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Examining the role of urban-industrial symbiosis in the circular economy: an approach based on N-Force field theory of change and N-ISM-Micmac

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Abstract
The circular economy (CE) refers to a new industrial paradigm that contrasts with the linear supply chain structure based on a "take, make, use, dispose" pathway. Due to its potential contributions to improving the CE, industrial symbiosis (IS) has been recognized as a feasible way to advance it. Urban symbiosis is an extension of IS that involves a series of symbiotic relationships among enterprises within the urban area. Combining urban and industrial symbiosis (Ur-IS) is a step toward better resource efficiency in urban areas and industrial zones and urban areas. However, while there are several driving forces for Ur-IS adoption, there are also many inhibiting factors. A comprehensive decision framework is needed to address the principal drivers and challenges for Ur-IS initiatives. Türkiye, designated as a candidate for full EU membership in 1999, also places importance on environmental sustainability goals and effective resource management in its own move towards a CE. Our literature review concluded that there is only one quantitative study investigating the driving and (or) restraining forces for Ur-IS adoption in emerging and industrialized countries. The main purpose of this study is to investigate the potential of Ur-IS implementation in Türkiye through the proposed Neutrosphopic-Simple Additive Weighting Method-based force field theory of change and the Neutrosphopic–Interpretive Structured Modeling-Cross-Impact Matrix Multiplication Method. The findings suggest that *lack of policies, lack of incentives and regulations,* and *vulnerability and supply uncertainty* are the most significant restraining forces for Ur-IS implementation in Türkiye. The research findings can assist decision-makers in Türkiye in effectively implementing Ur-IS.

Keywords Urban-Industrial symbiosis · Circular economy · Force field theory of change · Neutrosphopic-SAW · Neutrosphopic-ISM-MICMAC

1 Introduction

Over the last 150 years, a one-way model of production and consumption grounded in a linear “take, make, use, dispose” pathway has dominated the global economy (Ghosh 2020). In linear supply chains, products are manufactured from components, parts, and raw materials drawn from a wide range of suppliers. The products are then distributed, sold, and utilized. Once consumers are done with the product, it is typically disposed of as waste in a landfill or incinerated. However, with global population in the billions, and growing industrialization and resource consumption, it is clear that business models grounded in these traditional practices cannot be maintained for a sustainable future (Liu and Ramakrishna 2021). To address the negative environmental impacts of linearity on global economies and societies, governments and organizations around

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the world are turning to approaches based on sustainable development. This is widely recognized as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987), and requires a long-term, collaborative perspective anchored in the responsible and efficient use of natural resources (Álvarez and Ruiz-Puente 2017).

The concept of the circular economy (CE) emerged in the 1990s as one approach to address this problem, focusing, in particular, on mitigating the negative ecological effects of high growth and natural resource limitations (Pearce and Turner 1990; Wang et al. 2013). At its core, the CE challenges the current economic system based on excessive consumption of natural resources (Rizos et al. 2017). A CE is designed to be refreshing and reformative, always aiming for the highest utility of resources and cleaner technologies (Andersen 1997; Andersen 2007; The Ellen MacArthur Foundation, 2015). This economic model aims to decouple global economic growth from finite resource usage over the long-term. A CE may produce growth, create jobs, and minimize environmental consequences, such as carbon emissions. This has been widely recognized, and is increasingly applied, in the European Union (Wadström et al. 2021).

As demand for new economic models based on systems thinking grows, today's encouraging alignment of technological and societal variables may make the transition to a CE possible. Eradicating different wastes from the environment, through source reduction, recycling, remanufacturing, or reuse, will support addressing local and global challenges, such as climate change, biodiversity loss, waste generation, and pollution. Moreover, a CE also enables decision makers to address several urban and industrial challenges by reevaluating the use of materials, leading to new types of value generation. However, in many cities and the areas around them, resources are mismanaged or underutilized. Waste streams are more common in densely populated urban regions; therefore, resource recovery can be used to improve efficiency (Godina et al. 2022).

Chertow and Ehrenfeld (2012), Fraccascia and Giannoccaro (2020) and Veyssière (2021) explain that a CE is an "umbrella concept", drawing on contributions from other approaches, particularly industrial ecology and industrial symbiosis (IS). Industrial ecology takes its inspiration from the principles of biological ecosystems, with the goal of helping supply chain networks evolve into closed-loop industrial ecosystems at the facility-, supply chain-, regional-, and global levels (Chertow 2000). IS is a key tool in the emerging field of industrial ecology (Mortensen and Kørnøv 2019; Mallawaarachchi et al. 2020), and focuses on the flow of materials and energy through local and regional economies. IS stresses establishing knowledge webs containing new perspectives and forming symbiotic interactions among industrial organizations (Cecchin et al. 2020). IS is a collective approach to constructing a collaborative ecosystem to swap materials, energy, water, and/or by-products (Baldassarre et al. 2019).

Industrial zones are an integral part of urban ecosystems. Cities provide businesses with a number of benefits, including a sizable market, access to local suppliers, and a setting that fosters the development of technological innovations and expertise. Hence, it is suggested that in an urban setting and its environments, the integration of urban and industrial symbiosis (Ur-IS) can be promoted by employing the fundamentals of CE (Dong et al. 2014; Neves et al. 2020; Lu et al. 2020). Ur-IS has been incorporated into policy reports and recommendations to improve resource efficiency, eco-innovation, and green supply chains, among others (European Commission 2018; International Synergies 2019). For example, Tseng et al. (2018) argued that employing the IS technique will enable cross-industry partnerships comprising numerous supply chains in the CE model. In other studies, Domenech et al. (2019) discussed the potential of IS to contribute to Europe's transition to a CE, while Chen et al. (2022) concluded that IS has a positive effect on enhancing the circularity and sustainability of industrial parks in China.

The CE is also applicable to emerging economies, but it has been less studied in those contexts. As one prominent example, Türkiye's rising population and progress towards economic development and urbanization over the last three decades has created many challenges in waste management and underscored the need to shift to a more resource-efficient and environmentally friendly industrial structure. Türkiye's Eleventh Development Plan (2019) articulates that country's development vision, employing a long-term perspective and placing great importance on environmental sustainability goals and effective resource management. To achieve those goals, Türkiye's Circular Economy Platform: Türkiye Materials Marketplace (TMM), which is a public, online market designed to transfer used raw materials from one sector to another, was founded in 2019 (BCSD Türkiye 2019). Ur-IS is also included in Türkiye's regional policy documents to accomplish eco-efficiency and regional competitiveness goals (International Synergies 2019). To this end, many of Türkiye's national policy documents consider Ur-IS as a strategic tool for achieving these goals. Since Turkish industries are diverse and concentrated, there is a strong foundation for establishing effective Ur-IS (International Synergies 2019). Thus far, however, only two IS initiatives have been taken in the Cities of Iskenderun and Eskisehir. New research is needed to fully elaborate the potential for Ur-IS adoption in Türkiye.

Ur-IS is also included in Türkiye's regional policy documents to accomplish eco-efficiency and regional competitiveness goals (International Synergies 2019). Designated as a candidate for full membership for the European Union (EU) in 1999, Türkiye is building supportive institutions

and structures for potential Ur-IS initiatives. To this end, many of Türkiye's national policy documents consider Ur-IS as a strategic tool for achieving these goals. Nevertheless, they are not yet aligned in such a way that Ur-IS may be achieved effectively. However, since Turkish industries are diverse and concentrated, there is a strong foundation for establishing effective Ur-IS (International Synergies 2019). Thus far, only two pure IS initiatives have been taken in the City of Iskenderun and Eskisehir. Since IS has been identified as a critical instrument for the CE (European Commission 2018), new Ur-IS implementations are likely to be conducted in Türkiye. Therefore, to further boost Ur-IS adoption in Türkiye, new research is needed to elaborate its potential.

Despite many driving forces leading manufacturing and municipal supply chains to adopt Ur-IS around the world, there are also several restraining forces to its implementation (Gallaud and Laparche 2016; Cárcamo and Peñabaena-Niebles 2022). For example, while they vary depending on the context, key barriers could include technical, informational, organizational, regulatory, and infrastructural. In light of these barriers, addressing both the main drivers and barriers for Ur-IS initiatives through a comprehensive decision framework is critical. For example, Zhang et al. (2021) and Lahane et al. (2021) have argued that supply chain academics have paid little attention to the drivers and challenges in CE business models, including IS to enhance resource circularity, especially in the context of emerging countries. This is particularly critical in emerging countries given that they often have a weak legislative infrastructure (Sharma et al. 2019; Gedam et al. 2021; Ahmed et al. 2022). IS also deserves greater attention since it provides scope and opportunity for value recovery, which is also critical in emerging countries.

Despite its significance, our literature review in Section 2.2 suggested that there are few empirical studies (Golev et al. 2014; Bacudio et al. 2016; Sellitto et al. 2021; Sonel et al. 2022) that have investigated barriers to IS adoption. Among them, Bacudio et al. (2016)'s research is the only one that investigated the associations among driving and (or) challenging factors for IS adoption. The authors used DEMATEL to solely focus on the barriers to IS implementation in an industrial park in the Philippines. They suggested that lack of top management was the main causal barrier that may have an impact the other barriers. Since each country's experience with Ur-IS is unique, thus limiting the generalizability of the results, new studies should be conducted considering the peculiarities of specific countries. Türkiye is a developing country with distinct characteristics. Significantly, in 1995, Türkiye joined the European Union's Customs Union and in 1999, and it was designated as a candidate for full membership. Hence, Türkiye is subject to some direct regulatory adjustments from the EU.

