KAUNAS UNIVERSITY OF TECHNOLOGY

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ENHANCING TECHNOLOGICAL LEARNING THROUGH FIRMS' INTERACTIONS IN COLLABORATIVE INNOVATION NETWORKS

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List of abbreviations

BCSCM – Blockchain driven supply chain management
CB-SEM – Covariance based structural equation modelling
DGT – Digital trust
HC – Human capital
IC – Intellectual capital
IS – Innovation system
ISM – Interpretive structural modelling
MSP – Multisided platforms
NET – Networks
NIS – National innovation system
OI – Open innovation
PLS-SEM – Partial least square structural equation modelling
PTAC – Potential technological absorptive capacity
RC – Relational capital
RTAC – Realized technological absorptive capacity
SC – Structural capital
SCM – Supply chain management
SCMap – Supply chain mapping
SMEs – Small and medium enterprises
SP – Sustainable production
TAC – Technological absorptive capacity
TLT – Technological learning and trust
TO – Technological orientation

1. INTRODUCTION

1.1. Background of the study

Innovation has become the mainstay of modern economies. The locus of innovation is learning, a social activity that makes innovation processes cumulative and cooperative (Tanner, 2018; Zhang et al., 2020). Learning requires extensive collaborations and integration of various actors and stakeholders with diverse capabilities and knowledge. Such integrated interactions facilitate knowledge sharing, mutual learning, and responsiveness amongst the participating entities (Dyer, Nobeoka, 2000; Levén et al., 2014).

Firms that are engaged in technology-driven sectors often operate under complex and dynamic conditions. These conditions continuously alter due to the rapid changes in the technological environment (Bressler, Pence, 2019). Mohrman and von Glinow (1990) stated: "technological environment can simultaneously create new opportunities for entry, bankrupt existing companies, and render obsolete entire product lines and manufacturing and design processes overnight" (p. 264). Therefore, in order to manage such volatile and continuously changing situations, firms should constantly develop their technological learning.

Technological learning is a dynamic process for doing technology-related innovation (Oqubay, Ohno, 2019) that posits a long-term view of technological accumulation; technology is acquired for its potentiality (Dodgson, 2018). An essential part of technological learning is to gain knowledge of technology-related opportunities that rapidly change in the technological environment. Although it occurs in various domains, it predominantly focuses on the knowledge associated with manufacturing, R&D, and technical processes (Bhattacharya et al., 2021). Most importantly, the technological learning enables the detection of technological changes that threaten the existing ways of doing things and provides the potential for alternatives (Dodgson, 2022). Hence, technological learning is critically important to develop technology-related knowledge to prepare firms to improve their design, production, and manufacturing processes in the dynamic technological environment.

Dodgson described technological learning as "the ways firms build and supplement their knowledge base on technologies, products and processes, and develop and improve the use of the broad skills of their workforce" (2018, p. 10). Firms can improve their technological learning by continually developing and renewing their capabilities to deal with such conditions.

The sources of knowledge are widely distributed, that is why firms cannot manage their innovation individually by only relying on their limited knowledge and capabilities. Consequently, the innovation processes are rapidly shifting from in-house and closed (producer-led) towards a more open and collaborative mode (Fagerberg, Verspagen, 2021; Rothwell, 1994). In this way, collaborative innovation appears as a new paradigm for undertaking innovation (Chesbrough et al., 2014). It is described as the "creation of innovations across firms (and industries) boundaries through the sharing of ideas, knowledge, expertise, and opportunities" (Ketchen et

al., 2007, p. 372). And its "… main goal is to gain access to the partner's knowledge and competences, especially tacit knowledge" (Collins and Hitt, p. 152). Thus, various actors and partners, such as firms, research centers, users, suppliers, and other stakeholders, collaborate for innovation, and by doing this, they exchange their knowledge, expertise, and resources to achieve shared (or common) goals for innovation.

In order to facilitate these collaborations, collaborative innovation networks form and establish a well-structured system while managing learning interactions (Reypens et al., 2021). Collaborative innovation networks refer to the mechanism and process of integrating resources and knowledge distributed among various partners, customers, suppliers, and other stakeholders for co-creation and co-innovation (Möller et al., 2020). It is a logical result of increasing complexity, shorter product lifecycle, higher cost of R&D, and rapidly changing market of innovative products (Song et al., 2013). The examples of such networks are open innovation networks (Chesbrough, 2003), supply chain networks (Khan et al., 2022), multisided digital networks (Xie et al., 2016), international innovation networks (Liu et al., 2013), and national innovation system-based networks (Nelson, 1993). Knowledge creation is at the core of innovation networks; therefore, its role has become the cornerstone of successful innovation (Powell, Grodal, 2006). Firms must continually improve their knowledge base to innovate continuously; therefore, they progressively participate in at least one or a variety of collaborative innovation networks. In such networks, firms strategically transform their innovation goals while developing technological learning (Maguire, Hardy, 2006). In this way, the networks are considered as a dominating context where (technological) learning takes place (Vidmar et al., 2020). Furthermore, it is stated that "of central importance to the accumulation and transformation of capabilities in knowledge-intensive firms is the skill base in which firms invest in pursuing their innovative strategy" (Crespi et al., 2018, p. 5). Collaborative innovation networks, through learning, as well allow firms to identify the competitive strengths and weaknesses in their existing skill base and help renew their essential innovation-related competencies to improve technological learning (Karimi et al., 2021; Pan et al., 2019).

1.2. Definitions of the main terms

Technological learning (TL) is a dynamic process in firms to perform technology related innovation (Oqubay, Ohno, 2019) that posits a long-term view of technological accumulation, i.e., technology is acquired for its potentiality (Dodgson, 2022). In this way, "the ways firms build and supplement their knowledge bases on technologies, products, and processes, and develop and improve the use of the broad skills of their workforce" are as well referred as TL (Dodgson, 2018, p. 10).

Collaborative innovation is the "creation of innovations across firms (and industries) boundaries through the sharing of ideas, knowledge, expertise, and opportunities" (Ketchen et al., 2007, p. 372). Thus, "the main goal of collaborative innovation is to gain access to the partner's knowledge and competences especially to tacit knowledge" (Gallaud, 2013, p. 236).

Collaborative innovation networks refer to the mechanism and process of integrating resources and knowledge distributed among a variety of partners, customers, suppliers, and other stakeholders for co-creation and co-innovation. It is a logical result of the increasing complexity, shorter product lifecycle, higher cost of R&D, and rapid changing market of innovative products (Song et al., 2013). The examples of such networks are open innovation networks (Chesbrough, 2003), supply chain networks (Khan et al., 2022), digital multisided networks (Xie et al., 2016), global innovation networks (Spencer, 2003), and national innovation system-based networks (Nelson, 1993).

1.3. Statement of the problem

Technological learning enables firms to successfully innovate and upgrade technology. However, sudden and unpredictable changes in technological environments can alter the value of the firm's existing technological knowledge base or make it obsolete (Tushman, Anderson, 2018), such as Schumpeterian revolutions, technological discontinuities, and shortening of innovation and technology life cycles (D'Alvano, Hidalgo, 2014; Žižlavský, 2013). Since technological learning helps firms to build their knowledge bases related to technologies, it is vital to be enhanced in order to stay innovative in the dynamic technological environment.

The required sources of knowledge for technological learning are dispersed, and firms, individually, cannot have all those resources within their boundaries (Reypens et al., 2021). Therefore, firms must look outside of their boundaries and approach external actors and stakeholders. In this context, collaborative innovation networks can play an instrumental role in managing and combining distributed resources in one place (Moller et al., 2020). Small economies usually do not have strong knowledge base that would be available inside their borders; therefore, they inevitably have to participate in international networks of innovations (Langer et al., 2022). It applies to small and open economies, e.g., Lithuania, that are required to integrate with international collaborative innovation to bring about technological learning within their national innovation systems (NIS). The NIS of Lithuania encapsulates a number of domestic (sub)networks, such as research centers, incubation centers, universities, and science and technology parks. Lithuanian firms are linked to the networks from other European countries, as well as the United States and the United Kingdom.

Furthermore, it is equally important to acquire learning from international networks at the same time systematically transferring and integrating it into the NIS. However, the researchers have paid limited attention to learning interactions in networks of small economies. Therefore, the orchestration of innovation networks

for improving technological learning still remains an open question in such economies (Friesenbichler, Reinstaller, 2023). Technological learning in small and emerging economies depends on their participation in innovation networks from different countries (Myrzakhmet, Begimbay, 2022). Contrary to this, large and developed economies (e.g., USA, UK) are different and considered self-sufficient in technology related knowledge bases (Liu, Chan, 2022; Johns, 2022). Likewise, the arrangement of innovation networks for smaller and developing countries is different, that depends on the network partners, from the larger economies (Myrzakhmet, Begimbay, 2022). Therefore, exploring the relational view of capabilities for technological learning among the firms of small countries that are participating in innovation networks is essential. Although Podmetina et al. (2018) presented open innovation competencies and endorsed Mortara's (2010; 2014) view of interactive and technological skills implicitly at the individual and firm levels. However, they did not explicitly address the interplay of these capabilities at the network level. In this context, there is a critical void when technological learning is discussed at the network level. Therefore, the focus on the technological and interactive side of innovation capabilities needs serious attention (Mortara, 2010) at the network level. Moreover, in this sense, trust is one of the key components for firms to improve learning interactions within the networks (Brockman et al., 2018). In fact, it is considered as the basis for collaborative nature of innovations and learning interactions (Salampasis et al., 2015). Therefore, this study explores the orchestration of innovation networks and trust variables in a technological setting.

Furthermore, for internalizing and integrating technological learning gained from international innovation networks into NIS, the technological capabilities are instrumental (Fan et al., 2020). The existing studies have explored the role of absorptive capacity for learning (Cohen, Levinthal, 1990), while this study zooms in on its technological dimension through investigating technological absorptive capacity (TAC). In addition, technological orientation (TO) is studied in order to improve the technological learning interactions in collaborative networks. These capabilities are closely associated with technology related knowledge and interaction (García-Morales et al., 2007). As mentioned earlier, the composition of large and developed countries networks varies from small ones; this is why the variables of TAC and TO are appropriate to study in smaller and developing economies. Thus, the study discusses the role of these capabilities in advancing learning interactions in open innovation networks.

Additionally, technological learning is intertwined with the knowledge stock of firms that is directly related to the intellectual capital view. Intellectual capital encompasses the dimensions of human capital, relational capital, and structural capital of firms (Khan et al., 2022). It contributes to enhance the (explicit as well as tacit) exchanges to improve the knowledge base of firms in networks (Farzaneh et al., 2022). Once networks are orchestrated, they gradually develop and adopt the technology (Kergroach, 2019). Hence, the role of intellectual capital-based capabilities in improving the technological advancement of networks and their

visibility is worth exploring in the context of developing countries with the availability of human capital (Tsolakis et al., 2022).

Regarding the previous facts, policy makers have previously proposed the fourth industrial revolution and industry as a result of technological learning (as well called Industry 4.0). It was immediately embraced by the manufacturing sector as well as service sector at that time (in 2011). By doing this, they made extensive amounts of commitments to adopt, innovate, and use technology accordingly for the well-being of society. Although, as Kranzberg (1986) stated: "technology itself is neither good nor bad; nor is it neutral" (p. 545), it is how the technology is channelized and directed. The manufacturing sector failed to deliver its promises about the social well-being, human centricity, and sustainability (Renda et al., 2022). Instead, the notion of Industry 4.0 was heavily focused towards automation, efficiency, productivity, and profitability, while ignoring those values it had promised. Thus, in the current technological environment, this approach has become unacceptable for innovation, and the movement has already started to make the use of Industry 4.0 technologies more sustainable, human-centric, and resilient (Ghobakhloo et al., 2022). However, the foundation and guidelines to achieve this purpose are inadequate (Saniuk et al., 2022). Therefore, more research is needed to navigate the technological learning in such a way that it could build its knowledge base accordingly and contribute to the technological upgrading by following the principles of sustainable development in innovation networks. The current study explores this phenomenon and develops a framework for navigating technological learning according to this particular change in the technological environment.

Against this backdrop, this study focuses on technological learning in the context of highly dynamic and rapidly developing economies, such as Baltic countries in the European region and South Asian countries with rapid economic development based on technology-based firms and the availability of a large amount of human capital. Thus, the technological learning interactions in open innovation networks, digital supply chain networks, and networks based on national and international innovation systems are studied.

This study aims to enhance technological learning through firms' interactions in collaborative innovation networks. In this context, the study raises the research question: how the technological learning of firms participating in collaborative innovation networks can be enhanced.

The following sub-questions are developed under the umbrella of this broader research question.

1) How are innovation networks orchestrated with the aim of improving technological learning?

2) How do the capabilities such as digital trust, technological absorptive capacity (TAC), and technological orientation (TO) impact open innovation networks?

3) How do the firms' intellectual capital-based capabilities influence the technological advancement of networks?

4) In which strategic direction should the technological learning be navigated to carry out the technological upgrading with a sustainable approach?

1.4. Research methodology

This research examines direct and indirect interactions of technological learning in multiple collaborative innovation networks where several unique variables are included in those settings, such as innovation capabilities including digital trust, technological absorptive capacity (TAC), technological orientation (TO), and intellectual capital-based capabilities. Therefore, there is no best way to explore technological learning in these multiple interactions in different network archetypes. Therefore, various research methods were applied to achieve the set research objectives that were fulfilled and published as four high-quality research papers. The first research paper is titled as "The role of international networks in upgrading national innovation systems" (P-I) that studies the orchestration of innovation networks to improve technological learning. This research paper has applied a quantitative research method where SEM-PLS technique was applied on the collected data. The second paper is titled as "Industry 4.0 technologies, digital trust and technological orientation: What matters in open innovation?" (P-II). It studies the capabilities, including digital trust, technological absorptive capacity (TAC), and technological orientation for improving open innovation networks by applying PLS-SEM technique on the collected data. The third paper is titled as "Intellectual capital, blockchain-driven supply chain and sustainable production: Role of supply chain mapping" (P-III) have discussed the impact of intellectual capital-based capabilities (including human, relational, and structural capital) on the technological advancement of (supply chain) networks. This research paper has employed covariance-based structural equation (CB-SEM) to analyze the collected data and test the modelled relationships. In these research papers, the data was collected from the technology-based firms following the taxonomy of Pavitt (1984). The fourth research paper titled as "Identifying Industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values" (P-IV) have adopted interpretive structural modelling (ISM) method to identify the functions, components, and constituents to develop a strategy framework for sustainably undertaking technological learning. This research paper has applied expert based decision-making by embracing multicriteria decision-making (MCDM) to derive the framework.

