveness of circular activities. Therefore, training employees in Industry 4.0 technologies so that they have up to date information and can overcome the potential problems related to technological transition is essential. Hence, as stated by Kazancoglu and Ozkan-Ozen (2018), within Industry 4.0, the necessity of a systems approach and analytical thinking and subsequently the ability to handle complexity, problem solving capability and flexibility were arising features within the required labour profile. Moreover, the recruitment process should highlight the requirements for skills within Industry 4.0 technologies. All these managerial implications are important for successful sustainable operation management practices in the transition to a CE in the new industrial era.

6. Conclusions

CEs and Industry 4.0 principles have gained increasing attention; however, the integration of the two concepts has not been widely analysed. Industry 4.0 technologies, such as emerging technologies and smart manufacturing, have the ability to form a basis regarding responses for CE implementation in a sustainable supply chain context. It may be appropriate to analyse the relationship between the two concepts and identify the Industry 4.0 technologies for improving the CE performance within the sustainable supply chain. For this perspective, in this paper, firstly, the relationship between a sustainable supply chain and a circular economy was identified, and the risks of transition from a linear economy to a circular economy were presented. Then, the Industry 4.0-based responses were proposed in order to overcome the risks. It is very important to determine the importance weights of the 9 risks, and rank the 14 Industry 4.0-based responses, as the basis for organisations' roadmaps. The weight association of the 9 risks was found via the Fuzzy Analytical Hierarchy Process (AHP) technique, and the ranking of the responses was determined by TODIM.

The main contribution of this paper is a proposed framework, which presents

1. the risks in a process of transition of a sustainable supply chain from a linear economy to a circular economy, and
2. Industry 4.0-based responses to overcome the risks.

This study highlights, among others, the most important risk related to management and decision making are labour, quality and performance. The most important responses were found to be integrated business processes for cross-functional collaboration, modular processes for simplification and standardisation, continuous monitoring of the cost and performance through the supply chain by big data and analytics, and IoT technologies for monitoring and tracking reverse logistics activities for sustainable goals.

The main limitation of this research is that it is based on subjective judgements. Moreover, the case study was conducted in a specific context, in an emerging country, Turkey. Results may vary according to the transition level of the CE and Industry 4.0 adaptation. Further possible research could focus on applying the proposed framework in different sectors in Turkey, as well as in other developing countries. Also, a different MCDM technique rather than fuzzy AHP can be applied in order to find the weights of 9 risks.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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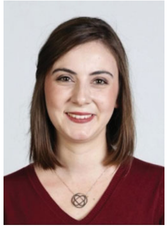

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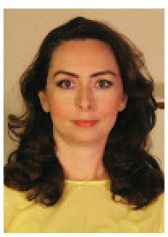

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