The main purpose of this study is, therefore, to explore the potential for implementing Ur-IS in support of a CE in Türkiye through an integrated decision framework. This study poses four research questions (*RQs*):

RQ$_1$: What are the driving and restraining forces for Ur-IS adoption in Türkiye towards CE?
RQ$_2$: Is there an asymmetry between the driving and restraining forces for Ur-IS adoption in Türkiye?
RQ$_3$: What are the associations among the restraining forces to Ur-IS adoption in Türkiye
RQ$_4$: How do the findings aid decision-makers in increasing the effectiveness of Ur-IS implementation towards CE in Türkiye?

To address these *RQs*, this paper proposes a decision framework that integrates force field theory (FFT) of change with multi-criteria decision-making (MCDM). FFT of change considers each transition to a new state to be a "dynamic balance of forces" acting in opposite directions (Lewin 1951a, b). Change occurs when the total of the forces opposing change and the forces promoting change is uneven. FFT of change is grounded on the idea that any social situation is a balance of these forces. The proposed decision-making framework also recognizes that, when making multi-criteria decisions, researchers usually assess the link between factors using two different techniques. For example, the Decision-making Trial and Evaluation Laboratory (DEMATEL) approach suggests that only one of the two variables affects the other and assumes the inter-variable relationship as one-way (Kumar and Dixit 2018). Although several extensions to DEMATEL improve its robustness, that one-way view of assuming an inter-variable link is a limitation. In this study, Neutrosphopic-Interpretive Structured Modeling (N-ISM)-cross-impact matrix multiplication (MICMAC) is proposed to ensure more reliability, neutrality, and consistency by effectively measuring uncertainty among the forces (Dohale et al. 2023).

This study, enabled by its comprehensive methodology, contributes to the literature in the following ways: (1) Only one study has been undertaken so far to examine the relationships among the drivers and barriers of Ur-IS implementation in various countries. Nonetheless, no research has been conducted to systematically address the driving forces (DFs) and restraining forces (RFs) for the adoption of Ur-IS in Türkiye through the FFT of change. The conventional FFT of change in this research was strengthened by N-SAW to overcome the uncertainty of expert judgments. (2) The findings of the proposed N-SAW-based FFT were used to expose the relationships between the forces using the proposed Neutrosphopic Interpretive Structured Modeling (N-ISM)-cross-impact matrix multiplication (MICMAC), which is important because treating all forces simultaneously is unrealistic and infeasible. (3) Policy implications

for Türkiye's potential Ur-IS initiatives towards CE were developed based on the findings.

The following section provides background information on Ur-IS as well as the DFs and RFs for improving Ur-IS toward a CE via the FFT of change. Then, Sects. 3 and 4.1 introduce the proposed methodology and application, respectively. Section 5.1 discussed the findings, including the key implications of the research. Lastly, Section 6 provides conclusions.

2 Background

2.1 Urban and industrial symbiosis (Ur-IS)

The term IS refers to the exchange of residue flows created by one production process and intended for another, such that waste or by-products from one process become resources for another (Chertow 2000, 2007). IS has also been defined as a systems approach to a more sustainable and integrated industrial system that discovers economic possibilities through taking advantage of underutilized resources (Lombardi and Laybourn 2012). Simply put, IS links industries together that are traditionally disconnected via the physical exchanges of resources, energy, water, and/or by-products to gain competitive advantage. Although opportunities through IS are frequently made possible by proximity to one another, creating synergy between companies is absolutely necessary (Chertow 2007). Lombardi et al. (2012) noted that IS has taken many forms across the world, from top-down government mandates to bottom-up autonomous projects, from self-initiated synergies to aided and coordinated IS networks.

Physical movements of material, energy, and water are frequently at the heart of IS. However, information sharing, experience, capacity, and logistics are all key factors to IS's economic and environmental benefits. More specifically, IS helps to close the loop of industrial processes through (European Commission, 2018): (1) increasing the time the material/substance remains in usage, before it becomes waste, (2) decreasing the amount of waste delivered to a landfill or disposed of in nature, (3) rising energy and material efficiency, (4) creating jobs and business opportunities through alternative uses of existing waste streams, and (5) enabling innovation to support a CE.

There are two main types of IS initiatives (Baas 2011). The first is called a *self-organized activity,* which involves direct interaction among industrial entities. In a self-organized activity, a central entity plays an important role in network coordination by supplying a huge number of potentially useful by-products and acting as a de facto coordinator and link between entities. *Managed networks* are the second type of IS initiative, which are coordinated by a third-party intermediary. Managed networks are mainly classified into two distinctive domains. While facilitated networks work with existing companies to raise awareness of IS through a coordination node as a change agent, managed networks are created through a central plan to attract new businesses, generally offering shared infrastructure and services. More information on the successful implementation of IS is available in Chertow (2000), Rahman et al. (2016), Mallawaarachchi et al. (2020), Neves et al. (2020), Turken and Geda (2020), Scafa et al. (2020), and Lawal et al. (2021).

The European Commission (2018) has highlighted the substantial potential for IS in Europe, indicating the possibility of a dramatic increase in its implementation going forward. This supports the argument that moving towards a low-carbon, resource-efficient industry and society necessitates the development and implementation of additional IS-based business models. To that end, IS is recognized as a tool for supporting green growth and eco-innovation by the Organization for Economic Cooperation and Development (Lombardi and Laybourn 2012).

Moreover, the concept of urban symbiosis is a supplement to IS that encourages symbiotic alliances between companies in urban locations (Van Berkel et al. 2009). It transfers resources from urban areas to areas with industrial purposes (Dong et al. 2014). It is argued that combining Ur-IS will bring enhanced resource efficiency in urban and industrial regions one-step closer. Simply put, by emphasizing the Ur-IS synergy rather than each industrial or urban symbiosis implementations alone, one can optimize the overall benefits of the symbiotic relationship (Lu et al. 2020).

2.2 Force field theory of change for building ur-is towards a CE

Kurt Lewin (1951a, b)'s approach for rationalizing change, which viewed organizational beliefs and actions as a dynamic equilibrium, provides the conceptual foundation for FFT of change. According to this behavioral approach, change occurs whenever there is an asymmetry between the total of the forces against change (*RFs*) and the sum of the forces for change (*DFs*). An imbalance might result from a change in the magnitude or direction of any of the forces, or the addition of a new force (Erol et al. 2022). Priorities and goals are established when the factors for and against change have been identified.

To structure Ur-IS adoption in Türkiye through FFT of change, we searched the literature for previous work on possible DFs and RFs for implementing Ur-IS. The following keywords directed our search in major databases: "drivers for Ur-IS", "restraining forces for Ur-IS", "barriers for Ur-IS", and "challenges for Ur-IS". Our review was limited to peer-reviewed academic papers through August 2022.

Tables 1 and 2 provide the descriptions and references for *DFs* and *RFs*, respectively.

The results of our comprehensive literature analysis demonstrated that most of the studies (Chertow 2000; Sakr et al. 2011; Rahman et al. 2016; Paivarinne and Lindahl 2016; Mortensen and Kørnøv 2019; Fraccascia et al. 2019; Huang et al. 2019; Mallawaarachchi et al. 2020; Neves et al. 2020; Turken and Geda 2020; Chertow et al. 2021; Lybæk et al. 2021; Lawal et al. 2021; Demartini et al. 2022; Cárcamo and Peñabaena-Niebles 2022) on Ur-IS are either conceptual or review-based.

Barriers to IS adoption have previously been empirically studied. Golev et al. (2014) performed an analysis using an IS maturity grid. In their study, the authors conducted a series of interviews with experts in Gladstone, Australia, and they concluded that commitment to sustainable development and cooperation were the most important barriers to IS implementation. Bacudio et al. (2016) conducted the only study exploring associations among the barriers to IS adoption using a quantitative method. They employed DEMATEL through data gathered from experts employed in an industrial park in the Philippines. They concluded that lack of top management was the main causal barrier with the potential to influence the others. The major limitations of Bacudio et al. (2016) are as follows: (1) The authors employed the traditional DEMATEL approach, which does not consider the uncertainty of the expert opinions. Fuzzy or rough extensions can be integrated with DEMATEL to address the ambiguities in the expert data. (2) The authors used DEMATEL to solely focus on the barriers to IS implementation in an industrial park in the Philippines. They suggested that lack of top management was the main causal barrier that may have an impact the other barriers. Since each country's experience with Ur-IS may be unique, thus limiting the generalizability of the results, new studies should be conducted considering the peculiarities of specific countries.

Ji et al. (2020) investigated the inhibiting and driving factors for enterprises to participate in symbiotic relationships through a survey study in China. They argued that lack of resources, lack of regulations and incentives, and lack of coordination among companies were the most significant hindering factors. In another study, Sellitto et al. (2021) conducted interviews with the managers of several manufacturing companies in Brazil to explore the enablers and challenges for IS adoption. They determined that excessive cost, discontinuity risk, and imbalance between availability and demand were the most vital barriers to symbiotic relationships in Brazilian manufacturing industries. Lastly, Sonel et al. (2022) explored the factors affecting IS collaboration. To this end, they identified the collaboration factors through a literature analysis and then ranked them using analytic hierarchy process. They concluded that environmental factors were the most essential.

Finally, our literature review shows that only Bacudio et al. (2016) analyzed the linkage among inhibiting factors of IS adoption in industrialized and (or) developing nations. Mallawaarachchi et al. (2020), Turken and Geda (2020), Zhang et al. (2021), and Ahmad et al. (2023) argued that new theory-based quantitative research is needed to demonstrate not only the barriers but drivers in implementing symbiotic alliances to enhance resource circularity in various countries. Hence, the major goal of this research is to propose an integrated decision framework to investigate the possibilities for deploying Ur-IS in the emerging country of Türkiye.