Three of these publications have applied a quantitative research method predominantly, in which the primary data was collected from various networks (e.g., supply chain networks, open innovation networks, digital networks, international networks, and innovation system-based networks). While in one publication, qualitative methodology is applied. The sets of collected data were undergone to a variety of analysis techniques suitable to the research objectives of each paper. The applied data analysis techniques include partial least-square structural equation modelling (PLS), covariance-based structural equation modelling (CB-SEM), and interpretive structural modelling (ISM). The following Table 1 highlights the

research methodology adopted in each of those publications to fulfil their micro-objectives as well as to cater the broader objective of this PhD research. Table 1 summarized the methodologies of all these papers.

Table 1. Research methodology applied in thesis publications

Paper	**Method(s)**	**Data type(s)**	**Sample(s)**	**Analysis method(s)**
1	Quantitative	Survey based primary data	131 Technology based firms*	PLS-SEM technique by applying *R*
2	Quantitative	Survey based primary data	324 Technology based firms*	PLS-SEM technique by applying *Smart PLS*
3	Quantitative	Survey based primary data	289 Technology based firms*	CB-SEM technique by applying *Smart PLS*
4	Qualitative	Expert panel meetings	11 experts of EU policy, industry, and academia	Interpretive structural modeling (ISM) technique

** Technology based firms as explained by Pavitt (1984)*

2. REVIEW OF THE ARTICLES

2.1. Overview of the articles

This section presents the reviews and contributions of four papers published in high-impacted and ranked journals including *Technological Forecasting and Social Change*, and *Sustainable Production and Consumption*. The respective objectives of this study are addressed through these research articles. Before discussing each research paper one by one, an overview and links between them as well as their connection with the broader aim of this study is explained below.

The first research question of this study is how innovation networks are orchestrated with the aim of improving technological learning. Thus, the technological learning interactions of firms in international and national networks are investigated. The first research paper (Paper I: "The role of international networks in upgrading national innovation systems") addresses this question. The second research question of the study is how do the capabilities such as digital trust, technological absorptive capacity (TAC), and technological orientation (TO) impact open innovation networks. The second research paper fulfills this objective (Paper II: "Industry 4.0 technologies, digital trust and technological orientation: What matters in open innovation?"). Further on, the third research question examines the impact of intellectual capital-based capabilities of firms on the technological advancement of firms and networks. Paper three (Paper III: "Intellectual capital, blockchain-driven supply chain and sustainable production: Role of supply chain mapping") answers this questions. Finally, the fourth objective of the study focused to identify the strategic direction in which the technological learning should be navigated for technological upgrading in the context of sustainability. In order to achieve this objective, paper four (Paper IV: "Identifying Industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values") develops a strategy framework and provides directions for technological learning in a changing technological environment.

The research questions of the study and the corresponding publications answering them are presented in Table 2.

Table 2. Contributions of publications to corresponding research questions

Research questions	**Publications**	**Core findings**	**Contributions to theory**	**Practical implications**
RQ#1: How are innovation networks orchestrated with the aim of improving technological learning?	"The role of international networks in upgrading national innovation systems"	Technological learning in national innovation system networks is fully mediated through international networks. International innovation development strategies promote technological learning in the national innovation system.	This study zooms in the relational view of technological learning among firms participating in the innovation networks. Thus, the theoretical contributions are made by focusing on the technological learning and the compound role of trust in the upgrading of national innovation systems through international networks. In this study, the first attempt is made to study the relationships of national and international networks.	Successful technological learning interactions and technological upgrading in NIS-based networks cannot be accomplished in a direct relationship. Instead, the integration of firms operating in NIS is inevitable with international networks of innovation in order to improve the technological learning.
RQ#2: How do the capabilities such as digital trust, technological absorptive capacity (TAC), and technological orientation (TO) impact open innovation networks?	"Industry 4.0 technologies, digital trust and technological orientation: What matters in open innovation?"	Digital trust improves the learning interactions in open innovation networks with the mediation of technological absorptive capacity and moderation of technological orientation in the firms.	The concept of digital trust is offered for open innovation networks that propel learning with the help of technology absorptive capacity and technological orientation. The adoption of Industry	The firms' conventional capabilities can be improved by developing digital and technological related capabilities (such as digital trust, technological absorption, and technology

			4.0 technologies improves conventional organizational challenges and capabilities. Traditional firms try to stay with the conventional technologies due to the innate distrust and uncertainty of new technologies. The study dispels this conventional fear and suggests that an organization adopting digital technologies can improve the digital trust.	orientation) in order to effectively manage learning interactions in collaborative innovation networks. Firms should as well deliberately make efforts to improve its technology-related absorption capacity to improve the orientation of technology-related knowledge to improve technological learning interactions for innovations.
RQ#3: How do the firms' intellectual capital-based capabilities influence the technological advancement?	"Intellectual capital, blockchain-driven supply chain and sustainable production: Role of supply chain mapping"	Technological advancement (BCSCM) and networks' visibility (SCMap) mediate the intellectual capital (human, relational, and organizational) and sustainable production. Intellectual capital as well exerts a significant direct impact on sustainable production.	Intellectual capital-based capabilities improve the technological advancement (e.g., digitalization) and visibility of the value chain. Further on, sustainable production is achieved with the help of digitalization and visibility.	Firms should develop their human, relational, and organizational capabilities in order to technologically upgrade the whole value chain. In this way, they can as well achieve the agenda of sustainable production that will benefit them in the form of competitive advantage and value the enhancement of existing offering/products.

RQ#4: In which strategic direction should the technological learning be navigated to carry out the technological upgrading with a sustainable approach?	"Identifying Industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values"	Sustainable development is driven by certain technological constituents and techno-functional design principles that improve the components of industry 5.0 for value creation. A strategy framework is developed to carry out technological learning to achieve sustainable development values.	Technological learning can be navigated and achieved in a sustainable manner with the joint role of industry 4.0 technologies, the notions of human-centricity, resilience, and sustainability. The study offers an industry 5.0 framework that channelizes technological learning through the functions of sustainability.	Firms can put their efforts towards sustainable technological upgrading by following functions, design principles, and technological components in order to enhance the value creation for the purpose of long-term benefits and competitive advantage. The adoption of a proposed strategy framework in innovation networks will enable and facilitate firms to achieve this goal.

The first paper (P-I) takes technological learning and trust (TLT) as an independent variable, variety of international innovation networks (INT.NET) as mediators, and national innovational innovation system-based networks (NIS) as dependent variables. The second paper (P-II) includes a dependent variable of digital trust (DGT), the mediating role of technological absorptive capacity (TAC) dimensions, moderating role of technological orientation (TO), and open innovation networks (OI) as a dependent variable. Third paper (P-III) has taken dimensions of intellectual capital, including human capital (HC), relational capital (RC), and structural capital (RC) as independent variables, technological advancement-based on blockchain-based supply chain management (BCSCM) and visibility capability-supply chain mapping (SCMap) as mediators, and sustainable production (SP) as dependent variable. Finally, the fourth paper (P-IV) presents the framework to develop technological learning according to the notion of sustainability. It represents the technological constituents, techno-functional design principles, smart components of industry 5.0, and sustainable development functions. The linkages of each article and research question are presented in Figure 1 below.

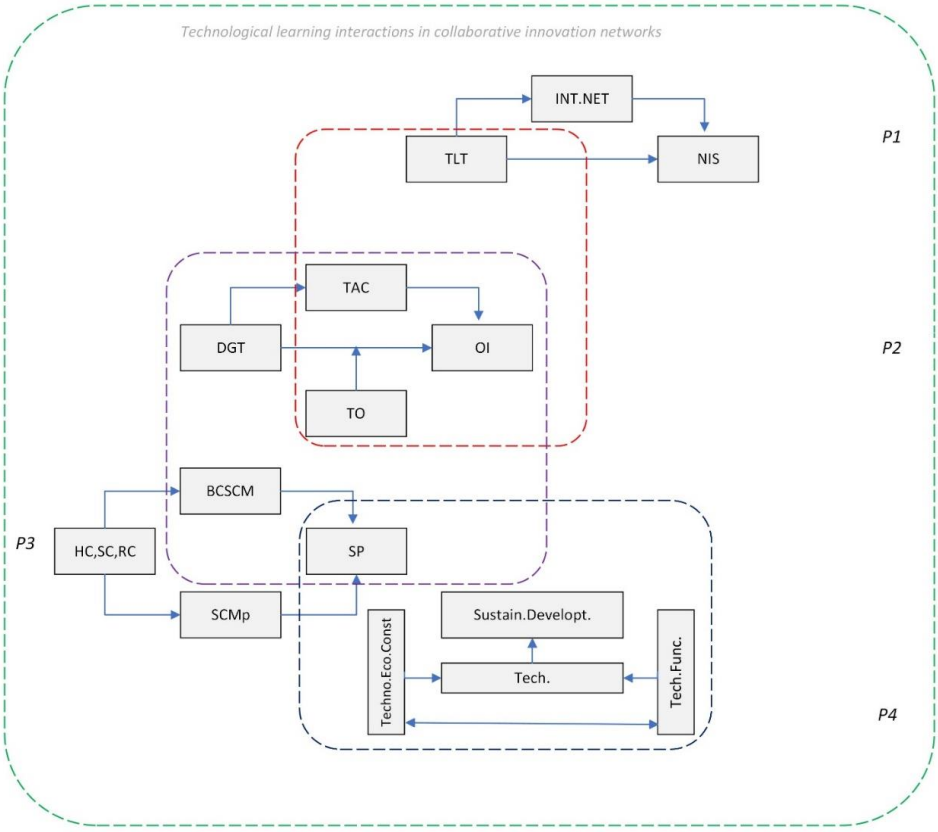

Fig. 1. Linkages of articles and objectives

2.2. Review of the articles

Paper 1: The role of international networks in upgrading national innovation systems. Published in *Technological Forecasting and Social Change*.

Research question#1: How are innovation networks orchestrated with the aim of improving technological learning?

Background

Technological learning plays an essential role in the technological improvement of firms (Radosevic et al., 2019). Therefore, it is critically important to understand the technological learning pattern in the national innovation systems (NIS) of a country. Numerous researches have studied the technological upgrading interaction in cases of large and developed economies; however, small, open and transitioning countries have been neglected. Small and open economies of Central Eastern Europe, including Lithuania, benefit from the international integration with international networks of innovation. This paper aimed to investigate the pattern of technological learning and the upgrading pattern in the NIS of Lithuania. The researchers, including Ghazinoory et al. (2014) and Brockman et al. (2018), have established that the institutional and social trust play an important role in improving open innovation networks. Post-Soviet studies on trust, including institutional, business and interpersonal trust, reveal specific conditions in which greater international institutional trust is demonstrated compared to the national institutional trust (Audretsch et al., 2018) and weak institutional trust (Amoros, Bosma, 2013). The research on the role of national innovation systems in firms' innovation behavior has mostly neglected this vital component or addressed it indirectly, despite the acknowledged importance of technology learning within the innovation networks. Based on this problem formulation, the aim is to discuss the role of international networks in upgrading national innovation systems-based networks, built on research in a small CEE economy. The core research question of this paper was as follows: how national and innovation networks reinforce technological learning within NIS from R&D firms' perspective. The data were collected from 131 technology-based firms in Lithuania by using a structured questionnaire. Therefore, this study investigated the mediating role of a variety of international innovation networks in relation to technological learning and trust (TLT) and national innovation system (NIS).

Contributions

Theoretical contributions

This research paper focuses on the relational view of technological learning among firms that are participating in innovation networks. Thus, the theoretical contributions are made by focusing on the technological learning and the compound role of trust in the upgrading of national innovation systems through international networks by focusing on Lithuania. The country that developed under a generally undermined trust in institutions, systems as well as societal trust has demonstrated a

transition towards innovation-driven growth in recent decade. Moreover, technological learning is studied as a phenomenon where learning resides in the networks of innovation (Yao et al., 2021). This research paper is the first ever attempt to study the relations between national and international networks. These interactions are explored at the firm and network's levels.

Practical contributions

This paper contributes by revealing a novel pattern in technological learning of small and open economies in transition. This study reveals that successful technological learning interactions and technological upgrading in NIS-based networks cannot be accomplished in a direct relationship. Instead, the integration of the firm's operating in NIS is inevitable with international networks of innovation in order to improve the technological learning. Moreover, trust embedded technological learning accomplished through internationalization influences the technological learning in NIS based networks.

Policy contributions

The results highlight the importance of the integration of international business and innovation systems, especially in small transition economies. Large transition economies as well benefit from such international linkages but rely on a more extensive arsenal of assets and opportunities in leveraging domestic and global capabilities (Liu, Chan, 2022; Johns, 2022). This realization has significant implications for policy making in small transition economies regarding the opening of their economies to foreign investment, allowing domestic actors to tap into global markets and resources, and long-term strategy development in domestic companies for technological and organizational upgrading.

A set of relational capabilities is required to enable technological learning by tapping the network-based sources (such as knowledge) (Mortara, 2010). Such capabilities can be intellectual capital-based capabilities related to learning, technological knowledge absorption, etc. In order to address these points, next research papers (P-II and P-III) study a variety of capabilities to improve the learning interactions and technological advancement in collaborative innovation networks.

Paper 2: Industry 4.0 technologies, digital trust and technological orientation: What matters in open innovation? Published in *Technological Forecasting and Social Change*.

Research question#2: How do the capabilities such as digital trust, technological absorptive capacity (TAC), and technological orientation (TO) impact open innovation networks?

Background

With the growing role of industry 4.0 technologies, technology-based firms are increasingly digitalizing their operations to improve learning interactions in open innovation networks. However, due to diverse backgrounds, cultures, languages, and

different locations, the distrust between stakeholders in such collaborative innovation networks is intensified (Xie et al., 2016). This fact highlights the relational view of learning interactions in innovation networks. Therefore, to address this problem, the establishment of trust is crucial for the success of knowledge and learning interactions between various types of stakeholders, including firms, suppliers, research centers, universities, community organizations, and authorities (Brockman et al., 2018). The networks that are created in technological infrastructure facilitate the interaction between stakeholders by integrating them through digital networks. Therefore, the study of trust that addresses the technological aspects of networks (such as a digital form of trust) is required in order to facilitate the learning interaction. The research question of this paper was how open innovation networks can be enhanced by the underpinning combination of digital trust, technological absorptive capacity, and technological orientation of firms. The data was collected from 324 Electrical and Electronics (EE) sector firms in Malaysia, Thailand, and Indonesia. In this research paper (P-II), a novel typology of digital trust is developed to manage the digitalized open innovation networks. Further on, the impact of digital trust is investigated in improving knowledge-based collaborations in open innovation networks. Since these networks are focused on exchanging knowledge related to the technology; hence, the absorptive capacity associated with technology is considered as technological absorptive capacity (TAC). Nevertheless, the key position of technological orientation (TO) of stakeholders and firms is strongly associated with such technological learning interactions. Thus, the impact of digital trust on improving TAC that leads to enhancing open innovation is investigated by taking TAC as a mediator. In addition, the moderating role of TO is studied in relation to digital trust and open innovation.