3 Methodology

This study uses an integrated decision framework that combines qualitative and quantitative research methods to address the research questions. Figure 1 depicts the approach adopted for acquiring, evaluating, and processing data. First, via the proposed *Neutrosophic Simple Additive Weighting (SAW)-based Force Field Theory of Change*, the DFs and RFs for IS adoption in Türkiye are evaluated. Then, using the proposed *ISM-MICMAC* in a neutrosophic environment with single-valued triangular neutrosophic numbers (SVTNN), the relationships between the forces are studied, allowing decision-makers to recommend strategies for effective IS implementation in Türkiye. Finally, the findings are validated utilizing the *Nominal Group Technique (NGT)*. We believe that it makes a significant contribution to the literature as it is the first study in which this integrated model is used.

The FFT of change has not, however, been used to systematically address the DFs and RFs behind the adoption of Ur-IS in Türkiye. N-SAW was used in this study to strengthen the traditional FFT of change in order to combat expert judgment uncertainty. Because handling all forces concurrently is impracticable and impractical, the results of the suggested N-SAW-based FFT were used to reveal the relationships between the forces utilizing the proposed Neutrosphopic Interpretive Structured Modeling (N-ISM)-cross-impact matrix multiplication (MICMAC).

The fundamental idea behind the SAW technique is to calculate a weighted average of how well each alternative performs across all criteria (Deni et al. 2013). The neutrosophic set (NS) can address the imprecise, ambiguous, and inconsistent information frequently appearing in real-world decision-making issues more effectively than the traditional fuzzy set model (Ali and Smarandache 2017).

In addition, ISM and MICMAC offer a decision support to visually display undesirable elements, challenges, and barriers in a system using hierarchical graphics using the associations between them. A graph of directed relationships is used to pinpoint a problem's underlying causes. To achieve this, the root causes of an issue are identified, and mutual relationships based

Table 1 Driving Forces (DF_s)

Driving Forces	*Descriptions*	*References*
The need for less waste and higher resource efficiency (DF_1)	Businesses, supply chains, and city municipalities should employ novel waste reduction policies to reach higher levels of resource efficiency so that they can maintain a lean structure and achieve competitive advantage. For example, as a novel approach to bolster CE, Ur-IS has potential to yield enhanced resource efficiencies	Aparisi (2010), Sakr et al. (2011), Lombardi and Laybourn (2012), European Commission (2018), International Synergies (2019), Turken and Geda (2020), Sellitto et al. (2021)
Availability of innovative approaches for reducing costs (DF_2)	New alternative strategies, such as Ur-IS, can contribute to cost reductions. For example, cost savings occur due to reductions in landfill diversions, virgin material use, water consumption, and hazardous material use and generation through Ur-IS adoption	van Beers et al. (2008), Chertow and Ehrenfeld (2012), Rahman et al. (2016), International Synergies (2019)
New laws and regulations (DF_3)	Environmental laws and regulations have been the primary impetus for improving circularity in industrial eco-systems, assisting in construction of pollution control and eco-friendly methods by altering the costs of pollution and cleaner manufacturing. New regulations including the European Waste Framework Directive have been enacted, which requires companies to take actions to shift the way they manage their operations. Compliance with them must be ensured	Gibbs and Deutz (2007), Aparisi (2010), Sakr et al. (2011), Lombardi et al. (2012), Tseng and Bui (2017), European Commission (2018), International Synergies (2019), Turken and Geda (2020)
The need for enhanced eco-innovation (DF_4)	Eco-innovation contributes to the diffusion of knowledge by enabling the transfer of knowledge between different entities and increasing collaboration between industrial companies and research institutions. In other words, eco-innovation can improve the sustainability of a business by actively promoting innovation and technological change. Novel tools, such as Ur-IS, bolster the eco-innovation capabilities of companies and supply chains through providing enhanced resource efficiencies	van Beers et al. (2008), Ghisellini et al. (2016), Fang et al. (2017), Govindan and Hasanagic (2018)
Changing strategies towards the CE (DF_5)	Linear business models leading to resource inefficiencies are no longer acceptable. Transitioning to a CE through eco-innovative strategies, including IS, is an aspiration for economies around the world. Supply chains can increase their CE performance through providing benefits such as CO_2 reduction, water savings, waste reductions, and resource efficiency. This can yield a improved competitive advantage against their rival chains	Gibbs (2003), Valentine (2016), Velenturf (2016), Ghali et al. (2017), Herczeg et al. (2018), European Commission (2018)
The need for more collaboration and trust (DF_6)	Supply chains require innovative strategies to improve mutually beneficial collaboration with other organizations. Moreover, effective strategies are grounded in trust between entities. As trust strengthens, it can provide a basis for even deeper collaborations. Ur-IS has the potential to improve collaboration among organizations	European Commission (2018), Symbiosis Center Denmark (2020)
Maintaining better corporate image (DF_7)	Contributing to a CE has the potential to improve corporate reputation. This can ultimately lead to better employee and customer retention, among other bottom-line benefits. More specifically, substantively implemented Ur-IS offers companies a means to enhance their corporate image and strengthen their credibility with existing customers and new potential customers	Lowe (2001), Mirata et al. (2005), Shi et al. (2010), Ohnishi et al. (2017)

Table 1 (continued)

Driving Forces	*Descriptions*	*References*
Rising stakeholder awareness for sustainability (DF_8)	Stakeholders are increasingly aware of the potential economic, environmental, and social benefits that may arise from the implementation of CE. Pressure from internal and external stakeholders can make senior managers are more likely to implement CE and IE-related business models, including Ur-IS	Grant et al. (2010), Valentine (2016), Velenturf (2016), Herczeg et al. (2018)
Availability of new technologies for greater integration (DF_9)	New technologies such as blockchain, internet of things, 3D manufacturing, and artificial intelligence are available for to strengthen supply chain integration, traceability, trust, and collaboration. Hence, as awareness and capacity increase, and implementation costs drop, growing accessibility to new technologies provide a further incentive to improve integration among organizations through Ur-IS	Lombardi and Laybourn (2012), Valenzuela-Venegas et al. (2016), European Commission (2018), Yazan and Fraccascia (2019)
The need for increased CE performance (DF_{10})	Through the ongoing transition from linear business models to a CE, supply chains have been trying to improve their CE performance. For example, new strategies, including IS, are needed to improve resource efficiency and to create value from waste, such as shared infrastructure and by-products. Supply chains must find better ways to recover the value of byproducts and waste in order to make the transition to an effective CE	Fichner et al. (2005), Valenzuela-Venegas et al. (2016), European Commission (2018)
Shifting competitive focus (DF_{11})	Companies must recognize that there are opportunities to collaborate on pre-competitive and mutually beneficial issues. This new strategy ensures that supply chains build an effective ecosystem through trust and integration. Effectively implemented Ur-IS can bolster cooperation	Aparisi (2010), Lombardi and Laybourn (2012), Valenzuela-Venegas et al. (2016), Neves et al. (2020), Wadström et al. (2021)
The need for providing more social benefits (DF_{12})	Innovative CE-based tactics and platforms, such as IE and Ur-IS, are required to expand job possibilities, improve working conditions, and, ultimately, contribute to improved societal welfare. As a result of CE implementation, societal sustainability should improve with time	Lowe (2001), Mirata et al. (2005), Valenzuela-Venegas et al. (2016), European Commission (2018)
New business model opportunities (DF_{13})	New Ur-IS -based business models for organizations have lately become accessible, assisting them in changing their view about industrial wastes. Companies must adopt a new mindset that views waste as a potential resource, though this will require continued improvements in collaboration and technical advancement	Aparisi (2010), Lombardi and Laybourn (2012), European Commission (2018), International Synergies (2019), Turken and Geda (2020), Sellitto et al. (2021)

on the strength of their influence are demonstrated (Shanker and Barve 2021). Note that assessing the causal linkages of the listed variables requires expert opinions. Experts, however, frequently struggle to find a connection or express confidence in a notion. Although this is a well-known issue, it is not widely explored . To address this problem, Smarandache introduces neutrosophy as an expansion or combination of fuzzy logic that also takes into account indeterminacy (Smarandache 1999). While fuzzy logic solely evaluates membership in terms of existence or absence, neutrosophic sets can attribute concepts when there are relationships between undefined concepts (Kandasamy and Smarandache 2003). Simply put, Neutrosophic Sets (NSs) are utilized to enhance the previous tools, including intuitionistic fuzzy sets by addressing the ambiguities more precisely (Sodenkamp et al. 2018). NS has the following benefits (Deli 2017; Abdel-Basset et al. 2018; Sodenkamp et al. 2018): Firstly, it depicts the degree of vagueness, which aids decision-makers in better conveying their thoughts. Second, it demonstrates the degree of disagreement among decision-makers. To reduce inconsistencies or correct discrepancies in expert choices and promote consistency, the NS-based approach combines the diverse interests of decision-makers into a single viewpoint. Third, NSs reveal positive, negative, and uncertain information more successfully than traditional and intuitionistic fuzzy sets. Lastly, indeterminacy in NSs resulting from uncertain and inconsistent data can be better addressed since it is accurately measured.

This study integrates traditional *FFT of Change* with *Neutrosophic SAW* based on Ajay et al. (2019) to calculate the total scores of DFs and RFs. Expert opinions are required in such analyses as the FFT are subject to idiosyncratic evaluations, which can lead to substantial uncertainty in the decision-making process (Dutta and Guha 2015).