Contributions

Theoretical contributions

This research paper presents the concept of digital trust to improve the learning interactions in networks. The study of digital trust is one of the earliest studies carried out in the open innovation networks. In addition, the effect of digital trust in improving technology related interactions is studied in the technology-based firms. In this scenario, the association of digital trust with technological absorptive capacity (TAC) and technological orientation (TO) for enhancing learning interaction in innovation networks is studied.

Practical contributions

This adoption of digital technologies can help improve the firms' innovation capabilities, in the form of trust improvement, a relational capability by forming 'digital trust'. Moreover, the technological side of capabilities, including technological absorptive capacity (TAC) and technological orientation (TO), can be improved through interactive capabilities, e.g., trust. Firms and networks can improve their audience and customers on virtual platforms by forming a digital trust.

Policy contributions

This research established that digital trust, technological absorptive capacity (TAC), and technological orientation (TO) improve technological learning interactions in open innovation networks. In these networks, the collaborations take place amongst various stakeholders, including firms, research institutes, customers, and suppliers. While doing technological learning, networks are technologically advanced by applying a variety of capabilities, e.g., human, social, and organizational, as well as the capabilities related to the network's visibility. The technological advancement is driven by industry 4.0 based digital technologies (e.g., Blockchain) that further promote the notion of sustainability (Mubarak et al., 2021). Correspondingly, next research paper (P-III) studies the intellectual capital-based capabilities that are needed to develop the networks (including supply chain networks) that lead to achieve sustainable production. Hence, the interplay of capabilities that improve technological based supply chain networks and sustainable production is investigated in proceeding article.

Paper 3: Intellectual capital, blockchain-driven supply chain and sustainable production: Role of supply chain mapping. Published in *Technological Forecasting and Social Change*.

Research question#3: How do the firms' intellectual capital-based capabilities influence the technological advancement?

Background

Industry 4.0 has accelerated the digital transformation of firms and networks. It has been established that industry 4.0 technologies facilitate the effective collaborations in open innovation networks that can lead to achieving sustainable innovation performance (Rauter et al., 2019). The researchers have argued that the technological frontiers of industry 4.0 can be utilized to support the technological advancement of critical business processes, such as value chain or supply chain networks (Khan et al., 2021). These digitalized networks contribute to the accomplishment of sustainability. It is one of the vital functions of technological learning. The interactions of firms in networks are highly considering sustainability in their production and processes, both internally and externally (Liang et al., 2022). Therefore, the firms are increasingly looking for technological developments of their supply chain networks in order to boost sustainable production. The technological development of supply chain networks can be accomplished through the adoption of flagship technologies of industry 4.0, such as blockchain, cyber physical systems, IoT, and several others. The technological advancement of supply chain networks can be facilitated through well integrated processes, stronger and trusted relationships with stakeholders, effective collaboration, technological learning, and trust among the network members (Wu, Zhang, 2022). These features can be accumulated through human capital, relational capital, and structural capital, in combination called intellectual capital (Khan et al., 2022). Scholars have proven that for technological upgrading or development of networks such as blockchain driven

supply network, the intellectual capital-based capabilities are critical assets. Without having strong human, relational, and structural capital, the strategic initiatives of technological developments can be disastrous (Muafi, Sulistio, 2022). Furthermore, the visibility of network partners and stakeholders is necessary for improving integration, trust, and sustainable production; hence, it is essential to study related tools for this purpose. These tools should enable the traceability and visibility of product, material, and raw material, such as location, origin of manufacturing, composition, identity, and other information at each stage of the supply chain (Ganesan et al., 2020) while improving the trust. Blockchain driven supply chain networks and supply chain mapping fit to solve this issue; however, much remains to be unknown due to the inconsistent and vague findings in literature (Wichmann et al., 2020). Although the fundamental link between intellectual capital (IC), technological advancement, and sustainable production is on the whole persuasive, more remains to be understood about its precise nature. Therefore, this paper has attempted to address this issue by refining and extending the understanding of the relationship of intellectual capital, networks advancement, and sustainability. The main research question of this paper was how intellectual capital can enhance the technological advancement and sustainable production. The data was collected from 289 technology-based firms in Pakistan and Bangladesh. Then, it was analyzed by employing CB-SEM technique to test the model of the study. In this context, this study has examined the impact of intellectual capital-based capabilities (human capital, relational capital, and structural capital) on sustainable production. Moreover, the mediating role of Blockchain driven supply chain management networks (BCSCM) and supply chain mapping in association with intellectual capital and sustainable production is studied.

Contributions

Theoretical contributions

This research paper contributes by understanding the association of capabilities, networks development, and sustainable production. In this context, the role of intellectual capital-based capabilities is studied for technological sophistication of supply chain networks. These advanced networks assist the sustainable production of firms. Moreover, the role of supply chain mapping as a tool is introduced to facilitate the integration, visibility, and trust in networks (Wu, Zhang, 2022). This study untangles the pattern of technology adoption and sustainability. It starts from the technology learning that has been acquired through intellectual capital, which further supports technology adoption strategy of networks, in which blockchain-based technology is infused in network for improving sustainable production.

Practical contributions

This research paper establishes that the firms should develop their intellectual capital-based capabilities including human, relational, and structural capital to

enhance learning. These capabilities manage the holistic aspects of learning interactions, including both explicit and tacit dimensions of knowledge. Likewise, they can as well succeed the technological upgrading of networks, such as the digitalization of networks that enables the improved innovation collaborations. Further on, these sophisticated networks promote sustainability in production and processes of firms.

Policy contributions

This research paper has established that the intangible capabilities for innovation including human, structural, and relational capital are vital capabilities for managing technological learning and upgrading in supply chain networks. These capabilities facilitate the technology driven supply chain networks to achieve the goal of sustainable production. Moreover, these capabilities as well improve the visibility of network participants that helps to streamline interactions and collaboration amongst them. Furthermore, this technological upgrading of innovation networks enhances sustainable production by encapsulating the goal of sustainability. The visibility and integration of networks can improve the trust in a network that can be practiced by applying the supply chain mapping strategy.

This research paper has revealed that the intellectual capital-based capabilities lead to the advancement of networks that further transform the production and process towards sustainability. This particular pattern and path of technological learning is unearthed where capabilities drive digitalization that supports sustainable production. Sustainability has become one of the overarching objectives of technological learning. Thus, the technological learning should progress in a sustainable approach in a holistic environment. The next research paper (P-IV) studies the phenomenon of sustainability by extracting the functions, components, constituents, and contexts in order to carry out the technological learning in the future accordingly.

Paper 4: Identifying Industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values. Published in *Sustainable Production and Consumption*.

Research question#4: In which strategic direction should the technological learning be navigated to carry out the technological upgrading with a sustainable approach?

Background

The prevailing notion of fourth industrial revolution as well known as industry 4.0 has offered profound contributions to the technological developments of the industry. However, the experts are convinced that it has failed to cater and deliver the goal of sustainability (Renda et al., 2022). It is highly focused on digital transformation, productivity, and profit centered motives (Kumar et al., 2021). To sum up, fourth industrial revolution revolves around technological development and technological upgrading with the previously mentioned objectives by satisfying the neoliberal capitalism, focusing on profitability and shareholder primacy and

ignoring the ‘stakeholders’ primacy (Sindhwani et al., 2022). In order to solve this issue, the European Union issued a policy document presenting the concept of industry 5.0 and introducing three dimensions: human-centricity to promote talent, diversity, and empowerment, resilience, i.e., agility and resilience with flexible and adaptable technologies, and sustainability, leading action to sustainability and respecting planetary boundaries (Renda et al., 2022). In fact, the EU Commission contemplates society 5.0 and considers industry 5.0 as a socio-economic shift towards sustainable future industry (Ghobakhloo et al., 2022). The EU Commission does not undertake industry 5.0 as an incremental and chronological development of industry 4.0, instead, it complements and, in many ways, extends its predecessor by adding the dimension related to socio-environment under the umbrella of sustainability (Breque et al., 2021). Therefore, technological learning is critical to achieve the goals of inclusive sustainability in such settings. Besides numerous ambiguities of definition, functions, and boundaries of industry 5.0, the literature has not provided a holistic explanation on how this phenomenon can deliver the promises of sustainable development in which technological learning should progress. The main research question answered by this paper was how industry 4.0 development can be attuned to sustainable development values through adjusting technological learning direction at the strategic level. The paper has identified the components, functions, and sustainability values of this concept where technological learning and its upgrading could be made. Moreover, a strategy roadmap is developed to show the ways industry 5.0 can deliver sustainable development.

Contributions

Theoretical contribution

The existing framework-based on fourth industrial revolution, as well called industry 4.0, has only focused on the technological dimension of firms and networks advancements. Thus, the attention remains to increase on productivity, profitability, and automation. The consideration of sustainability was not explicitly addressed. Thus, this research paper is one of the seminal studies that extends the notion of industry 5.0 by studying the reference model of sustainability. Moreover, this study has developed and presented a strategy roadmap of industry 5.0 and holistic environment for the first time to progress technological learning and upgrading by upholding the notion of sustainability including all factors and actors.

Practical contributions

This research paper extends the notion of progressing technological learning and technological upgrading to achieve sustainable development values, set by the European Union Commission (Renda et al., 2022). This paper has identified a set of highly interrelated sustainable functions of future technological and industrial development that are supported by the technological constituents, smart components, and techno-functional design principles. Altogether, these elements support sustainable development values including human-centric (social), economic

resilience, and environmental sustainability. The illustration of identified functions, technological constituents, and techno-functional design principles is given in Annex 1, P-IV.

Policy contributions

A reference model for sustainable industrial development has been composed to undertake technological learning in the future, as shown in Figure 6 of P-IV, Annex 1. This research paper as well presents a holistic strategy framework in which technological learning and its upgrading can be made in a sustainable and futuristic way.

2.3. Summary of the articles review

Both the first and second research papers are focused on technological learning that leads towards the technological upgrading interaction in a sustainable way, which is the focus of next two research papers. These interactions are happening in a variety of collaborative innovation networks, including open innovation networks, supply chain networks, global innovation system networks, digital networks, national innovation system networks, and innovation system networks. Technological learning that has been obtained from international networks improves the national innovation system networks. Technological learning is stimulated with the help of the trust (P-I). Moreover, the capabilities including digital trust, technological absorptive capacity (TAC), and technological orientation improve learning interactions in open innovation networks (P-II).

The intellectual capital-based capabilities, including human, relational, and structural capital, support the technological advancement (digitalization) of networks. Moreover, these capabilities improve visibility, integration, and trust in networks. These networks, in return, support sustainable production (P-III). Finally, a holistic framework, covering functions, technological components, design principles, and constituents, is presented to navigate technological learning and its upgrading in the context of sustainability (P-IV).

In this way, the first two research papers focus on the orchestration of technological learning in innovation networks and studying of capabilities required to improve innovation networks. The third paper discusses the capabilities for technological upgrading (advancement) of networks to facilitate sustainable production. The fourth research paper presents an inclusive framework and strategy roadmap for undertaking technological learning and its upgrading by addressing the context of sustainability.

3. FINDINGS, IMPLICATIONS, LIMITATIONS, AND FUTURE RESEARCH

3.1. Findings

i. Research question#1: How are innovation networks orchestrated with the aim of improving technological learning?

Technological learning and trust improve the national innovation system networks through firms' engagement in international networks of innovation. International innovation development strategies promote technological learning in the national innovation system.[1]

The results of P-I ("The role of international networks in upgrading national innovation systems") reveal that technological learning and trust do not directly improve the national innovation system (NIS) networks. However, with the mediation of multiple international networks, the technological learning interactions have proven beneficial to the NIS of the country. This reveals a specific pattern of technological learning that the internationalization and integration with international networks enables successful interactions of technological learning and upgradation in the NIS-based networks. Therefore, the capacity of firms to encourage their international integration, improving relational capabilities and technological knowledge, is of critical importance.

Technological learning within national innovation systems is defined by the quality and diversity of the innovation networks. This implies the need at the policy level to draw greater attention to the facilitation of diversity of innovation networks, including user-driven innovation networks, international innovation alliances, global innovation systems, value chain-based networks, and other more traditional international R&D networks. As the success of the upgrading of national innovation systems depends on the success and direction of international innovation network embeddedness, the technological learning at the global scale should be facilitated by direct and indirect policy measures and include direct support to network formation as well as multi-cultural and multicultural collaborative innovation skills. These extend far behind team diversity management, as institutional components play an important role in including informal and formal institutions. Foreign network formation requires a different set of open innovation and networking skills that needs to be developed at the firm's level in order to enable successful international network-based technological learning. Knowledge transfer to small and medium businesses is meaningful only when it is fully connected to the innovation activities that take place within a smaller business. Therefore, any meaningful knowledge transfer for SMEs requires a better understanding of innovation activities and capabilities within these organizations. SMEs' innovation activities are an amalgam of technology adoption, product and process development, and intensive marketing

[1] Reproduced from Petraite et al. (2022) with permission from Elsevier. The research (Petraite et al., 2022) is one of the publications conducted by the author of this dissertation.

activity. Moreover, at the firm level, innovation capabilities development should focus on strategic innovation partnership management and networking capabilities along with the development of dynamic capabilities as well as trust management. In combination with the absorptive capabilities, more attention must be paid to relational and transformative dimensions of technological learning, the networks of innovation, innovative culture, innovation behavior, dynamic capabilities, intellectual capital, etc. In addition, these capabilities should be investigated in a variety of collaborative innovation networks, including open innovation networks, digital networks, multisided platform-based networks, etc. The development of such capabilities will not increase the technological learning within these networks and lead to further improvement of national or domestic innovation system networks of a country.

ii. How do the capabilities such as digital trust, technological absorptive capacity (TAC), and technological orientation (TO) impact open innovation networks?

Digital trust improves the learning interactions in open innovation networks with the mediation of technological absorptive capacity and moderation of technological orientation in the firms.[2]

The results of P-II ("Industry 4.0 technologies, digital trust and technological orientation: What matters in open innovation?") reveal positive direct impact of digital trust on the open innovation. Moreover, the positive mediating role of both dimensions of technological absorptive capacity (TAC), including potential-TAC (PTAC) and realized-TAC (RTAC), was found between digital trust and open innovation of firms. Furthermore, the positive moderating role of technological orientation (TO) was found as well in association with digital trust and open innovation. Furthermore, in order to identify the differences in the results with respect to the size of the firms, i.e., small and large firms, PLS-MGA (PLS-multi-group analysis) was applied. As a result, the differences were detected, and it has been found that in large firms, the impact of digital trust on the open innovation is greater compared to SMEs. Furthermore, the results show a significant difference in the indirect effect (through the potential technological absorptive capacity, PTAC) of digital trust on the open innovation; whereby, PTAC played a more significant role in large firms compared to SMEs. Although in the case of other indirect effects of digital trust through realized technological absorptive capacity (RTAC) on open innovation and the moderating role of technological orientation (TO), no significant differences have been found. The results of this study revealed a significant role of digital trust in open innovation. Furthermore, the obtained findings revealed a significant mediating role of both TAC dimensions including RTAC and PTAC in association with digital trust and open innovation. The results as well show the moderating role of technological orientation in all cases.