3.1 Neutrosophic SAW-based FFT of change

The FFT of change, introduced by Kurt Lewin (Lewin 1951a, b), is a problem solving and action planning technique to boost a decision-making process (Schewering 2003). In a dynamic context, Lewin's FFT depicts two sets of forces: RFs that attempt to maintain the status quo and DFs that push for change (Chen et al. 2017). The FFT framework aids in the identification of both DFs and RFs, as well as what needs to be done to balance the two forces and attain what Lewin referred to as equilibrium (Mak and Chang 2019). Figure 2 illustrates the FFT structure with RFs and DFs .

FFT of Change may be accomplished in stages (Chen et al. 2017; Mak and Chang 2019). First, all forces in favor of change (DFs) and opposed to change (RFs) on one side are identified. Then, the total scores on each side are assessed through calculating the impact of each force. If the overall score of DFs is higher than that of RFs, the organization is more likely to execute to new strategy. Otherwise, measures to address the imbalance should be undertaken.

This research employs *Neutrosophic-SAW* to compute the aggregate scores of DFs and RFs. SAW, developed in 1945 by Churchman and Ackoff, was first used to address the portfolio problem (Ajay et al. 2019). Traditional *SAW* is a basic and straightforward MCDM method that ranks alternatives by additive aggregation of their performance values under all criteria (Anggraeni et al. 2018). However, crisp numbers in *SAW* may not always help decision-makers address uncertainty and subjectivity effectively (Stevic et al. 2019). To address, this study employs the neutrosophic SAW (*N-SAW*) method, combining the SAW method and single-valued triangular neutrosophic numbers (SVTNN) (Ajay et al. 2019):

Step 1. Determine the criteria (factors/forces) C_j from a group of experts E_k for the decision-making problem.

Step 2. Select the relevant truth, intermediacy, and falsity membership rating values of each criterion based on the single-valued triangular neutrosophic numbers (SVTNN) (Table 3).

Step 3. Calculate the average (L_j^i), defuzzified (e) and normalized (w) values of the neutrosophic score of single-valued triangular numbers $(p_1^1, q_1^2, r_1^3), \left(p_2^1, q_2^2, r_2^3\right), \ldots\ldots, \left(p_j^1, j_j^1, q_j^1\right)$ of each criterion through Eqs. (1–3).

$$\left(L_j^i\right) = \frac{\left(p_{1+\ldots\ldots}^i p_{2+}^i p_{j+}^i\right)}{j}, \; wherei = 1, 2, 3. \tag{1}$$

$$e = \frac{p + q + r}{3},$$

where

$$p = \left(L_j^1\right), q = \left(L_j^2\right), r = \left(L_j^3\right), \tag{2}$$

$$w = \frac{e_i}{\sum e_i} \tag{3}$$

Step 4. Find the centroid value as Eq. (4) where α, β, and λ are normalized weighted values of truth, intermediacy, and falsity membership functions, respectively.

$$w_j = \frac{\alpha + 2\beta + \lambda}{4} \tag{4}$$

3.2 Neutrosophic interpretive structural modeling (N- ISM)

Once *Neutrosophic SAW-based Force Field Theory* was conducted, *N-ISM-MICMAC* was proposed to assess the relationships between the RFs to IS implementation in

Table 2 Restraining Forces (RF_s)

Restraining Forces	*Descriptions*	*References*
Lack of policies and top management commitment (RF_1)	Organizational rules, goals, and performance indicators must motivate managers to design and engage in Ur-IS initiatives. This can boost the company's long-term sustainability. Lack of rules and dedication to CE-based business models result in poor operational bottom-lines	Chiu and Yong (2004), Gibbs and Deutz (2007), Golev et al. (2014), Li et al. (2015)
Negative effect of existing culture (RF_2)	To transition from an individualistic attitude to a cohesive CE system, businesses and orgaizaions must undertake a considerable cultural revolution. While not completely abandoning competition, of course, they much move to more cooperative and collaborative cultures. Current cultural characteristics can make wide adoption of collaboration-based CE techniques difficult	Gibbs and Deutz (2007), Aparisi (2010), Sakr et al., (2011), Paquin et al. (2014), Kosmol and Otto (2020)
Lack of knowledge and proper training (RF_3)	Stakeholders' primary emphasis is on their core businesses, which is the most significant impediment to the complete creation and execution of CE-based plans. A lack of means to educate prospective stakeholders generally causes a lack of knowledge of CE-based tactics and concepts	Chiu and Yong (2004), Gibbs and Deutz (2007), Sakr et al. (2011), Li et al. (2015), Notarnicola et al. (2016)
Lack of effective information system (RF_4)	CE and its accompanying techniques may be characterized as a process of learning in which cross-company collaboration fosters knowledge interchange and integration. The lack of an adequate information system has a detrimental influence on successful communication and information sharing with other supply chain players	Heeres et al. (2004), Dong et al. (2016), Fraccascia and Yazan (2018), Harris and Pritchard (2004), Kosmol and Otto (2020), Ferreira et al. (2023)
Lack of incentives and regulations (RF_5)	Inter-company collaboration and the sharing of potentially beneficial by-products and wastes are sometimes hampered by a lack of incentives and regulations. Because specific permissions and licenses are usually necessary to interchange items categorized as waste, the absence of distinction between wastes and secondary materials under EU-based legislation restricts the exchange, reuse, and recycling of wastes across firms	Gibbs and Deutz (2007), Dong et al. (2016), Aparisi (2010), Costa et al. (2010), Lehtoranta et al. (2011), Sakr et al. (2011), Lombardi and Laybourn (2012), Sharma et al. (2019)
Lack of short-term economic benefits (RF_6)	Financial hurdles might limit short-term gains even for technically viable strategies, due to the cost of Ur-IS projects compared to other kinds of waste disposal or treatment, as well as landfill prices. In Türkiye, landfill costs are currently low, and dumping remains a cost-effective choice (landfill cost has been growing in the past years, and it is expected to do so in future). Ur-IS implementation may be a lengthy and difficult process	Gibbs (2003), Heeres et al. (2004), Aparisi (2010), Lombardi and Laybourn (2012)
The need for high investment (RF_7)	Waste to raw material conversion may necessitate additional investments since it frequently demands the purchase of new equipment that must be operated and maintained. However, financial resources are sometimes in short supply in promoting Ur-IS	Sakr et al. (2011), Chiu and Yong (2004), Aparisi (2010), Gallaud and Laparche (2016), International Synergies (2019)

Table 2 (continued)

Restraining Forces	*Descriptions*	*References*
Lack of geographical proximity (RF_8)	Geographical vicinity is beneficial to building IS. This can lower transportation costs, which can be a factor in waste exchange, but can also help build trust between organizations by making information sharing and informal monitoring simpler and less expensive. Therefore, establishing collaborative ties may be hampered by a lack of proximity	Baas and Boons, (2004), Heeres et al. (2004), Paquin et al. (2014)
Lack of infrastructure (RF_9)	Well-built infrastructure is required for long-term waste, energy, and by-product interchanges. IS exchanges, for example, may be challenging since by-product transformations and adjustments must be completed prior to exchange. The potential pathways for waste streams are hampered by a lack of human capital, infrastructure (especially R&D labs), and technical resources	Aparisi (2010), Li et al. (2015), Gallaud and Laparche (2016), Singh et al. (2018), Agudo et al. (2023)
Inability or unwillingness to share information (RF_{10})	Stakeholders may have multiple competing objectives, with could contribute to a lack of information sharing. Furthermore, due to privacy or competitive concerns, businesses may be hesitant to provide information	Sakr et al. (2011), Levanen and Hukkinen (2013), Paquin et al. (2014), Gallaud and Laparche (2016), Kosmol and Otto (2020)
Inflexible organizational systems and processes (RF_{11})	Businesses may not have the flexibility to change their operations to meet Ur-IS 's demands. Ineffective Ur-IS implementation may result if this sort of flexibility is not available	Aparisi (2010), Li et al. (2015), Singh et al. (2018), Kosmol and Otto (2020)
Lack of trust and collaboration among organizations (RF_{12})	In symbiotic supply chains, trust is at the heart of the network and serves as a fundamental mechanism for collaboration. An Ur-IS initiative is grounded in shared objectives and common values. As a result, one of the most significant obstacles to establishing a successful Ur-IS is a lack of trust. The lack of trust between actors makes it difficult for them to interact and collaborate	Gibbs et al., (2005), Chertow and Lombardi (2005), Park et al. (2008), Aparisi (2010), Sakr et al. (2011), Paquin et al. (2014), Neves et al. (2020)
Vulnerability and supply uncertainty (RF_{13})	The proliferation of eco-industrial projects is inhibited by risk and uncertainty. IS necessitates a new manner of doing business, which may result in some operational unpredictability. Cooperation between enterprises means increased levels of interdependency and IS increases supply risk uncertainty. Mitigation strategies are also currently lacking	Gibbs (2003), Babazadeh et al. (2017), Li et. al. (2017), Neves et al. (2020), Turken and Geda (2020)
Lack of a facilitator (RF_{14})	Facilitators lead the implementation of Ur-IS projects. They may come from the private or public sectors, to aid in forming and maintaining symbiotic relationships. Absence of facilitators may cause ineffectiveness during the implementation of Ur-IS	Fraccascia et al. (2019), Turken and Geda (2020)

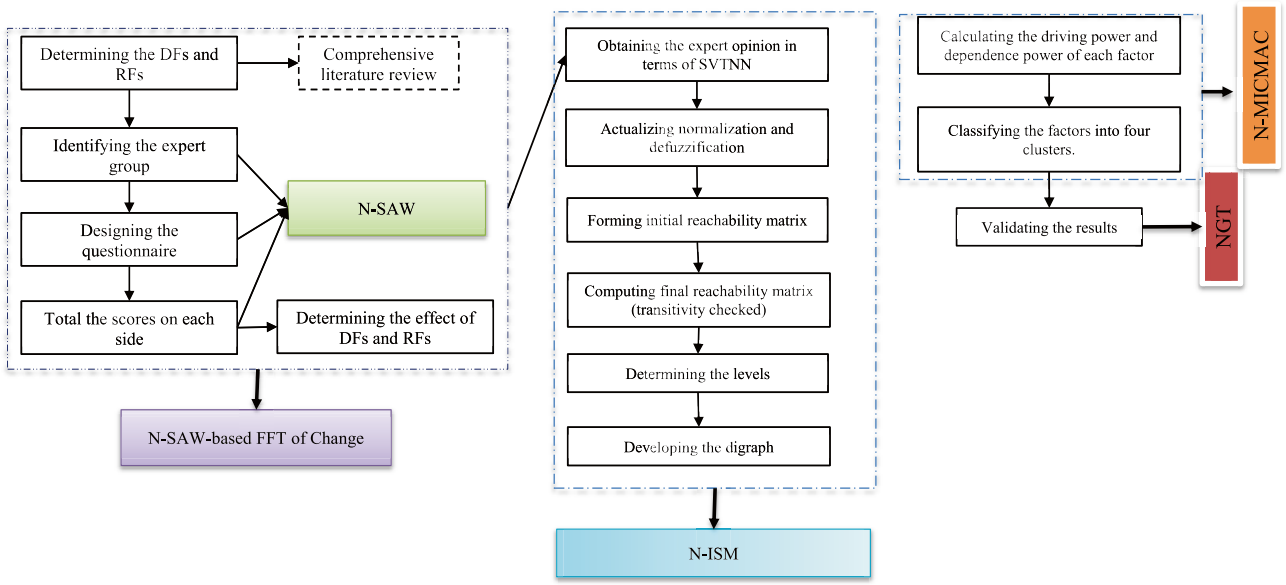

Figure 1. The Proposed Methodology

Fig. 1 The Proposed Methodology

Türkiye. By developing a hierarchical structure model, Warfield (1974) established the interpretative structural modeling (ISM) technique, which is used as a complex system analysis tool to find underlying interaction links among individual parts (Song et al. 2017). The mathematical foundation of the ISM methodology includes digraphs theory, the expert elicitation technique, matrix operation theory, and computer assisted computation. ISM uses the digraph theory to depict the system components and associations among them (Chang et al. 2013). The traditional ISM method is based on the contextual linkages among the system units, which are identified by assuming that each pair of system units has only a binary relationship. However, it overlooks the strength of contextual links between system components and has an influence on expert judgment elicitation results for system unit relationships (Parameshwaran et al. 2015). In this study, the SVTNN is incorporated into the ISM technique because the SVTNN can better cope with expert judgment information (Tseng 2013). The phases of the proposed *N-ISM* method are outlined with help of Wang et al. (2018) Jain and Raj (2021), Srivastava and Dashora (2021), and Yadav and Singh (2020).

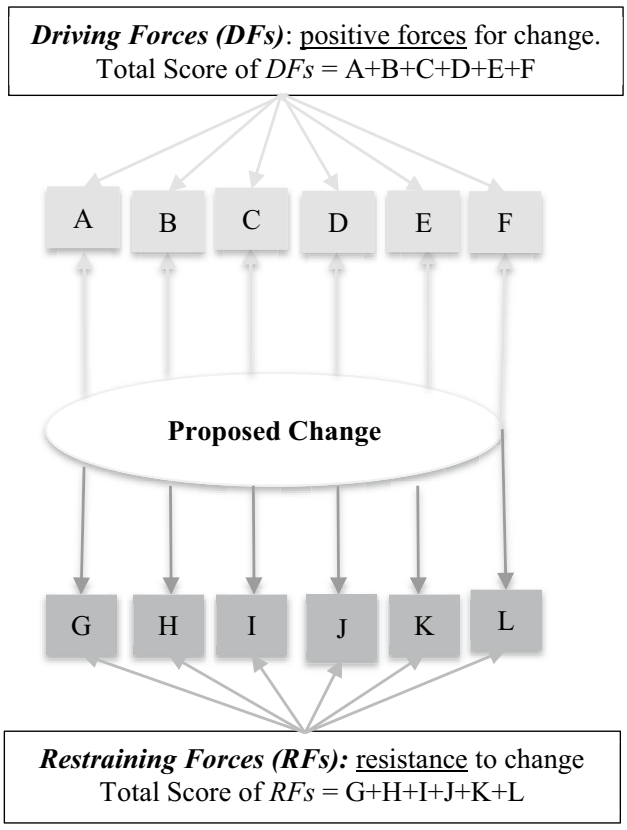

Fig. 2 FFT of Change Framework

Step 1. Identifying the Criteria (Factors/Forces): Define the set of criteria as *C*.

Step 2. Obtaining the expert opinion in terms of SVTNN: Once the criteria (factors/forces) have been determined, the bilateral relations are evaluated by the experts using the linguistic variables in Table 4. There may be one-way or two-way interaction between the criteria, or they may be independent of each other. These cases are represented using the notation below.

Table 3 Linguistic terms and their corresponding SVTNN

Linguistic Terms		*SVTNN*		
		Truth-membership (T)	Intermediacy-membership (I)	Falsity-membership (F)
1	Very Low (VL)	0.00	1.00	1.00
2	Medium Low (ML)	0.17	0.85	0.83
3	Low (L)	0.33	0.75	0.67
4	Medium (M)	0.50	0.50	0.50
5	High (H)	0.67	0.25	0.33
6	Medium High (MH)	0.83	0.15	0.17
7	Very High (VH)	0.00	1.00	1.00

Table 4 *SVTNN* Scale

Linguistic Terms		*SVTNN*		
		Truth-membership (T)	Intermediacy-membership (I)	Falsity-membership (F)
4	Very high influence (VH)	0.90	0.10	0.10
3	High influence (H)	0.80	0.20	0.15
2	Medium influence (M)	0.50	0.40	0.45
1	Low influence (L)	0.35	0.60	0.70
0	No influence (N)	0.10	0.80	0.90

Note that the geometric mean technique is used to reveal the strength of any contextual link between two components displayed in Eq. (5). The ultimate intensity of any two-factor contextual associations may be characterized as Y_{ij} where the parameter x_{ij} is the expert's opinion of the power of contextual link between the factor *i* and factor *j*

V criterion i affects criterion j (i to j there is a one-way relationship).

A criterion j affects criterion i (from j to i there is a one-way relationship).

X criteria *i* and *j* affect each other (there is a bidirectional relationship between *i* and *j*).

O *i* and j criteria do not affect each other.

$$Y_{ij} = \frac{\sum_{m=1}^{k} x_{ij}}{k} \tag{5}$$

Step 3: Actualizing normalization and defuzzification: Then, the normalization and defuzzification processes are conducted using procedures adopted from Srivastava and Dashova (2021) and Wang et al. (2018).

Step 4: Forming initial reachability matrix: In the fourth stage, the reachability matrix should be created. To obtain this matrix, the numerical values of 1 and 0 are used instead of the linguistic variables we expressed in step 2. That is, 1 is used if criterion *i* affects criterion *j*. However, if criterion *i* does not affect criteria *j*, 0 is utilized. In this system, since the definition is made unidirectional from *i* to *j*, the entire matrix area must be filled.

Step 5: Computing the final reachability matrix (transitivity checked): The transitivity of the connections between the criteria should be checked. For example, suppose that a unidirectional relationship is defined from criterion C_3 to criterion C_2. On the other hand, suppose also that from C_2 to C_5 a one-way relationship is defined. In this case, it can be concluded that there is a relationship from C_3 to the C_5, according to the transitivity feature. The final reachability matrix is formed by repeated matrix multiplication operations until the reachability matrix becomes stationary.

Step 6: Determining the levels: After the final reachability matrix has been obtained, leveling is performed. For this separation, reachability set, antecedent set, and intersection sets for each criterion should be calculated. The reachability set contains a criterion itself and all the criteria it accesses with arrows coming out of it while the antecedent set includes a criterion itself and other criteria that can access this variable. The intersection set is the intersection of the reachability and antecedent sets for each criterion. If the accessibility set and the intersection set are equal for a criterion, then the level of this criterion is *I*.

Step 7: Developing the digraph: In this step, an ISM model based on the final reachability matrix is drawn. Then, the transitive relations are removed from the graph. Lastly, the theoretical conflicts of the ISM model are investigated, and the needed adjustments on the model are made.

3.3 N-MICMAC

In this study, once the proposed *N-ISM* has been finalized, the *Matrix of Cross Impact Multiplications Applied to Classification* (MICMAC) is used. *MICMAC* is based on matrices' multiplication characteristics to compute the driving and dependence power of each force. In other words, MICMAC is utilized to categorize the RFs in terms of their driving and dependence powers. In this study, the SVTNN are integrated with the MICMAC approach. This section discusses the *Neutrosophic (N)-MICMAC* approach briefly:

Step 1. Calculating the driving power and dependence power of each factor: The driving power for each factor may be calculated by totaling each row of the final reachability matrix, while the dependence power for each factor can be computed by adding each column of the final reachability matrix (Wang et al. 2018). They are calculated by solving the following formulas (Eqs. 6–7).

$$DR - p_i = \sum_{j=1}^{n} \pi'_{ij} \tag{6}$$

$$DE - p_j = \sum_{i=1}^{n} \pi'_{ij} \tag{7}$$

$DR - p_i$ and $DE - p_j$ signify the driving power and dependence power of each criterion, respectively. π'_{ij} denotes element of final reachability matrix.