[2] Reproduced from Mubarak and Petraite (2020) with permission from Elsevier. The research (Mubarak, Petraite, 2020) is one of the publications conducted by the author of this dissertation.

The first implication of this study is the adoption of Industry 4.0 technologies in improving conventional organizational challenges and capabilities. Traditional firms try to stay with the conventional technologies due to the innate distrust and uncertainty of new technologies. The obtained findings dispel this conventional fear and suggest that an organization adopting digital technologies can improve digital trust. The adoption of digital technologies cannot be immediate; the organization must develop a comprehensive technological adoption strategy. The development of such strategy allows firm to evaluate the suitability of the latest technologies for the implementation in the organization and helps in the adoption of contemporary technologies. The results imply that an organization should deliberately make efforts to improve its technology-related absorption capacity to improve the orientation of technology-related knowledge in order to facilitate innovations. Integrating the human resource development strategy with the technological strategy of a company can play a vital role in improving its TO and TAC. Based on the findings, it is suggested for large organizations to adopt Industry 4.0 technologies in order to improve their open innovation performance. It was recommended that SMEs should focus on improving their TO and RTAC. Thus, SMEs should focus on improving their TO and TAC in order to prepare a necessary ground for adopting the industry 4.0 digital technologies, which further can augment the firm's open innovation.

iii. How do the firms' intellectual capital-based capabilities influence the technological advancement?

Intellectual capital capabilities including human capital, social capital, and structural capital facilitate the technological development of (supply chain) networks and help to achieve sustainable production.[3]

The study implies that technological upgrading and development of processes and networks, such as blockchain based supply chain network management (BCSCM), can directly contribute to achieve the goal of sustainability. The findings of P-III uncover a significant direct impact of intellectual capital on sustainable production. However, a significant indirect impact of intellectual capital on sustainable production through blockchain based supply chain development (BCSCM) and supply chain mapping has been found. The results as well revealed a significant direct impact of technology advancement of networks (BCSCM) on sustainable production. However, in order to manage technological upgrading, firms ought to have a stronger level of human, relational, and structural capital, i.e., intellectual capital capabilities. Therefore, firms are recommended to develop their capabilities of intellectual capital first in order to successfully progress technological development. Moreover, the higher level of intellectual capitals can support sustainable production by streamlining and facilitating technological development of business networks and processes. These capabilities improve the visibility through mapping of networks (supply chain mapping) of firms that contribute to enhancing

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the integration and trust in the network. The intellectual capital-based capabilities support firms to technologically advance their networks that lead to implementing the goals of sustainability through sustainable production and processes.

iv. In which strategic direction should the technological learning be navigated to carry out the technological upgrading with a sustainable approach?

When doing technological learning and technological upgrading, sustainable development with the inclusion of social, economic, and ecological factors is critical to undertake. Sustainable development is driven by the technological constituents and techno-functional design principles that improve the components of industry 5.0 for the value creation.[4]

The findings of P-IV ("Identifying Industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values") highlight that industry 5.0 can deliver sustainable development values through sixteen functions: open sustainable innovation, sustainable thinking, upskilling and reskilling, value network integration, supply chain adaptability, supply chain modularity, system integration and interoperability, service-orientation and personalization, circular intelligent products, employee technical assistance, intelligent automation, renewable integration, data sharing and transparency, operational and resource efficiency, renewable integration, and real-tie communication. These functions are inter-related and should be developed in a specific manner in order to capitalize on the synergies and complementarities to achieve the technological learning and its upgrading by delivering sustainable development values. These functions are jointly supported by the technological constituents and techno-functional design principles that utilize the smart technological components. Overall, they navigate how to carry out technological learning in the context of sustainability. Thus, a reference model as well as a strategy framework have been developed to direct technological learning with sustainability.

3.2. Implications of the study

Theoretical implications

This study has offered the following contributions to the theory. First and foremost, it is addressing the notion of studying interactive, social, and relational side of innovation related capabilities in technological learning (P-I, P-II). This interactive side of innovation capabilities will help future research to develop further propositions. Second, this research provided a novel concept of 'digital trust' in the context of technological interactions of innovation networks (P-II). Previous studies had studied the element of trust by focusing on the conventional social trust dimensions, whereas this study takes distinction by presenting the digital trust in the

[4] Reproduced from Ghobakhloo et al. (2022) with permission from Elsevier. The research (Ghobakhloo et al., 2022) is one of the publications conducted by the author of this dissertation.

context of technological learning. Further on, the extant research had emphasized technologically advanced networks for sustainable production, leaving the question of how to achieve it unanswered. This study has established that the intellectual capital-based capabilities support the technological advancement of networks. These networks further lead to achieve sustainable production (P-III). Furthermore, previous researchers have focused and heavily addressed the technological advancement of networks and operations in a sustainable way. Thus, they highlighted the shortcomings of the fourth industrial revolution by pointing out its failures. However, the way to achieve this vision and objective has not been addressed in literature. This study (P-IV) has provided a reference model and a comprehensive strategy framework for technological learning upgrading in the context of sustainability. In this way, a new perspective for technological learning and upgrading in the realm of sustainability is presented.

Policy and firm related implications

This research provides guidelines for managers to enhance the collaborations and technological learning in networks of innovation. The foremost is the opening of innovation process and participation in collaborative innovation networks to improve technological learning. The engagement of firms in international networks benefits in the form of improved learning due to the proximity of many stakeholders with developed innovation locations. The learnings gained from such international networks can be applied to domestic or national innovation networks. Moreover, an interactive set of innovation capabilities including technological absorptive capacity, technological orientation and trust is recommended for improving technological learning interactions and collaborations in the networks (P-I, P-II). These capabilities can help to technologically develop and advance the networks by supporting the technology adoption. Intellectual capital-based capabilities should be utilized to technologically upgrade the networks (P-III). These upgraded networks should be capitalized to achieve sustainability in production and processes. Therefore, the firms can gain the benefits of upgrading their networks as well as sufficing the agenda of sustainability, which is increasingly promoted and incentivized by the government. Moreover, the pattern of technological learning and upgrading of innovation network revealed in this study will propel the efforts of policy makers towards developing a national innovation system. Finally, this study offers a comprehensive strategy roadmap and framework to both policy makers and managers in order to accelerate the technological learning and upgrading by practicing the sustainability practices in the future (P-IV).

3.3. Limitations and future research

This research has covered a limited number of innovation capabilities. Due to the research focus on technological learning notion, this research has considered only the interactive side of innovation capabilities that is directly related to this phenomenon. These capabilities include technological abortive capacity, technological orientation, digital trust, human capital, structural capital, social

capital, and network visibility (supply chain mapping) capability. Future researchers are suggested to explore other capabilities related to technological learning and technology upgrading.

For the purpose of data analysis, PLS-SEM techniques are used that have a limitation, because it analyzes the whole structural model by assessing all the modelled paths. However, with the removal of one variable, the results of the model can be different.

Moreover, this study has applied interpretive structural modelling (ISM) to develop the phenomenon of industry 5.0 for sustainability. This method relies on the knowledge of experts (respondents) to formulate the relationships. Different levels of understanding and biases of experts can affect the results. This study has addressed this issue in the subsequent panel meetings.

However, it is recommended to test the developed relationship by applying statistical modelling techniques on a large number of responses. The relationships that were identified in the studies are extensive and large in number; therefore, multiple studies were suggested to cater them.

Further on, the data collection was administered both in-person and online mode due to COVID-19 restrictions in the period of 2020–2022. The full process of in-person data collection could have given a more enriched understanding for the discussion section of the research. However, the insights of this study are not compromised in any way by neglecting any essential protocol of research and provide novel contributions to theory, policy, and practice.

The specific limitations and future research directions are given below by referring to the publications of the dissertation.

Paper 1 [5]

The limitations of the research stem from the research scope and focus, i.e., the entire study has specifically targeted innovative firms from small open economy that face innovation driven growth challenges, namely Lithuania. In addition, the study encompassed R&D intensive SMEs only that shape a specific behavioral pattern and demonstrate higher innovation capabilities, including open innovation as compared to the general sample. The attention should be drawn to the small size of the economy that in combination with the diversity of desired technological knowledge and pressure of rapid internationalization, due to the limited or absent domestic demand, force firms to develop international networks at the very early development stages. A similar tendency has been approached at the level of regional innovation systems and cluster studies (Radziwon, Bogers, 2019). The studies have highlighted the importance of soft skills, especially trust for technological learning across domains, where geographical and cultural proximity plays an important role. Still, technological proximity remains dominant variable, and this study did not explicitly address it. Therefore, the role of technological proximity in combination with the mediating role of international innovation networks in upgrading national innovation

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systems shall be studied further. The role of societal trust in open innovation has been proven to be of critical importance for innovation driven economies (Brockman et al., 2018); however, in the domain of internationally embedded R&D intensive SMEs, it can be replaced by the innovation network-based trust that reaches outside the national borders. Central Eastern European economies still feature some similarities, what concerns societal trust; however, the landscape is rapidly changing in the CEE and Europe at large, and the interfirm trust component in relation to societal trust shall be further studied for deepening the understanding of technological learning and upgrading at the NIS level.

Paper 2 [6]

The first and foremost limitation of this study is the collection and analysis of time series data. As the cross-sectional data was collected in two phases from three countries, if a researcher got the same data longitudinally, it could depict a comprehensive picture. Second, future researchers can extend their sample by including firms from other industries in order to see the stability of the results across both manufacturing and service sectors. Moreover, the high-tech, manufacturing, service, and growth firms should be undertaken to exam the interplay of digital trust and open innovation, as those firms have reputation of accomplishing productive innovation outputs. Finally, the role of organizational structure should be mentioned, which researchers can include in order to see the heterogeneities across various styles of organizational structures.

Paper 3 [7]

First, the recommendation to adopt a network visibility strategy (SC mapping) and BCSCM can be one of the strategic approaches. It was suggested for future researches to look into the other appropriate strategic routes to capitalize on IC, SC mapping, and BCSCM for attaining sustainable production. Second, the use of cross-sectional design for testing the basic hypotheses of the study is another principal limitation. Using the case study approach and considering the case of firms that have already implemented the SC mapping and BCSCM can provide an in-depth understating of this paradox. Additionally, the case-based approach can play a significant role in clarifying SC mapping and BCSCM effects on sustainable production.

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Paper 4 [8]

Overall, this paper has identified the functions through which Industry 5.0 might potentially deliver its intended sustainable development values and accordingly engage in technological learning and technological upgrading. The study modeled the sequence in which these functions should be developed based on the ISM technique and further identified their possible interactions. The standard methodology to develop interpretive model and strategy roadmap was used; however, the following limitations should be taken into consideration while interpreting the results:

- The roadmap is limited to the contextual properties under which it has been developed, particularly concerning the experts' demographics.
- Although the study identified the sequential relationships between each pair of functions, it could not conclusively determine the strength of the relationships, mainly due to the limitation of the ISM methodology.
- The functions introduced root in the early contributions of literature to the Industry 5.0 phenomenon. This topic is new and evolving, and literature on Industry 5.0 is equally embryonic. It is expected that the width and breadth of the Industry 5.0 sustainability functions will grow in the future considerably.
- The study explained how Industry 5.0 could function in promoting sustainable development. Nonetheless, it was unconscionable for the present study to explain how industries and businesses should transform from Industry 4.0 or even older industrial frameworks to Industry 5.0.

Future research is invited to extend the conducted work in the following manners. Due to the methodological constraints, the opinions of European experts were merely reviewed when identifying the contextual relationships among the functions. Although Industry 5.0 is primarily a European initiative, it is expected to become a global reality as Industry 4.0 once did. Using the opinion of a broader spectrum of experts from various socio-economic contexts and resynthesizing the relationships among the sustainable development functions of Industry 5.0 can serve as an important avenue for future research.

While it has been acknowledged that Industry 5.0 has the capacity to promote sustainable development, it is not a self-propelled phenomenon. Indeed, the composed model described a hypothetical best-case scenario where all necessary conditions for materializing Industry 5.0 were in place. Future research is invited to explore how Industry 5.0 technology development and implementation roadmap should be developed to support collaborative innovation, shared research, and collaborative technology diffusion initiatives across regions. In addition, Industry 5.0 is partly a technology driven phenomenon, which relies on the value network-wide integration, interconnectivity, and data-driven operations. The high pace of digital transformation under Industry 5.0 renders cybersecurity as a vital enabler of

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this phenomenon. The width and breadth of cyber risks under Industry 5.0 call for future research on secure and resilient approaches to cybersecurity. Furthermore, the identification of how the power of public private stakeholder collaboration can be harnessed for shaping Industry 5.0 supportive policies, initiatives, and regulatory frameworks represents an important avenue for future research. Finally, future research can address this knowledge gap by conducting in-depth analyses of how businesses can integrate sustainable development values of Industry 5.0 into their corporate strategies and develop measurable indices to assess their progress towards those values.

SANTRAUKA

Tyrimo kontekstase

Inovacijos tapo pagrindine šiuolaikinės ekonomikos atrama. Inovacijų vieta – mokymasis, kai į jį žiūrima kaip į socialinę veiklą, dėl kurios inovacijų procesai yra kaupiami ir bendradarbiauja (Tanner, 2018; Zhang ir kt., 2020). Mokymuisi būtinas platus bendradarbiavimas ir integracija su skirtingais veikėjais ir suinteresuotosiomis šalimis, turinčiomis skirtingus gebėjimus bei žinias. Tokios integruotos sąveikos palengvina dalijimąsi žiniomis, abipusį mokymąsi ir grįžtamąjį ryšį tarp dalyvaujančių subjektų (Dyer ir Nobeoka, 2000; Levén ir kt., 2014).

Technologijomis pagrįstuose sektoriuose gyvuojančios įmonės dažnai veikia sudėtingoje ir dinamiškoje aplinkoje. Šios sąlygos nuolat kinta dėl sparčių technologinės aplinkos pokyčių (Bressler ir Pence, 2019). Mohrman ir von Glinow (1990) teigė, kad „technologinė aplinka vienu metu gali sukurti naujas rinkos galimybes, priversti bankrutuoti esamas įmones ir per naktį paversti atgyvenusiomis ištisas produktų linijas ir gamybos bei projektavimo procesus“ (p. 264). Todėl, norėdamos valdyti tokias nepastovias ir nuolat kintančias situacijas, įmonės turėtų nuolat tobulinti savo technologinį mokymąsi.