Step 2: Classifying the factors into four clusters: The factors can be categorized into four clusters based on their driving and dependence power. These clusters are provided as follows (Baykasoglu and Golcuk 2017): Autonomous factors, which have few interactions with other factors, indicate weak dependence and weak driving power. Dependent factors with strong dependencies on other factors represent weak driving power and strong dependence power. Linkage factors possess strong driving and dependence power. They affect other factors, while other factors also influence them. Lastly, driving factors significantly affect other factors. In other words, they have strong driving power but weak dependence power.

3.4 Validation using nominal group technique (NGT)

This research employs *NGT* to validate the findings. *NGT* is a qualitative approach to obtain stakeholder assessment employing both individual and group opinions. In other words, *NGT* provides a prioritized list of actions and/or policy recommendations (Rankin et al. 2016). *NGT* has been implemented in various ecosystems including healthcare services (Holmes et al. 2012), consumer preference research (Coker et al. 2014), and health promotion (Hutchings et al. 2013). *NGT* is beneficial for identifying problems, developing solutions, and generating priorities (Delbecq and Van de Ven 1971).

4 Application and the findings

In this study, the methodology exhibited in Fig. 1 was employed. The results are presented in the following sub-sections.

4.1 Identifying the DFs and RFs

To begin, the previous literature on potential DFs and RFs for Ur-IS implementation was reviewed. Based on the findings of this search, a thorough list of DFs and RFs was identified to provide a basis for studying Ur-IS adoption in Türkiye through *FFT of Change*. The DFs and RFs are provided in Tables 1 and 2, respectively. These findings address the first research question (RQ_1).

4.2 Neutrosphopic-SAW-based FFT of change

The next stage involved calculating the score of each DF and RF through *Neutrosphopic-SAW*. To accomplish this, the DFs and RFs identified in Section 4.2 were used. Next, as shown in Table 5, we formed a group of experts to create a robust FFT via expert judgments (Shafaghat et al. 2021). Due to potential biases and information gaps, understanding the factors influencing a policy's success is challenging. A brainstorming of forces, on the other hand, can assist the expert group in understanding how each DF and RF potentially impacts the strategy they're contemplating (Thomas 1985).

There is no hard and fast method for identifying the optimal number of experts to contact. While the ideal number of experts in such studies is therefore unclear (Bulut and Duru 2018; Erol et al. 2022), the large number of experts with a range of relevant experiences in this study provide a strong basis for addressing the research questions.

After providing the initial list of the DFs and RFs through a literature review, a virtual 30-min meeting was held. In that meeting, the expert panel evaluated the DFs and RFs for relevance and completeness and agreed that no adjustments were necessary. To avoid group members interacting with one another, questionnaires were formed and distributed to the Expert Group via an online platform once the DFs and RFs were ready. The experts were requested to rate the significance of DFs and RFs through a 1–7-point Likert scale.

After obtaining the experts' responses, the N-SAW was used as given in Section 3.1. Finally, the individual and overall scores for DFs and RFs were computed as provided in Table 6.

Our findings in Table 6 suggested that DF_3 (New laws and regulations), DF_5 (Changing strategies towards CE) and DF_{10} (The need for increased CE performance) turned out to be the most significant DFs, while RF_1 (Lack of policies and top management commitment), RF_5 (Lack of incentives and regulations), RF_{12} (Lack of trust and collaboration among organizations) and RF_{14} (Lack of a facilitator) were the most essential RFs. Lastly, because the overall score of RFs exceeds that of DFs, it is necessary to explore the associations among the RFs. These findings address the second research question (RQ_2).

4.3 Neutrosphopic-ISM

This stage of the research used *Neutrosphopic-ISM* to identify the relationships amongst the *RFs*. The expert panel was given the *Neutrosphopic-ISM* questionnaire, which was designed to evaluate how RFs interact with each other. The experts used the scale in Table 4 to answer the questions. After the expert group's responses were collected and aggregated, the *Neutrosphopic ISM* method's process stages were implemented in the order listed in Section 3.3.

Table 5 The Expert Group

Members	*Size*	*Features*
Faculty members	17	They are scholars at several engineering and business schools in Türkiye, who have performed research on industrial symbiosis and other CE-based business models.
Governmental officers	13	They work for the Ministry of Industry and Technology in Türkiye. So far, they have participated in projects on industrial ecology and symbiosis towards an enhanced CE in Türkiye.
Top managers	18	They have a minimum of 6 years of practical experience on sustainability, industrial ecology, and circularity.
Sustainability experts employed for various urban municipalities	15	They are professionals who have performed projects towards CE and CE-related business models.

First, clarification and normalization processes were carried out. Next, as shown in Table 7, the N-initial reachability matrix was created by the evaluations in the matrix using the opinions provided by the majority of the experts, as in the study of Ravi and Shankar (2005). In other words, they are the most repeated values by the experts in the expert group in Table 7.

In the following stage, the stages listed in Section 3.3 were followed in order. To this end, first the transitivity was checked. Then, the final reachability matrix was created as shown in Table 8.

By using the final reachability matrix, the reachability, antecedent and intersection sets are obtained. According to these sets, a 6-step interaction model between *RFs* is developed as presented in Fig. 3.

The interactions among the RFs are indicated according to the direction of the arrows. For example, Fig. 3 indicates that RF_7 is affected by the rest of the *RF*s. In another example, note that RF_6 and RF_{10} affect each other.

4.4 Neutrosphopic-MICMAC

In this section, driving and dependence power values for RFs were calculated using Eqs. (6) and (7), as provided in Table 9. Considering the DR and DE values, the criteria were divided into four groups as in Fig. 3.

According to Fig. 4, the clusters can be summarized as follows: Lack of policies and top management commitment (RF_1), Lack of incentives and regulations (RF_5), Vulnerability and supply uncertainty (RF_{13}), and Lack of geographical proximity (RF_8) turned out to be the RFs with high driving powers. Linkage RFs with high driving and dependent powers are: Negative effect of the existing culture (RF_2), Lack of knowledge and proper training (RF_3), Lack of effective information system (RF_4), Lack of infrastructure (RF_9), Inflexible organizational systems and processes (RF_{11}), Lack of trust and collaboration among organizations (RF_{12}), and Lack of a facilitator (RF_{14}). Lastly, Lack of short-term economic benefits (RF_6), The need for high investment (RF_7), and Unwillingness to share information (RF_{10}) were found to be the most dependent RFs with higher dependence powers.

4.5 Validation through NGT

A validation through a virtual *NGT* was conducted to validate the results obtained in the proposed *N-ISM-MICMAC*. To achieve that, the expert panel was initially given the findings shown in Fig. 3 as a starting point. After that, they participated in a virtual meeting for around 40 min. This online meeting was conducted in September 2022. During the meeting, the driving, linkage, and dependent challenges were explained to the expert group. Then, they examined and discussed their reasonableness. Finally, after reaching agreement on the validity of the findings, they concluded that no adjustment was required.

5 Discussion and implications

This research delivered several important findings. First, based on the proposed *N-SAW-based FFT of Change*, the overall score of RFs outstripped that of DFs, highlighting

Table 6 Total Score of DFs and RFs

Driving Forces (DFs)		*Restraining Forces (RFs)*	
DF_1	5.33	RF_1	6.33
DF_2	4.33	RF_2	4.00
DF_3	6.67	RF_3	5.67
DF_4	3.00	RF_4	5.67
DF_5	6.67	RF_5	6.33
DF_6	6.33	RF_6	5.00
DF_7	5.67	RF7	4.00
DF_8	5.67	RF_8	5.33
DF_9	3.00	RF_9	5.33
DF_{10}	6.67	RF_{10}	5.33
DF_{11}	6.00	RF_{11}	6.00
DF_{12}	4.33	RF_{12}	6.33
DF_{13}	5.00	RF_{13}	5.00
		RF_{14}	6.33
Total Score of DFs	**68.67**	**Total Score of RFs**	**75.33**

Table 7 N-Initial Reachability Matrix

RF	*14*	*13*	*12*	*11*	*10*	*9*	*8*	*7*	*6*	*5*	*4*	*3*	*2*	*1*
1	O	O	X	O	V	O	O	V	O	A	O	O	X	-
2	O	O	V	A	X	O	O	O	O	O	O	O	-	
3	X	O	O	O	X	O	O	O	O	O	O	-		
4	O	V	V	O	O	O	O	X	O	O	-			
5	O	O	O	O	O	V	O	O	O	-				
6	O	O	O	O	O	O	O	O	-					
7	O	O	O	A	O	X	O	-						
8	O	O	O	O	O	O	-							
9	O	V	O	O	O	-								
10	X	O	X	O	-									
11	O	O	O	-										
12	O	O	-											
13	O	-												
14	-													

the importance of studying the role of RFs in effectively implementing Ur-IS in Türkiye. Among the individual scores, New laws and regulations (DF_3), Changing strategies towards CE (DF_5), and The need for increased CE performance (DF_{10}) were found to be the most important DFs for IS adoption in Türkiye. Lack of policies and top management commitment (RF_1), Lack of incentives and regulations (RF_5), and Lack of a facilitator (RF_{14}) were determined to be the most significant RFs for Ur-IS implementation in Türkiye. These findings address the study's first (RQ_1) and second (RQ_2) research questions.