Technologinis mokymasis yra dinamiškas su technologijomis susijusių inovacijų diegimo procesas (Oqubay ir Ohno, 2019), kurio metu sukuriamas ilgalaikis technologijų kaupimo vaizdas, technologijos įgyjamos dėl savo potencialo (Dodgson, 2018). Esminė technologinio mokymosi dalis – įgyti žinių apie su technologijomis susijusias galimybes, kurios sparčiai kinta technologinėje aplinkoje. Nors jų pasitaiko įvairiose srityse, tačiau pagrindinis dėmesys skiriamas žinioms, susijusioms su gamyba, MTEP ir techniniais procesais (Bhattacharya ir kt., 2021). Svarbu tai, kad technologinis mokymasis leidžia aptikti technologinius pokyčius, kurie kelia grėsmę esamiems veiklos būdams ir suteikia alternatyvų potencialą (Dodgson, 2022). Taigi, technologinis mokymasis yra itin svarbus siekiant plėtoti su technologijomis susijusias žinias, kad įmonės būtų pasirengusios tobulinti projektavimo ir gamybos procesus dinamiškoje technologinėje aplinkoje.

Dodgsonas (2018: p. 10) apibrėžė technologinį mokymąsi kaip „būdus, kuriais įmonės kuria ir papildo savo žinių bazę apie technologijas, produktus bei procesus ir plėtoja bei tobulina plačių savo darbo jėgos įgūdžių naudojimą“. Įmonės gali pagerinti savo technologinį mokymąsi nuolat tobulindamos ir atnaujindamos savo gebėjimus atitikti šias sąlygas.

Kadangi žinių šaltiniai yra prieinami visiems, įmonės negali individualiai valdyti savo inovacijų, pasikliaudamos tik savo ribotomis žiniomis ir galimybėmis. Vadinasi, inovacijų procesai sparčiai pereina nuo vidinio ir uždaro (gamintojo vadovaujamo) prie atviresnio ir bendradarbiavimu paremto režimo (Fagerberg ir Verspagen, 2021; Rothwell, 1994). Tokiu būdu bendradarbiavimo inovacijos iškyla kaip nauja inovacijų paradigma (Chesbrough ir kt., 2014). Bendradarbiavimas apibrėžiamas kaip „inovacijų kūrimas peržengiant įmonės (ir pramonės) ribas, dalijantis idėjomis, žiniomis, patirtimi ir gebėjimais“ (Ketchen ir kt., 2007, p. 372).

Ir jo „<...> pirminė paskirtis yra gauti prieigą prie partnerio žinių bei kompetencijos, ypač tyliųjų žinių“ (Collins ir Hitt, p. 152). Tai darydami įvairūs veikėjai ir partneriai, pavyzdžiui, įmonės, tyrimų centrai, vartotojai, tiekėjai ir kitos suinteresuotosios šalys, bendradarbiauja siekdamos naujovių. Tai darydami jie keičiasi žiniomis, patirtimi ir ištekliais, kad pasiektų atskirus (arba bendrus) inovacijų tikslus.

Siekiant palengvinti šias mokymosi sąveikas, bendradarbiaujantys inovacijų tinklai formuojasi ir sukuria gerai struktūrizuotą sistemą valdydami mokymosi sąveikas (Reypens ir kt., 2021). Bendradarbiavimo inovacijų tinklai reiškia išteklių ir žinių, paskirstytų įvairiems partneriams, klientams, tiekėjams ir kitoms suinteresuotosioms šalims, integravimo mechanizmą ir procesą, siekiant bendrai kurti ir bendrai dalytis inovacijomis (Möller ir kt., 2020). Tai logiškas didėjančio sudėtingumo, trumpesnio produkto gyvavimo ciklo, didesnių MTEP sąnaudų ir sparčiai besikeičiančios naujoviškų produktų rinkos rezultatas (Song, Ming ir Wang, 2013). Tokių tinklų pavyzdžiai yra atviri inovacijų tinklai (Chesbrough, 2003), tiekimo grandinės tinklai (Khan ir kt., 2022), daugiašaliai skaitmeniniai tinklai (Xie, Fang ir Zeng, 2016), tarptautiniai inovacijų tinklai (Liu ir kt., 2013) ir nacionalinėmis inovacijų sistemomis pagrįsti tinklai (Nelson, 1993). Žinių kūrimas yra inovacijų tinklų pagrindas; todėl jo vaidmuo tapo sėkmingų inovacijų kertiniu akmeniu (Powell ir Grodal, 2006). Įmonės turi nuolat tobulinti savo žinių bazę, kad galėtų nuolat kurti naujoves; todėl ilgainiui dalyvauja bent viename ar įvairiuose bendradarbiavimo inovacijų tinkluose. Tokiuose tinkluose įmonės strategiškai transformuoja savo inovacijų tikslus plėtodamos technologinį mokymąsi (Maguire ir Hardy, 2006). Taigi, tinklai laikomi dominuojančiu kontekstu, kuriame vyksta (technologinis) mokymasis (Vidmar ir kt., 2020). Be to, teigiama, kad „įgūdžių bazė, į kurią įmonės investuoja siekdamos savo inovacijų strategijos, yra esminis dalykas žinioms imlių įmonių gebėjimų kaupimui ir transformavimui“ (Crespi ir kt., 2018, p. 5). Bendradarbiaujantys inovacijų tinklai per mokymąsi taip pat leidžia įmonėms nustatyti esamos įgūdžių bazės konkurencines stipriąsias bei silpnąsias puses ir padėti atnaujinti pagrindines su inovacijomis susijusias kompetencijas, kad būtų pagerintas technologinis mokymasis (Karimi ir kt., 2021; Pan ir kt., 2019).

Tyrimo problema

Technologinis mokymasis leidžia įmonėms sėkmingai diegti naujoves ir atnaujinti technologijas. Tačiau staigūs ir nenuspėjami technologinės aplinkos pokyčiai gali pakeisti įmonės turimos technologinių žinių bazės vertę arba padaryti ją atgyvenusia (Tushman ir Anderson, 2018). Pavyzdžiui, Schumpeterio revoliucijos, technologiniai sutrikimai ir inovacijų bei technologijų gyvavimo ciklų sutrumpėjimas (D'Alvano ir Hidalgo, 2014; Žižlavský, 2013). Kadangi technologinis mokymasis padeda įmonėms kurti su technologijomis susijusias žinių bazes, labai svarbu jį tobulinti, kad išliktų naujoviškas dinamiškoje technologinėje aplinkoje.

Technologiniam mokymuisi reikalingų žinių šaltiniai yra išsklaidyti, o atskira įmonė negali turėti visų tų išteklių savo rezervuose (Reypens ir kt., 2021). Todėl

įmonės privalo ne tik veikti savo viduje, bet ir kreiptis į išorės veikėjus bei suinteresuotąsias šalis. Šiame kontekste bendradarbiavimo inovacijų tinklai gali atlikti svarbų vaidmenį valdant ir koordinuojant paskirstytuosius išteklius vienoje vietoje (Moller ir kt., 2020). Smulkios ekonomikos paprastai neturi stiprios vidinės žinių bazės; todėl jos neišvengiamai turi dalyvauti tarptautiniuose inovacijų tinkluose (Langer ir kt., 2022). Tai taikoma smulkioms ir atviroms ekonomikoms, tokioms kaip Lietuvoje, kuri turi integruotis į tarptautinio bendradarbiavimo inovacijas, kad įgyvendintų technologinį mokymąsi savo nacionalinėse inovacijų sistemose (NIS). Lietuvos NIS apima daug vietinių (sub)tinklų, tokių kaip tyrimų centrai, inkubaciniai centrai, universitetai, mokslo ir technologijų parkai. Lietuvos įmonės yra prijungtos prie tinklų iš kitų Europos šalių, taip pat JAV ir Jungtinės Karalystės.

Be to, ne mažiau svarbu mokytis iš tarptautinių tinklų ir kartu sistemingai juos perkelti bei integruoti į NIS. Tačiau mokslininkai mažai dėmesio skyrė mokymosi sąveikai smulkių ekonomikų tinkluose. Todėl inovacijų tinklų organizavimas siekiant pagerinti technologinį mokymąsi tokiose ekonomikose vis dar lieka atviras klausimas (Friesenbichler ir Reinstaller, 2023). Technologinis mokymasis mažose ir kylančios ekonomikos šalyse priklauso nuo jų dalyvavimo inovacijų tinkluose iš įvairių kitų šalių (Myrzakhmet ir Begimbay, 2022). Priešingai, stambios ir išsivysčiusios ekonomikos (pvz., JAV, JK) skiriasi nuo kitų ir yra laikomos nepriklausomomis su technologijomis susijusių žinių bazėmis (Liu ir Chan, 2022; Johns, 2022). Be to, inovacijų tinklų išdėstymas mažesnėse ir besivystančiose šalyse, kuris priklauso nuo tinklo partnerių, skiriasi nuo stambesnių ekonomikų (Myrzakhmet ir Begimbay, 2022). Todėl labai svarbu ištirti mažų šalies įmonių, dalyvaujančių inovacijų tinkluose, santykinį požiūrį į technologinio mokymosi galimybes. Nors Podmetina ir kt. (2018) pristatė atvirų inovacijų kompetencijas ir parėmė Mortaros (2010; 2014) požiūrį į interaktyvius ir technologinius įgūdžius netiesiogiai asmens ir įmonės lygmeniu, tačiau aiškiai neaptarė šių galimybių sąveikos tinklo lygmeniu. Tokiame kontekste, kai apie technologinį mokymąsi diskutuojama tinklo lygmeniu, atsiranda kritinė tuštuma. Todėl dėmesys technologinei ir interaktyviai inovacijų galimybių pusei turi būti skiriamas rimtai (Mortara, 2010) tinklo lygmeniu. Be to, šia prasme pasitikėjimas yra vienas iš pagrindinių komponentų, padedančių įmonėms tobulinti mokymosi sąveiką tinkluose (Brockman ir kt., 2018). Tiesą sakant, tai yra inovacijų ir mokymosi sąveikos bendradarbiavimo pobūdžio pagrindas (Salampasis ir kt., 2015). Todėl šiame tyrime nagrinėjamas inovacijų tinklų organizavimas ir pasitikėjimo kintamieji technologinėje aplinkoje.

Be to, norint integruoti technologinį mokymąsi iš tarptautinių inovacijų tinklų į NIS, technologinės galimybės yra labai svarbios (Fan ir kt., 2020). Esami tyrimai nagrinėjo mokymosi kaip gebėjimo įsisavinti vaidmenį (Cohen ir Levinthal, 1990), o šis tyrimas priartina jo technologinę dimensiją prie technologinio įsisavinimo pajėgumo (TAC) tyrimo. Be to, technologinė orientacija (TO) tiriama siekiant pagerinti mokymosi sąveiką bendradarbiavimo tinkluose. Šios galimybės yra glaudžiai susijusios su technologinėmis žiniomis ir sąveika (García-Morales ir kt.,

2007). Kaip minėta anksčiau, didelių ir išsivysčiusių šalių tinklų sudėtis skiriasi nuo mažųjų; štai kodėl tikslinga tirti BLSK ir TO kintamuosius mažesnėse ir besivystančiose šalyse. Taigi tyrime aptariamas šių gebėjimų vaidmuo skatinant mokymosi sąveiką atviruose inovacijų tinkluose.

Be to, technologinis mokymasis yra susipynęs su įmonių žiniomis, kurios tiesiogiai susijusios su intelektinio kapitalo požiūriu. Intelektinis kapitalas apima žmogiškojo kapitalo, santykių kapitalo ir įmonių struktūrinio kapitalo dimensijas (Khan ir kt., 2022). Tai padeda sustiprinti mainus (aiškius ir numanomus), siekiant pagerinti įmonių žinių bazę tinkluose (Farzaneh ir kt., 2022). Sukūrę tinklus, jie laipsniškai kuria ir perima technologiją (Kergroach, 2019). Taigi, intelektualiu kapitalu pagrįstų pajėgumų vaidmenį gerinant tinklų technologinę pažangą ir jų matomumą verta ištirti besivystančių šalių, turinčių žmogiškąjį kapitalą, kontekste (Tsolakis ir kt., 2022).

Papildydami ankstesnius faktus, politikos formuotojai anksčiau pasiūlė ketvirtąją pramonės revoliuciją ir pramonę, kuri būtų technologinio mokymosi rezultatas (taip pat vadinama pramonė 4.0). Tuo metu (2011 m.) pramonė iš karto ją priėmė, kartu įsipareigodama pritaikyti ir naudoti technologiją visuomenės labui. Nors, kaip teigė Kranzbergas (1986), „pati technologija nėra nei gera, nei bloga; ji taip pat nėra neutrali“ (p. 545), todėl technologija visada yra nukreipta kokia nors linkme. Pramonės šakos nesugebėjo įgyvendinti savo pažadų dėl socialinės gerovės, orientacijos į žmogų ir tvarumo (Renda ir kt., 2022). Vietoj to, pramonės 4.0 koncepcija buvo sutelkta į automatizavimą, efektyvumą, produktyvumą ir pelningumą, nepaisant pažadėtų verčių. Taigi, dabartinėje technologinėje aplinkoje šis požiūris tapo netvarus naujovėms, ir jau prasidėjo judėjimas, kad pramonės 4.0 technologijos taptų tvaresnės, labiau orientuotos į žmogų ir atsparesnės (Ghobakhloo ir kt., 2022). Tačiau šio tikslo siekimo sistema ir gairės yra nepakankamos (Saniuk ir kt., 2022). Todėl reikia daugiau tyrimų, kad technologinis mokymasis būtų orientuotas taip, jog jis galėtų atitinkamai kurti savo žinių bazę ir prisidėti prie technologinio atsinaujinimo, vadovaujantis darnaus vystymosi principais inovacijų tinkluose. Šis tyrimas taip pat nagrinėja šitą reiškinį ir sukuria technologinio mokymosi orientavimo į šitą konkretų technologinės aplinkos pokytį pagrindą.

Tyrimo tikslai ir uždaviniai

Šiame tyrime pagrindinis dėmesys skiriamas technologiniam mokymuisi itin dinamiškų ir sparčiai besivystančių ekonomikų, tokių kaip Baltijos šalys Europos regione ir Pietų Azijos šalys, kuriose sparčiai randasi technologijomis pagrįstos firmos ir kurios turi daug žmogiškojo kapitalo, kontekste. Tai darant, tiriamos technologinės mokymosi sąveikos atviruose inovacijų tinkluose, skaitmeniniuose tiekimo grandinės tinkluose ir tinkluose, pagrįstuose nacionalinėmis bei tarptautinėmis inovacijų sistemomis.

Šiuo tyrimu siekiama pagerinti technologinį mokymąsi per įmonių sąveiką bendradarbiavimo inovacijų tinkluose. Šitame kontekste keliamas tyrimo klausimas,

kaip galima pagerinti įmonių, dalyvaujančių bendradarbiavimo inovacijų tinkluose, technologinį mokymąsi.

Tokiu tikslu po aptarto platesnio tyrimo klausimo yra iškelti toliau pateikiami klausimai.

1) Kaip diegiami inovacijų tinklai, siekiant pagerinti technologinį mokymąsi?

2) Kokiu būdu tokios galimybės kaip skaitmeninis pasitikėjimas, technologinis įsisavinimo pajėgumas (TAC) ir technologinė orientacija (TO) veikia atvirus inovacijų tinklus?

3) Kaip firmų intelektinio kapitalo pajėgumai daro įtaką tinklų technologinei pažangai?

4) Kokia strategine kryptimi reikėtų nukreipti technologinį mokymąsi į technologijų tobulinimą taikant tvarų požiūrį?

Mokslinės naujovės ir autoriaus indėlis

Šis tyrimas įnešė daug esminių ir naujų indėlių. Pirma, tyrimo metu buvo stebimos technologinio mokymosi santykinės dimensijos tarp įmonių inovacijų tinkluose. Tada technologinis mokymasis buvo tiriamas kaip reiškinys, kai mokymasis vyksta inovacijų tinkluose, kur įmonės gali pasiekti tinklo išteklius. Svarbiausia, kad tai pirmasis bandymas susieti firmos ir tinklo lygmens technologinį mokymąsi tiek per nacionalinius, tiek per tarptautinius inovacijų tinklus. Be to, skaitmeninio pasitikėjimo sąvoka taip pat pirmą kartą išplėtota inovacijų valdymo literatūroje; skaitmeninis pasitikėjimas empiriškai apibrėžtas kaip esminis gebėjimas stiprinti technologinio mokymosi sąveiką atviruose inovacijų tinkluose. Be to, įrodyta, kad pajėgumai, grįsti intelektiniu kapitalu, yra tinklų technologinio tobulinimo varomoji jėga. Šie pažangūs tinklai sudaro sąlygas tvariai gamybai. Galiausiai tyrime pateikiama holistinė tvaraus technologinio tobulinimo strategijos sistema. Apskritai šis tyrimas paaiškina būdus, kaip pagerinti technologinį mokymąsi per įmonių tarpusavio sąveiką, vykstančią bendradarbiavimo inovacijų tinkluose, aptariant atvirus inovacijų tinklus, tiekimo grandinės tinklus, skaitmeninius tinklus, tinklus, pagrįstus nacionalinėmis inovacijų sistemomis, ir tarptautinius tinklus.

Mokslinių tyrimų metodologija

Tyrime nagrinėjama tiesioginė ir netiesioginė technologinio mokymosi sąveika keliuose bendradarbiaujančiuose inovacijų tinkluose, kur į šiuos parametrus įtraukiami keli unikalūs kintamieji, tokie kaip inovacijų pajėgumai, įskaitant skaitmeninį pasitikėjimą, technologinį įsisavinimo pajėgumą (TAC) ir technologinę orientaciją (TO) bei intelektinį kapitalą, ir jais pagrįstos galimybės. Nėra vieno geriausio būdo tirti technologinį mokymąsi šiose įvairiose sąveikose tarp skirtingų tinklo archetipų. Todėl iškeltiems tyrimo tikslams pasiekti buvo taikomi įvairūs tyrimo metodai, kuriais dirbant skirtingi tyrimai buvo atlikti ir paskelbti kaip keturi kokybiški mokslo darbai. Pirmasis mokslinis darbas pavadintas „Tarptautinių tinklų

vaidmuo gerinant nacionalines inovacijų sistemas“ (P-I), kuriame nagrinėjamas inovacijų tinklų derinimas siekiant pagerinti technologinį mokymąsi. Šiame darbe taikytas kiekybinis tyrimo metodas, kai surinktiems duomenims buvo pritaikyta SEM-PLS technika. Antrasis straipsnis pavadintas „Pramonės 4.0 technologijos, skaitmeninis pasitikėjimas ir technologinė orientacija: kas svarbu atviroms inovacijoms“ (P-II). Jis tiria galimybes, įskaitant skaitmeninį pasitikėjimą, technologinį įsisavinimo pajėgumą (TAC) ir technologinę orientaciją kuriant atvirus inovacijų tinklus, taikant PLS-SEM metodus surinktiems duomenims. Trečiajame dokumente „Intelektualus kapitalas, blokų grandinėmis valdoma tiekimo grandinė ir tvari gamyba: tiekimo grandinės žemėlapių vaidmuo“ (P-III) buvo aptartas intelektiniu kapitalu pagrįstų pajėgumų (įskaitant žmogiškąjį, santykių ir struktūrinį kapitalą) poveikis dėl technologijų pažangos (tiekimo grandinės) tinkluose. Moksliniame darbe surinktiems duomenims analizuoti ir modeliuotiems ryšiams patikrinti buvo taikomas kovariaciniu pagrindu sukurtas struktūrinių lygčių modeliavimas (CB-SEM). Šio tyrimo metu duomenys buvo renkami taikant Pavitto (1984) taksonomijos metodus. Ketvirtajame moksliniame darbe, pavadintame „Pramonės 5.0 indėlio į tvarų vystymąsi nustatymas: tvarumo vertybių pateikimo strategijos planas“ (P-IV), buvo priimtas aiškinamojo struktūrinio modeliavimo (ISM) metodas, siekiant nustatyti funkcijas ir komponentus, kad būtų galima sukurti strategiją, tvaraus technologinio mokymosi sistemą. Šiame moksliniame darbe kuriant sistemą buvo pritaikytas ekspertų žiniomis pagrįstas sprendimų priėmimas, apimantis daugiakriterį sprendimų priėmimą (MCDM).

Trijuose iš šių leidinių buvo taikomas kiekybinis tyrimo metodas, renkant pirminius duomenis apie įvairius tinklus (pvz., tiekimo grandinės tinklus, atvirus inovacijų tinklus, skaitmeninius tinklus, tarptautinius tinklus ir inovacijų sistemomis pagrįstus tinklus). Nors viename leidinyje taikoma kokybinė metodika. Surinktiems duomenų rinkiniams taip pat buvo taikomi įvairūs analizės metodai, kad atitiktų kiekvieno darbo tyrimo tikslus. Taikomi duomenų analizės metodai apima dalinį mažiausiųjų kvadratų struktūrinių lygčių modeliavimą (PLS), kovariacija pagrįstą struktūrinių lygčių modeliavimą (CB-SEM) ir interpretacinį struktūrinį modeliavimą (ISM).

Pagrindiniai rezultatai ir išvados

1. Technologinis mokymasis ir pasitikėjimas leidžia tobulinti nacionalinius inovacijų sistemos tinklus įmonėms įsitraukus į tarptautinius inovacijų tinklus. Tarptautinės inovacijų plėtros strategijos skatina technologinį mokymąsi nacionalinėje inovacijų sistemoje.

2. Skaitmeninis pasitikėjimas gerina mokymosi sąveiką atviruose inovacijų tinkluose, tarpininkaujant technologiniam įsisavinimui ir technologinės orientacijos mažinimui įmonėse.

3. Intelektinės kapitalo galimybės, įskaitant žmogiškąjį kapitalą, socialinį kapitalą ir struktūrinį kapitalą, palengvina (tiekimo grandinės) tinklų technologinę plėtrą ir padeda pasiekti tvarią gamybą.

4. Mokantis technologijų ir technologinio tobulinimo, labai svarbu laikytis tvaraus vystymosi strategijos, įtraukiant socialinius, ekonominius ir ekologinius veiksnius. Tvarų vystymąsi skatina technologinės sudedamosios dalys ir technologinio-funkcinio projektavimo principai, kurie patobulina pramonės 5.0 komponentus vertės kūrimui.

Išvados atskleidžia, kad technologinį mokymąsi ir pasitikėjimo sąveiką nacionalinėje inovacijų sistemoje (NIS) galima pagerinti įmones internacionalizuojant. Tokiu būdu įmonės dalyvauja tarptautiniuose inovacijų tinkluose ir perkelia žinias bei idėjas savo šalies inovacijų tinkluose. Be to, pasitikėjimas tų tinklų tarptautiniu institucionalizavimu taip pat pasitelkiamas tobulinant vidaus sistemų (NIS) tinklus. Antrojo mokslinio darbo išvados rodo, kad skaitmeninis pasitikėjimas yra tinkama galimybė pagerinti technologinio mokymosi sąveiką atviruose inovacijų tinkluose. Šios sąveikos pagerinamos tarpininkaujant technologiniam įsisavinimui ir mažinant technologinę orientaciją. Trečiojo tyrimo išvados rodo, kad technologinė pažanga arba tinklų atnaujinimas gali prisidėti prie tvarios gamybos. Tačiau ši pažanga valdoma pasitelkiant aukštesnio lygio intelektinio kapitalo galimybes, įskaitant žmogiškąjį, santykių ir struktūrinį kapitalą. Galiausiai, ketvirtojo darbo išvados atskleidžia tvaraus vertybių vystymosi funkcijas per technologijų projektavimo principus ir technologines sudedamąsias dalis. Tai darant parengiamas strateginis planas, skirtas technologiniam mokymuisi ir technologiniam atnaujinimui tvarumo kontekste. Tokiu būdu technologinis mokymasis daro įtaką tinklų technologinei pažangai, todėl pakanka tvarumo tikslo. Šią technologinę pažangą lemia aibė galimybių diegti naujoves (inovacijas).

Išvados ir rekomendacijos

Reikėtų atkreipti dėmesį į tarptautinį įmonių dalyvavimą, ypač mažose ir kylančios ekonomikos šalyse, siekiant plėtoti technologinio mokymosi sąveiką TIS. Be to, įmonės turėtų pagerinti savo technologijų įsisavinimo gebėjimus ir technologinę orientaciją, kad optimizuotų technologinio mokymosi naudą. Įmonės turėtų stengtis pirmiausia plėtoti savo žmogiškąjį, santykių ir struktūrinį kapitalą, kad sėkmingai valdytų technologinį tinklų atnaujinimą, kuris padėtų pasiekti tvarios gamybos tikslą. Galiausiai, tobulinant technologinį mokymąsi, reikia nepamiršti darnaus vystymosi funkcijų ir projektavimo principų, kad būtų užtikrintas įtraukus darnus vystymasis.

Tyrimo pasekmės

Šis tyrimas pasiūlė tokius indėlius į teoriją. Visų pirma kalbama apie interaktyviosios, socialinės ir santykinės su inovacijomis susijusių technologinio mokymosi gebėjimų (P-I, P-II) pusės studijavimo sąvoką. Tokia interaktyvi inovacinių galimybių pusė paskatins būsimus tyrėjus remtis parengtais pasiūlymais. Antra, šis tyrimas pateikė visiškai naują „skaitmeninio pasitikėjimo“ koncepciją

inovacijų tinklų technologinės sąveikos (P-II) kontekste. Ankstesniuose tyrimuose pasitikėjimo elementas buvo tiriamas sutelkiant dėmesį į įprastus socialinio pasitikėjimo aspektus, o šiame tyrime skaitmeninis pasitikėjimas pateikiamas technologinio mokymosi kontekste. Be to, išlikę tyrimai pabrėžė technologiškai pažangius tvarios gamybos tinklus, o į klausimą, kaip tai pasiekti, nebuvo atsakyta. Šis tyrimas parodė, kad intelektiniu kapitalu pagrįstos galimybės palaiko tinklų technologinę pažangą. Šitie tinklai toliau padeda siekti tvarios gamybos (P-III). Be to, ankstesni tyrėjai daug dėmesio skyrė tinklų ir operacijų technologinei pažangai tvarumo aspektu. Tai darydami jie pabrėžė ketvirtosios pramonės revoliucijos trūkumus, nurodydami jos nesėkmes. Tačiau atsakymų, kaip įgyvendinti šią viziją ir tikslą, literatūroje visai nebuvo. Šis tyrimas (P-IV) pateikė orientacinį modelį ir išsamią technologinio mokymosi tobulinimo strategijos sistemą tvaraus vystymosi kontekste. Tokiu būdu pateikiama nauja technologinio mokymosi ir tobulėjimo perspektyva tvarumo srityje.

Šis tyrimas suteikia vadovams gaires, kaip pagerinti bendradarbiavimą ir technologinį mokymąsi inovacijų tinkluose. Svarbiausia yra sudaryti sąlygas inovacijų procesui ir dalyvauti bendradarbiavimo inovacijų tinkluose, siekiant pagerinti technologinį mokymąsi. Įmonių įsitraukimas į tarptautinius tinklus yra naudinga geresnio mokymosi forma, nes daugelis suinteresuotųjų šalių yra arti išplėtotų inovacijų vietų. Tokiuose tarptautiniuose tinkluose įgytos žinios gali būti pritaikytos šalies ar nacionaliniams inovacijų tinklams. Be to, siekiant pagerinti technologinio mokymosi sąveiką ir bendradarbiavimą tinkluose (P-I, P-II), rekomenduojamas interaktyvus inovacinių galimybių rinkinys, įskaitant technologinį įsisavinimo pajėgumą, technologinę orientaciją, pasitikėjimą. Šios galimybės taip pat gali padėti technologiškai plėtoti ir tobulinti tinklus, remiant technologijų diegimą. Tinklų technologiniam atnaujinimui (P-III) turėtų būti pritaikytos intelektinio kapitalo galimybės. Tokie atnaujinti tinklai turėtų būti kapitalizuojami, kad būtų užtikrintas gamybos ir procesų tvarumas. Čia įmonės taip pat gali gauti naudos ne tik atnaujindamos savo tinklus, bet ir vykdydamos tvarumo darbotvarkę, kurią vis labiau skatina vyriausybė. Be to, šiame tyrime atskleistas technologinio mokymosi ir inovacijų tinklo tobulinimo modelis paskatins politikos formuotojų pastangas plėtoti nacionalinę inovacijų sistemą. Galiausiai šiame tyrime tiek politikos formuotojams, tiek vadovams pateikiamas išsamus strateginis planas ir sistema, siekiant paspartinti technologinį mokymąsi ir tobulėjimą, ateityje taikant tvarumo praktiką (P-IV).