Our findings on RFs are consistent with those of Ji et al. (2020) and Sellitto et al. (2021), indicating that environmental drivers, such as compliance with legal requirements, are critical in encouraging greater implementation of IS. More broadly, the results are also consistent with other findings and arguments in the IS literature although there are a few differences. For example, Chertow (2000), Chertow (2007), and Lu et al. (2020) argued that companies are interested in joining IS and (or) Ur-IS initiatives in order to obtain both economic and environmental bottom-line benefits. In a similar vein, many businesses engaging in IS exchanges do so, at least in part, for the possible economic rewards, according to a qualitative study on industrial symbiosis in the UK (Paquin and Howard-Grenville 2012). Paquin et al. (2014) concluded that companies are more likely to initiate IS exchanges with higher economic values. These findings are all broadly consistent with our results. Golev et al. (2014) argued that lack of commitment to sustainable development and cooperation are key barriers, which is broadly consistent with our results. As a final example, Ji et al. (2020) concluded that insufficiency in legal frameworks, incentives, policies, and

Table 8 Final reachability matrix

RF	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
1	0.583	0.750	0.900	0.583	0.647	0.587	0.583	0.529	0.582	0.585	0.409	0.267	0.583	0.583
2	0.583	0.283	0.250	0.583	0.858	0.908	0.583	0.308	0.258	0.583	0.583	0.583	0.583	0.583
3	0.583	0.800	0.903	0.571	0.355	0.251	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583
4	0.535	0.383	0.267	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583
5	0.583	0.583	0.583	0.583	0.417	0.267	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583
6	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583
7	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.725	0.900	0.583	0.442	0.267	0.583	0.583
8	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583
9	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.774	0.904	0.584	0.393	0.263	0.583	0.583
10	0.559	0.581	0.584	0.583	0.610	0.583	0.583	0.317	0.260	0.583	0.583	0.583	0.583	0.583
11	0.585	0.573	0.582	0.587	0.310	0.260	0.583	0.779	0.900	0.583	0.388	0.267	0.583	0.583
12	0.487	0.562	0.561	0.559	0.619	0.585	0.583	0.338	0.263	0.583	0.583	0.583	0.583	0.583
13	0.583	0.583	0.583	0.250	0.250	0.250	0.583	0.583	0.583	0.583	0.583	0.583	0.583	0.583
14	0.583	0.774	0.904	0.584	0.643	0.580	0.583	0.333	0.267	0.583	0.583	0.583	0.583	0.583

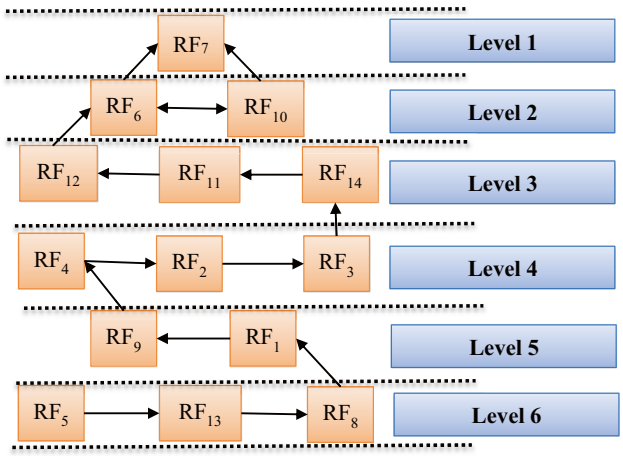

Fig. 3 Interrelationships among the RFs

collaborations proved to be the most significant barriers, which also corroborate our results. The existing research has, however, also revealed findings our study contradicts. For example, Yang et al. (2022) stated that the excessive cost of implementing IS is the leading inhibiting factor, which is inconsistent with our results.

Second, the findings of the proposed *N-ISM-MICMAC* analysis provided a graph classifying the RFs based on their driving and dependence powers. The analysis suggested that Lack of policies and top management commitment (RF_1), Lack of incentives and regulations (RF_5), Vulnerability and supply uncertainty (RF_{13}), and Lack of geographical proximity (RF_8) were the RFs with high driving powers. These forces have a large impact on the others. These findings address the third research question (RQ_3).

Table 9 Values of DR and DE

RFs	Driving Power (DR)	Dependence Power (DE)
RF_1	7.173	7.999
RF_2	7.533	8.207
RF_3	8.131	8.451
RF_4	7.602	7.801
RF_5	7.683	6.625
RF_6	8.167	7.188
$RF7$	8.167	6.667
RF_8	8.167	6.205
RF_9	8.168	7.834
RF_{10}	6.778	8.169
RF_{11}	7.863	7.965
RF_{12}	7.685	7.597
RF_{13}	7.667	6.867
RF_{14}	8.168	8.167

Our results on the driving RFs are partially consistent with the cause barriers determined by Bacudio et al. (2016). They used DEMATEL to identify cause-and-effect barriers to IS adoption in the Philippines. With that in mind, even if the outputs of DEMATEL and ISM-MICMAC are not directly compatible, the authors concluded that lack of top management and lack of incentives were the main cause barriers. This substantially corresponds to the driving RFs in our study. However, there are also differences between the findings of Bacudio (2016) and this study. For example, Bacudio et al. (2016) did not consider the factor on lack of regulations, which is one of the most important RFs with high driving power in our study. Bacudio et al. (2016) also considered lack of funding as a major cause effect, while the need for high investment and funding turned out to be a dependent factor in our study. The findings of our study suggested that the need for high investment and funding can be addressed right after effective regulations and incentive mechanisms have been implemented. Moreover, Chertow (2007), Gibbs and Deutz (2007), Abreu and Ceglia (2018), and Domenech et al. (2019) identified the key obstacles facing IS adoption in Europe. They also suggested that the main obstacles to IS adoption were ineffective economic incentives and legislative issues.

The proposed *N-ISM-MICMAC* analysis also indicated the forces with simultaneously high driving and dependence power. This cluster of factors, called linkage factors, both impact other factors and can be influenced by them. In this study, the following RFs proved to be the key linkage factors: Negative effect of the existing culture (RF_2), Lack of knowledge and proper training (RF_3), Lack of effective information system (RF_4, Lack of infrastructure (RF_9), Inflexible organizational systems and processes (RF_{11}), Lack of trust and collaboration among organizations (RF_{12}), and Lack of a facilitator (RF_{14}). These findings are partially consistent with Bacuido et al. (2016), which found that "Lack of willingness to collaborate", "Lack of an institutional support for integration, coordination and communication", and "Lack of technology and infrastructure readiness" are both influencing (driving) and influenced (dependent) barriers.

Moreover, the proposed *N-ISM-MICMAC* analysis indicated that Lack of short-term economic benefits (RF_6), The need for high investment (RF_7), and Unwillingness to share information (RF_{10}) were the most dependent RFs with higher dependence power. Bacuido et al. (2016) suggested that lack of information sharing is an effect barrier, which supports our findings. However, no previous study has considered "Lack of short-term economic benefits", "The need for high investment", and "Vulnerability and supply uncertainty" as dependent RFs. We'll further elaborate on why certain RFs are classified in specific clusters in Section 5.2.

Lastly, the challenges located in quadrant IV are denoted as autonomous and display weak driving and dependence

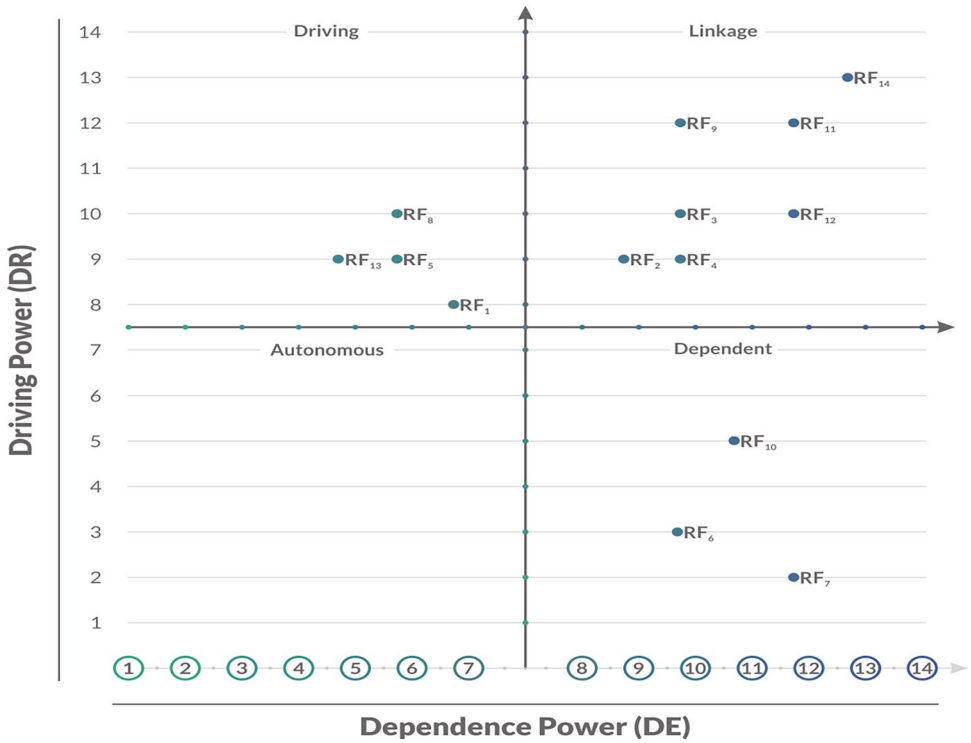

Fig. 4 The Results of N-MIC-MAC

power. Our findings indicated that none of the RFs in this study lie in the autonomous cluster. In other words, we suggest that all RFs considered in this study play a significant role in Ur-IS adoption.