Studijų apribojimai

Tyrimas apėmė ribotą skaičių inovacijų galimybių. Kadangi mokslinis dėmesys sutelktas į technologinio mokymosi sampratą, tyrime buvo nagrinėjama tik interaktyvioji inovacinių galimybių pusė, kuri yra tiesiogiai susijusi su minimu reiškiniu. Tokios galimybės apima nepasitenkinimą technologijomis, orientaciją į technologijas, skaitmeninį pasitikėjimą, žmogiškąjį kapitalą, struktūrinį kapitalą, socialinį kapitalą ir tinklo matomumo (tiekimo grandinės pavaizdavimo) galimybes.

Būsimiems mokslininkams siūloma ištirti kitas galimybes, susijusias su technologiniu mokymusi ir technologijų atnaujinimu.

Duomenų analizės tikslais taikomi PLS-SEM metodai, kurių apribojimas yra tas, kad jais analizuojamas visas struktūrinis modelis, įvertinant visus modeliuotus kelius. Tačiau, pašalinus vieną kintamąjį, modelio rezultatai gali būti skirtingi.

Be to, šiame tyrime taip pat taikytas aiškinamasis struktūrinis modeliavimas (ISM), siekiant plėtoti pramonės 5.0 reiškinį tvarumui užtikrinti. Aptariamas metodas paremtas ekspertų (respondentų) žiniomis formuojant ryšius. Skirtingas ekspertų supratimo lygis ir šališkumas gali turėti įtakos rezultatams. Nors tas klausimas buvo išspręstas vėlesniuose komisijos posėdžiuose.

Tačiau rekomenduojama patikrinti nustatytą ryšį taikant statistinio modeliavimo metodus daugeliui atsakymų. Mūsų tyrime nustatyti ryšiai yra platūs ir esminiai, todėl siūlomi keli tyrimai.

Be to, dėl Covid-19 apribojimų 2020–2022 m. laikotarpiu duomenys buvo renkami tiek bendraujant asmeniškai, tiek internetu. Visas asmeninio duomenų rinkimo procesas galėjo suteikti daugiau įžvalgų apie tyrimo diskusijų dalį. Tačiau šio tyrimo įžvalgos jokiu būdu nepažeidžia jokio esminio tyrimo protokolo ir suteikia naujų indėlių į teoriją, politiką ir praktiką.

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Paper 1

Petraite, M., Mubarak, M. F., Rimantas, R., & von Zedtwitz, M. (2022). The role of international networks in upgrading national innovation systems. *Technological Forecasting and Social Change*, 184, 121873.

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The role of international networks in upgrading national innovation systems

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ABSTRACT

Technological learning within national innovation systems (NIS) stands at the core of technological upgrading at the firm and economy level. The common understanding is that NIS are the primary source of technological knowledge acquisition for innovating firms, but the opening of economies, the globalization of innovation networks, and the rapid internationalization of innovative firms challenge this view – especially with respect to small open economies in transition. We applied PLS-SEM to data from 131 R&D intensive firms responding to a survey investigating the mediating role of international networks for technological learning within Lithuania's NIS. The findings demonstrate a full mediating role of global innovation system networks in facilitating technological learning within NIS, partially contradicting the prevailing understanding of the primary importance of NIS based networks for firm learning. Technological learning of firms, and thus the upgrading of the NIS they are embedded in, relies more on international networks than previously assumed. These results call for a more careful design and facilitation of technological learning networks, recognizing global networks as a complementary and necessary component in NIS upgrading. This study contributes to the literature of technological learning within national innovation systems, with a special focus on R&D intensive firms leading the technological upgrading of a country's NIS.

1. Introduction

Research on transition and emerging economies has mainly focused on large economies such as China, India, Brazil and Russia, primarily because of the significance of these economies in the global community, the relative ease of conducting empirical research in large economies, and the availability of data in these countries. Small transitioning economies tend to be less well covered in terms of publicly available data and are less accessible to study (which makes subsequent research publication less likely). They have fewer means at their disposal to pursue national innovation policies. Because of their relative economic insignificance, they attract less interest from the public, including research funding. As a result, we know relatively little about the transition and technology upgrading mechanisms in smaller economies (Radosevic et al., 2019).

Given this bias in existing research, most of our assumptions about small country transitions are based on large country transitions. However, large countries differ from small countries in several ways relevant to their technological catch-up, including the presence of a large domestic market, large domestic variance of knowledge pools and economic conditions, and a greater variety of opportunities for economic and technological upgrading. Smaller countries do not have these characteristics and thus are more likely to be externally (i.e., internationally) oriented in their transformation. Simultaneously, several features of big transition economies are also evident in small transition economies, such as a relatively low level of trust in the country's bureaucracy and public institutions, a relatively low level of innovation (particularly in the early phases of the transformation) in comparison to rapid economic development, and widespread mistrust in the business community on how individual entrepreneurs will perform (as opposed

Abbreviations: NIS, National Innovation System; PLS-SEM, Partial least squares structural equation modeling; R&D, Research and Development; SME, Small and medium-sized enterprise; OI, Open Innovation; IS, Innovation System; AVE, Average Variance Extracted; CEE, Central Eastern Europe; OECD, Organisation for Economic Co-operation and Development; EFA, Exploratory Factor Analysis; CFA, Confirmatory Factor Analysis; VIF, Variance Inflation Factor.

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to seeking their luck in emigration).

In our research, we examine the role of the national innovation system-based networks in transforming the small-country economy through upgrading its technological and technological learning capabilities for innovation performance of firms operating in national innovation system-based networks. The concept of national innovation system (NIS) appeared in science, technology, and innovation studies in the late 1980s (Freeman, 1987; Lundvall, 1992; Nelson and Rosenberg, 1993). This framework suggested that the research system's ultimate goal is to facilitate innovation and acknowledged that the NIS is merely a component of a broader system that encompasses government, academia, industry, and the environment. The NIS concept also highlighted the linkages between the components or sectors as the "cause" of innovation systems' performance. However, we do not investigate the national innovation system per se in our study, instead we focus on firms operating in national innovation system based *networks*. R&D-intensive firms are considered as a vital source of economic growth based on technology upgrading (Radosevic et al., 2019), including foreign firms with inbound R&D investments in a country's innovation system as well as domestic firms' engagement in international innovation. Many Central Eastern European (CEE) economies are facing challenges in domestic technology absorption and their participation in global value chains (Radosevic, 2022), providing both the need and the opportunity to investigate technology learning in international networks.

The paper targets a continuing dialogue on national innovation systems-based networks (Freeman et al., 1982; Edquist and Lundvall, 1993), focusing on re-examining technology learning patterns in the post-soviet Eastern European context. Following Lundvall (2015), we define the national innovation system (NIS) as an open, evolving and complex system that encompasses institutions and economic structures, whereas the quality of its elements and the relationships between elements determine the rate and direction of innovation. Research on the knowledge and learning economy has emphasized learning within geographical proximities and knowledge spill-over effects on regional technological capability building. Lundvall (2015) noted that the relationships between users and producers are based on interactive organizational learning where the parties build channels for information transfer and develop a common language. Certain individual attributes, such as shared culture, shaped by common education and work experience, make it easier to interact among national borders. Empirical network analysis (Rothwell, 1994) showed that the networks most frequently mobilized for innovation were national rather than local or global.

In the context of open economies, the role of relationships is further amplified, productive interactions across divisional borders within the organization, external organizations such as suppliers, users, and knowledge institutions are considered as critical for open innovation success. Wang et al. (2012) revealed that open innovation (OI, Chesbrough, 2003) within national innovation systems-based network is linked to a country's specific context, that encompasses both, firm level capabilties, and system level capabilties. OI practices depend heavily on the internal capability of firms to leverage outbound and inbound knowledge and on the availability of sufficient external knowledge and other important resources. A well-equipped functional NIS largely determines the supply of external knowledge. This strong interdependence makes NIS more important than ever before. Open innovation is an emerging, collaborative, multi-actor, and multi-level process that involves business, government, research, and civil society (Radziwon and Bogers, 2019).

There is general consensus in the literature that it is the responsibility of firms to build robust and internationally competitive innovation systems. In their study of technology-intensive firms in Central and Eastern Europe, Radosevic and Yoruk (2012) found that the most important factors for innovation success were interaction with users, understanding of markets, and technological collaboration with other firms, confirming that firm innovation behaviour patterns were generally the same in rapid innovation driven transition countries as in developed innovative economies. However, given the complexity of innovation transactions, NIS and other innovation systems (IS) based technological learning can only take place under favourable socio-institutional conditions. Traditionally, the focus of study has been addressing formal institution, with less attention to the soft institutions, such as firms innovative capabilities, technological learning, dynamic capablities, and last but not least relational capabilties such as partnership managemnt and trust skills. In their study of 34 countries, Ghazinoory et al. (2014a,b) confirmed the strong positive effect of institutional trust and networking on entrepreneurship. Interpersonal trust and networks were shown to have a strong influence on knowledge development at the national level. Therefore, broader underlying contextual factors that are defined by societal rather than economic growth need to be considered when studying innovation and technology upgrading. Further studies by Brockman et al. (2018) established societal trust as a key factor in influencing the efficiency of open innovation. Post-soviet studies on trust – including institutional, business, and interpersonal trust – reveal specific conditions where higher international institutional trust is demonstrated compared to the national institutional trust (Audretsch et al., 2018) and weak institutional trust (Amorós and Bosma, 2013). Research on the role of national innovation systems on firm innovation behaviour has mostly neglected this vital component or addressed it indirectly, despite the acknowledged importance of technology learning within innovation networks. The principal question on how organizational capabilities associated with technology learning, knowledge exchanges, and trust for innovation impact the networking patterns within NIS environments remains open. However, in light of the relatively weak NIS performance within well-performing transition economies (in terms of general macroeconomic indicators), this issue raises critical importance.

Based on this problem formulation, we aim to discuss the role of international networks in upgrading national innovation systems-based networks built on research in a small CEE economy. The results highlight the importance of international business and innovation systems integration, especially in small transition economies. Large transition economies, also benefit from such international linkages but rely on a more extensive arsenal of assets and opportunities in leveraging domestic and global capabilities. This realization has significant implications for policy making in small transition economies regarding opening up their economy to foreign investment, allowing domestic actors to tap into global markets and resources, and long-term strategy development in domestic companies for technological and organizational upgrading. Future research will need to qualify better the effect of the international contribution for small transition economies (e.g., which resources and assets matter most) and the sources of international partners and competitors (e.g., whether those are from other large transition economies or already advanced industrialized economies countries).

This study fills a research gap by focusing on technological learning and compund role of trust in upgrading national innovation systems through international networks – empirically investigated in the context of Lithuania, a small CEE economy on the European periphery, which has demonstrated rapid eonmic growth, and reached the level of highly developed economies in 20 years of development (WB, 2022) under generally undermined trust in institutions, systems, and also societal trust by post-soviet legacy and is demonstrating the transition towards innovation driven growth in the recent decade.

Analysing the results of a survey of 131 firms in the small transition economy of Lithuania with SEM-PLS, we find that the linkages of domestic firms with the international community (in terms of access to international business networks, to global innovation systems based networks, and through domestic foreign competition and presence of foreign innovation actors) are significantly more critical for the development of the national innovation system-based firms' network than predicted by large economy transition research. Domestic organizational and technological knowledge is inconsequential for the

improvement of the national innovation system-based network unless associated with the international networks and competition; we interpret these findings as a technology learning and associated trust benefit granted to international experience (in the case of domestic firms operating in a global context) and international reputation (in the case of foreign competitors operating domestically). Furthermore, innovation performance, productivity, and success are highly influenced by user networks – i.e., communities in which domestic and international actors pursue innovation within shared markets or platforms – and again neutral concerning national innovation systems-based network otherwise.

The paper is structured as follows. The first part discusses the theoretical underpinning of technology learning and its manifestation in various innovation networks, especially national and global innovation systems based and value chain-based networks. We also develop the hypothesis for empirical modelling of the mediating role of international networks for technological learning within the national innovation system based networks. The second part of the paper focuses on the research methodology (survey-based data collection on innovative firms within a small open economy), data presentation, hypothesis testing using SEM PLS modelling, and analysis. Finally, we provide key findings, discussion and implications.

2. Literature review and hypothesis development

2.1. Firms internationalization strategy and technological learning

Dodgson (1991:110) defines technological learning as "the ways firms build and supplement their knowledge-bases about technologies, products, and processes, and develop and improve the use of the broad skills of their workforces." In contrast, Kim (1997) uses technological learning simply to depict the dynamic process of acquiring technological capability. Hitt et al. (2000) suggested that "technological learning is linked to the firm's ability to develop, maintain and exploit dynamic core competencies" which are related to technology. Therefore, technological learning is the development of knowledge about technologies, products and processes while developing the competencies in order to enhance technological capabilities.

Technological learning enables technology-driven companies to acquire and sustain knowledge (Simpson et al., 2001) both for competitive advantage and for developing entire emerging industries. For instance, Dodgson (1991) describes the learning characteristics of a leading European biotechnology company, Kim (1997) investigates both macro and micro levels of analysis to explain the dynamics of learning in several highly successful Korean technology-based industries, and Carayannis (2000) identifies learning practices used by US and European companies that have demonstrated long-term success and prosperity in a variety of technology-driven sectors. Other research emerging in the 1990s highlighted the importance of learning in high-tech or technology-driven industries (Hitt et al., 2000; Ernst, 1998; Kazanjian et al., 2000; Hobday, 1994; Bohn, 1994; Zahra et al., 2000).

At the level of international networks, knowledge and learning are seen as sources to compete globally and considered at least as valuable as physical assets if not more (Barney, 1991; Grant, 1996; Sanchez and Heene, 1997; Conner and Prahalad, 1996). The notion of technological learning also implies an ongoing and interactive process that can accommodate the emerging, unexpected characteristics of innovation and new knowledge creation. The interactions among all the actors of an innovation system are fundamental sources of knowledge and learning in the system and constitute an essential part of the innovation process (Lundvall, 1992; Malerba and Nelson, 2011).

Simpson et al. (2001) reiterated that it is of utmost importance for technology-driven companies to have relationships with customers, suppliers, users, and other external partners, and to learn from their experiences via their inclusion in collaborative innovation networks. These relations lead to learning by interaction where trust is established and eventually reinforcing the interaction with stakeholders, which is essential for firms to innovate with external partners. Additionally, Simpson et al. (2001) confirmed that innovative firms establish relationships with innovation-based partners, such as external research institutes or universities, to learn from them. Furthermore, the knowledge obtained from external sources and partners is utilized by integrating it into their processes, products, and services (Simpson et al., 2001; Mahmood and Mubarik, 2020). In a nutshell, technological learning can be acquired from various actors such as technology developers, suppliers, lead users, industry associations, service providers, and multiple networks and their connections (Musiolik and Markard, 2011; Musiolik et al., 2020).