5.1 Managerial and policy implications

The findings have several managerial implications. First, the findings provide needed direction for key stakeholders in manufacturing industries as they move towards greater circularity and sustainability. This study identified and sorted the driving and dependent RFs to IS adoption for Turkish manufacturing industries. Our findings suggested that, although IS can aid in enhancing the CE in Türkiye, Lack of policies and top management commitment (RF_1) and Lack of incentives and regulations (RF_5) have the highest driving powers. These RFs must therefore be addressed by decision-makers if IS is to be successfully and widely adopted. Simply put, adequately addressing these factors is critical. As Sakr et al. (2011) have shown, the government's heavy engagement in the construction of IS-based business models might be a double-edged sword if not handled properly. In a similar vein, Heeres et al. (2004) argued that some industries may consider IS as a job creation initiative, rather than an approach to improve the environmental performance of the companies, if it is not effectively implemented.

Furthermore, our findings suggest that improvement in linkage challenges, including Negative effect of the existing culture (RF_2), Lack of knowledge and proper training (RF_3), Lack of effective information system (RF_4), Lack of infrastructure (RF_9), Inflexible organizational systems and processes (RF_{11}), Lack of trust and collaboration among organizations (RF_{12}), and Lack of a facilitator (RF_{14}) also depend on building effective policies, top management commitment, incentives, and regulations. Both organizational and governmental initiatives are therefore required. For example, national policies, incentives, and regulations for IS established by the government provide the needed foundation on which to build effective IS initiatives. These, however, are insufficient if managers do not address the core internal drivers of effective IS implementation. It is also critical to recognize that linkage factors influence the others. This means that, although an effective information system, for example, is important in implementing an IS initiative, it is insufficient on its own. The DFs and RFs exist in a broader context, that must consider their interactions.

Lastly, our findings reveal that Lack of short-term economic benefits (RF_6), The need for high investment (RF_7), and Unwillingness to share information (RF_{10}) were both highly driven and dependent on the other RFs to IS adoption. In other words, the input from the Expert Group showed that the RFs on economic benefits, the need for high investment, and sharing information are contingent upon improving the driving RFs such as building effective policies, top management commitment, incentives, and regulations. Government-based incentives and regulations in Türkiye can ease the burden of high investment costs on companies and pave the way for better economic benefits both in the short- and long-term.

In summary, given the driving and dependent challenges to Ur-IS adoption in Türkiye, we suggest that unless effective policies, top management commitment, incentives and regulations towards IS implementations are at least partly achieved, stakeholders in Turkish manufacturing industries may not be eager to consider investing in IS. Our suggestions for key stakeholders are summarized in Table 10. These suggestions also serve as an answer to the fourth research question (RQ_4).

5.2 Theoretical implications

This research employed a decision structure that incorporates *N-SAW-based FFT of change* into *N-ISM-MICMAC* to identify the driving and dependence powers of the RFs to Ur-IS adoption in Türkiye. The contextual links between system units are the foundations of the classic SAW and ISM techniques. They assume that each pair of system units has only a binary relationship. Nevertheless, processing data in traditional ISM and SAW affects the findings of expert judgment elicitation for system unit relationships and ignores the degree of contextual links between system components. Therefore, the SVTNN is used in this study because it can handle expert judgment better than the traditional ISM and SAW.

Structured decision architectures, including the one proposed in this study deliver a framework for making decisions, which can give rise to well-informed reasoning. Therefore, the purpose of the structured decision approach in this study is to increase decision-makers' comprehension of the problem by guiding them in identifying the preferred course of action by addressing their own and other stakeholders' priorities, values, and objectives. In other words, the proposed decision framework complements and challenges intuitive judgment and experience rather than aiming to replace it. Its goal is to make subjective judgments, as well as the broader decision-making process, visible.

Furthermore, note that the purpose of this research is not to find an optimal answer on the concerns of IS adoption in Türkiye, but to create something that would assist a decision-maker in aligning their actions with their desired objectives. In conclusion, each element of the proposed decision framework is critical, and each step should be accomplished carefully and diligently.

Table 10 Suggestions for stakeholders

Stakeholders	***Responsibilities***
Local and National Government Agencies	• Enacting a legislative structure to boost Ur-IS. • Building an incentive framework. • Allocating more research funds to national research institutes for effective IS-based business models towards CE. • Establishing macro policies towards Ur-IS. • Constructing an effective industrial park infrastructure, including energy installations, water and effluent treatment, and waste processing.
Non-Governmental Organizations, Labor Unions, Industrial Park Managements, and Business Associations	• Assessing the economic benefits of deploying Ur-IS both in the short- and long-term. • Supporting increased customer awareness towards Ur-IS. • Helping to increase interest in Ur-IS. • Formulating new Ur-IS -based business models. • Building a system to measure the performance of Ur-IS activities through relevant indicators.
Companies	• Enhancing top management commitment. • Ensuring that both white- and blue-collar employees have sufficient training on Ur-IS. • Adopting effective Ur-IS strategies. • Pursuing and developing collaborations with other companies.
Urban Municipalities	• Establishing urban municipal policies towards Ur-IS integration. • Building policies and strategies to address vulnerabilities, including supply uncertainties and trust. • Picking effective facilitators. • Developing collaborations with other organization towards Ur-IS integration.
Research and Educational Institutions	• Building knowledge on Ur-IS. • Disseminating the existing knowledge. • Developing tools to assess the feasibility of Ur-IS adoption for specific cases.
Supply Chains	• Establishing effective symbiotic supply chain tactics towards effective Ur-IS implementation. • Developing technically effective Ur-IS eco-systems. • Conducting simulation studies on how to build effective Ur-IS contracts.

6 Conclusion

Supply chain disruptions resulting from human-made and natural catastrophes have revealed the vulnerabilities in the present economic model. In recent years, a series of major disruptions, including a global pandemic and a major war in Europe, have severely impacted many global supply and manufacturing systems. These catastrophes have once again demonstrated the limitations of the linear take-make-use-dispose system, and underlined that we urgently need to alter our economic model. Moving towards a CE, in which resources are kept in the economy for longer periods of time and waste is reduced, will help improve the sustainability and resilience of modern economies. Industrial symbiosis, which is tied to the notion of industrial ecology, is an innovative strategy to boost resource productivity and is a key business model to achieving a CE and sustainable growth. IS, according to the European Commission, is one of the most important techniques for strengthening the CE.

Türkiye, an emerging country, joined the Customs Union of the European Union (EU) in 1995 and was acknowledged as a candidate for full membership in 1999. As a result, the EU required Türkiye to make some regulatory revisions. Over the last three decades, Türkiye 's increasing industrialization and urbanization have resulted in several challenges with respect to resource circularity and waste management. The need for Türkiye to transition to a more resource-efficient and environmentally friendly industrial structure is increasingly recognized. To address these challenges, many national policy documents in Türkiye now consider Ur-IS as a key strategic tool.

However, despite several driving forces, there are many barriers to implementing Ur-IS. Hence, addressing the main impetus and challenges for Ur-IS initiatives through a comprehensive decision framework is critical. Our literature review concluded that only two studies have systematically investigated the driving and (or) restraining forces for Ur-IS implementation in advanced and (or) emerging countries. Hence, the main purpose of this study was to explore the potential for Ur-IS adoption in Türkiye through an integrated decision framework. To this end, a decision framework that incorporated force field theory of change into MCDM was proposed, specifically applying *N-SAW-based FFT* and *N–MICMAC*.

The contributions of this study are as follows: *(1)* To date, there have been several conceptual and review-based studies regarding the challenges and drivers of Ur-IS. However, only a handful of studies have examined the challenges and drivers of Ur-IS adoption through quantitative analyses in different countries. In this study, the lists of RFs and DFs of Ur-IS adoption were identified using both a literature review and expert viewpoints. *(2)* To date, only one previous study has addressed the associations between the challenges to Ur-IS adoption. However, no study has analyzed the driving and dependency powers of the RFs to Ur-IS adoption towards CE in Türkiye. In this study, *N-ISM-MICMAC* was proposed to determine the associations among RFs to Ur-IS adoption in Türkiye. *(3)* Managerial and policy implications of our findings were also discussed to boost effective Ur-IS implementation in Türkiye.

There are limitations to this study, which provide insight into avenues for future research. For instance, since this research is predicated on data gathered from a particular expert panel in a certain country, the findings may not hold for Ur-IS initiatives in other countries. While the methodology applied in this study is generalizable, each country's achievement in Ur-IS is unique, potentially limiting the generalizability of the specific findings. Hence, new research into the distinctive Ur-IS practices of different nations should be carried out. Lastly, to cope with the subjectivity of expert judgments, other robust approaches based on new fuzzy and rough sets extensions can be applied.

Data availability Data can be provided if requested.

Declarations

Conflict of interest The authors of this manuscript certify that the authors have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare that are relevant to the content of this article. The authors have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no stocks or shares in companies (including holdings of spouse and/or children) that may gain or lose financially through publication of this manuscript; consultation fees or other forms of remuneration from organizations that may gain or lose financially; patents or patent applications whose value may be affected by publication of this manuscript. The authors do not have any research grant from funding agencies and/or research support (including salaries, equipment, supplies, reimbursement for attending symposia, and other expenses) by organizations that may gain or lose financially through publication of this manuscript. The authors have no interest that goes beyond financial interests that could impart bias on the work submitted for publication such as professional interests, personal relationships, or personal beliefs.

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