In a globalized economy, innovation processes and industrial dynamics depend on multi-level networks that transcend traditional spatial and sectoral boundaries (Hipp and Binz, 2020). Innovation is a dominant form of knowledge production and learning, represented as either science-technology-innovation (STI) or doing-using-interacting (DUI). STI-based knowledge is highly analytical and depends upon formalized, lab-based R&D. Since this form of knowledge can be codified into patents, papers, blueprints, etc., it is relatively easily transferable in space (Hipp and Binz, 2020).

Modern products are developed with technological knowledge from a diverse set of actors and industries distributed worldwide (Stephan et al., 2017). Studies have shown that a more internationalized and cross-sectoral perspective helps to efficiently achieve national/regional industrial development and innovation objectives (Graf and Kalthaus, 2018; Beuse et al., 2018; Grau et al., 2012). This perspective could improve firms' technological learning, as they seem to experience increasingly fast reconfiguration for innovations when they are embedded in international or global structures (Dewald and Fromhold-Eisebith, 2015; Binz and Truffer, 2017; Lee and Malerba, 2017).

The determinants of innovation and technological learning do not only reside in organizations and their local innovation systems (NIS) based networks (Pan et al., 2018; Jacobsson and Bergek, 2011), they are also located in broader and even international innovation systems. In order to be part of such international innovation-based networks, firms need to devise strategies to internationalize their innovation to improve their local/domestic innovation system.

The sectoral configuration of the industry consists of a technology value chain and all actors that produce these technologies, often from different sectors that supply key inputs or intermediary goods (Malerba, 2002; Hipp and Binz, 2020). This technology value chain contributes to improving technological learning at each step by providing critical tangible and intangible inputs (Stephan et al., 2017). Similarly, firms engaged in the global value chain can influence the other firms through knowledge spill-overs which enhance their technology-related learning (Hoppmann, 2018). Some parts of the value chain may depend on sectoral configurations and supportive innovation system structures where standardized knowledge, international mass markets, and fierce price-based competition play a key role (Hipp and Binz, 2020). In summary, the technological learning of firms is increased by playing a role in international innovation networks, which can be achieved by pursuing an innovation internationalization strategy. We call this type of internationalization as innovation development strategy whereby NIS networks are developed with the help of internationalization. Against this backdrop, we formulate our first hypothesis as:

Hypothesis 1. Innovation development strategy enhances technological learning.

2.2. Technological learning and international networks

Literature on innovation studies has analysed the combination and recombination of previously unconnected ideas that generate new knowledge and, ultimately, technological innovations (Aghion et al., 2009). These technological innovations are achieved through

technological know-how (or learning), which are acquired through internationalization (of innovation) strategy, including geographic terms which leads to diffusion of innovation in the shape of knowledge-spill overs (Audretsch and Feldman, 1996; Tojeiro-Rivero and Moreno, 2019). Technology learning also affects the networks of international research and cooperation between various firms and stakeholders. Global innovation systems (GIS) based networks acknowledge the importance of technological learning to achieve technical innovations.

Firms strategically shape the innovation and technological development in these networks by setting new technical standards (Garud et al., 2002), enhancing business models (Kaplan and Murray, 2010), introducing or learning new practices (Maguire et al., 2006). These elements strengthen the network by providing positive externalities to foster the fabric of innovation, locally and globally (Musiolik and Markard, 2011). Inter-organizational networks have been recognized as facilitators of interactive learning and knowledge generation (Lundvall, 1992; Ozman, 2009). A systematic analysis of formal networks, incl. inter-organizational structures, where firms and other actors come together to achieve common aims, is essential to understand processes of innovation system-based networks building better. Trust is a crucial component for knowledge and technology learning (Musiolik and Markard, 2011). Shaikh and Levina (2019) found that the presence of trust, commitment, and reputational complementarity is vital for business networks & alliances and R&D networks which are formed to enhance technology learning.

Musiolik and Markard (2011) found that German firms paid particular attention to building trust and reputation. Their efforts cascaded the actions to improve communication in the collaborative knowledge networks. When the trust was increased, they could sign further projects with the partners and actors in international networks, including user networks, R&D networks, and competitors. Nevertheless, similar arrangements were succeeded with their competitors, which later became coopetitors. Consequently, their relationships in the international network became more robust and more stable. Hence, we argue that along with technological learning, the element of trust can positively impact the international networks towards improving the innovation of networks member domestically.

2.3. International networks and national innovation system based networks

An innovation ecosystem is the evolving set of actors, activities, and artifacts. The institutions and relations, including complementary and substitute relations, are essential for the innovative performance of an actor or a population of actors (Granstrand and Holgersson, 2020). In innovation studies, the concept of innovation systems has been widely used, often with different qualifiers such as national innovation systems (Freeman, 1987; Lundvall, 1992) or sectoral innovation systems (Breschi and Malerba, 1997). The late 1980s saw the emergence of a new and more systemic understanding of innovation and diffusion processes. The resulting "National Innovation System" framework (Lundvall, 1992; Nelson and Rosenberg, 1993; Freeman, 1987) has attracted significant attention among both researchers and policymakers, resulting in the increased importance of the larger field of Innovation Systems (IS) research (Rakas and Hain, 2019). Subsequent research generated a cascade of different IS frameworks differing in their analytical and conceptual focus, highlighted elements and dimensions, system boundaries, and units of analysis, such as regional (Cooke, 2001; Malmberg and Maskell, 2002), sectoral (Breschi and Malerba, 1997; Malerba, 2002, 2005), technological (Carlsson and Jacobsson, 1997; Bergek et al., 2008; Hekkert et al., 2007), business (Whitley, 2000), and social systems of innovation and production (Amable, 2000), as well as national systems of entrepreneurship (Acs et al., 2014). Its community of users has expanded along the same lines as researchers from adjacent fields have become interested in a systemic approach to studying innovation. The main thrust of the NIS approach is that innovation and technical change are the outcomes of a complex pattern of interactions among a wide variety of actors such as firms, universities, and government research institutes. The NIS literature argues that the interactions within national boundaries are the most relevant (Cirillo et al., 2019).

Various types of international networks have been considered as drivers of firm performance, which further influences local innovation systems (Laursen and Salter, 2006; Nieto and Rodríguez, 2011). Nevertheless, they enable firms to acquire external knowledge at the local level and through building pipelines to benefit from knowledge hotspots worldwide (Bathelt et al., 2004; Tojeiro-Rivero and Moreno, 2019). The tendency to acquire external knowledge through mechanisms such as cooperation agreements or outsourcing is a strategy to become more innovative by leveraging knowledge external to the firm; it also helps to overcome shortcomings due to a purely internal structure/way of thinking of the enterprise (OECD, 2008).

Empirical evidence has shown that different networks play different roles in forming an innovation system, and they depend on different kinds of resources to achieve their goals. Some networks rely mainly on the resources of their members, while others develop a broad range of network resources. The German company IBZ, for example, utilized a variety of network resources and influenced its National Innovation Program as well (Musiolik et al., 2012).

Networks can also be based on established organizations and use the resources primarily already available in these organizations. The underlying strategy is to identify complementary resources of different actors, combine them (through the membership of the actors that control them) in a network, and apply them directly towards the network goals (Musiolik et al., 2012). Strong international networks are essential in this scenario as they enable the assimilation and utilization of complementary resources among actors, thus accelerating innovation (Musiolik et al., 2012; Carlsson and Jacobsson, 1997).

In this way, the international networks help to develop the resources of participants/stakeholders by enabling the collaboration between the actors/firms having common strategic interests and goals. In doing so, they exchange their tangible and intangible resources - including premises, technology, knowledge, and expertise - in order to achieve synergic outcomes. Furthermore, with the increasing interactions and cooperations with each other, firms tend to trust their exchange partners which enhances reputation of networks that ultimately improves the networks including international and domestic ones. In their research, Musiolik et al. (2012) reported that collaborative knowledge interactions of firms taken place in innovation networks improved the domestic innovation system in the German context. Hence, the inclusion/participation of firms in innovation networks can upgrade technological learning in the national innovation system based networks of a country through trust building and reputation enhancement.

Many studies have provided empirical evidence that networking strategies positively and significantly impact innovation performance (Nieto and Rodríguez, 2011). On the one hand, collaborative research with a broad range of partners may enable innovating firms to acquire the required information from various sources, leading to more synergies and intake of complementary knowledge, thus promoting innovation performance. In this sense, collaboration with other organizations is necessary to solve new problems for which the market does not have a proper solution, leading to more interactions among organizations (Tojeiro-Rivero and Moreno, 2019). This kind of strategy requires face-to-face contacts, reducing the likelihood of appropriation of some specific ideas/projects because both enterprises know each other's projects while building a relationship of trust. At the same time, collaboration may give access to more intangible and tacit knowledge and know-how not easy to spill over. Indeed, previous literature has recognized that cooperation embeds a complex/technical knowledge structure related to the appearance of new types of problem-solving requirements (Teirlinck and Spithoven, 2013).

Firms also build strategic alliances with other local and international firms with the intent of tapping into partners' resources and capturing

long-term value from these relationships. Such partnerships are typically governed by contractual or equity arrangements with clear mutual obligations. Organizations have begun to seek strategic alliances with open innovation communities (Shaikh and Levina, 2019). These alliances enable firms to tap into resources more quickly than the competition and innovate by combining diverse sources of expertise (Hoang and Rothaermel, 2005) compels organizations to look beyond their boundaries (Parmigiani and Rivera-Santos, 2011; Lorenzoni and Lipparini, 1999). Following this mindset, companies, especially technology firms, increasingly embrace open innovation communities as part of their innovation strategy (Dahlander, 2007; Greenstein and Nagle, 2014; Dahlander and Gann, 2010); the decision of which communities to partner with is becoming more important as these alliances cover joint R&D and marketing activities, mutually complementary technology assets and skills, and joint standard-setting. The open and user innovation literature shows that firms that engage with open innovation communities over the long term often share very similar aims (Afuah, 2018; Von Hippel, 2005).

But firms also partner with communities in order to innovate on specific tasks, e.g., by tapping into the resources that they are missing internally (Afuah and Tucci, 2012; Felin and Zenger, 2014) but for which they have a relevant absorptive capacity (Lichtenthaler and Lichtenthaler, 2009), complementary IP (Lakhani and Lonstein, 2011), and access to markets (Vanhaverbeke et al., 2008). The literature argues that these complementary resources enable partners to capture the value generated by their relationship with the community. Besides value creation, relations in a business network help foster new ties through trust-building mechanisms, potential partners' global and local reputations, and social network position (Carson et al., 2006).

In recent years, there has been some criticism and questioning of the relevance of a (nationally bounded) systemic approach to innovation in a world characterized by increasingly globalized value chains (Pietrobelli and Rabellotti, 2009; Szapiro et al., 2016; Mubarik et al., 2021; Wan et al., 2022). However, it is equally essential to develop the local system of innovation as well. Therefore, it is pertinent to explore how networks can play their part in creating or improving NIS. Thereby, we regard GIS, user networks, business networks & alliances, foreign lead users, and R&D networks as part of an international network. In a nutshell, technological learning improves the international innovation networks that further enhance the NIS. Thus, we formulate the following hypotheses:

Hypothesis 2. Technological learning and trust has a positive impact on National Innovation Systems based networks.

Hypothesis 3. International networks mediate technological learning and trust within National Innovation Systems based networks.

2.4. Operational model

The research model of our study posits that innovation internationalization strategy enhances technological learning and trust in networks, which further improves the NIS. We test its manifestation in the NIS networks, where international innovation networks are taken as mediators. Innovation development strategy is an independent variable that positively improves technological learning and trust as Hypothesis 1 (H1). Technological learning and trust also mediate the relationship between innovation development strategy and NIS, mainly by enhancing NIS, as Hypothesis 2 (H2). International innovation networks are mediating the relationship between technological learning & trust and NIS, as Hypothesis 3 (H3). In doing so, we have tested the hypothesis explained and highlighted in the operational model of research given below in Fig. 1.

3. Methodology

In this study, the case of a CEE country – Lithuania – is taken for analysis as a low trust economy context. The post-soviet contexts (with few exceptions) form a high level of mistrust due high corruption level and at least partial institutional inefficiency (WEF, 2022; WB, 2022). Still, the economies are demonstrating sufficient growth and vitality, with relatively moderate innovation performance demonstrated by national innovation systems. After over 30 years of free economy, Lithuania has transitioned from the post–soviet economy of a low-income country with labour intensity driven competitiveness towards a productivity and innovation driven economy as indicated by high average income, innovation driven exports, and high economic freedom (WEF, 2022). Lithuania joined the EU in 2004, which provided an opportunity for international trade and value chain integration and resulted in high openness of economy and trade ranked 15th by World Bank (WB, 2022). Current development marks an important transition stage from productivity driven to the innovation driven economy, which is taking a particular pattern from the firm's behaviour and technology capability building perspective. This forms our case study context for hypothesis testing.

In particular, we explore the link between firm's innovation internationalization (strategy), technological learning & trust and a combination of various networks employed in order to benefit from the domestic innovation systems based on a survey of innovative firms in Lithuania and applying partial least squares structural equation modelling (PLS-SEM) as a data analysis method. The sampling technique for this primary data collection followed probability sampling, more accurately, stratified random sampling, dividing the population based on the sector classification in NACE Rev. 2 for statistical classification of economic activities in the European Community.

The analysis is thus based on primary data of 131 innovative firms from Lithuania's private sector. The data analysis methodology involved two steps: first, formation and verification of the variables via factor analysis; second, the formation of complex cause-effect relationship model and testing hypotheses via PLS-SEM. For the analysis of the domain dimensionality, the exploratory factor analysis (principal component analysis) was conducted for each construct domain and one or several meaningful dimensions were identified. When used as a data analysis method, SEM reveals the structure of causal paths relating constructs (latent variables), and specifically PLS, or variance-based SEM, helps to deal with the problems in traditional covariance-based SEM including problematic measurement model identification when

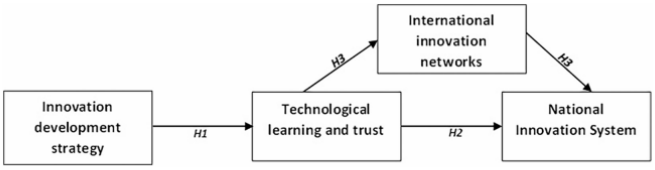

Fig. 1. Operational model of study.

models are complex and sample sizes are relatively small (Hair et al., 2011). The estimation of the structural model in PLS-SEM is similar to OLS regression and therefore rules of thumb that require from 10 to 30 cases per independent variable suggest that >10 independent variables (incoming arrows representing causal direction) can be included at any part of the model for a sample of 131 cases. Despite its seeming linearity, the model encompasses high number of different paths that lead to ("cause") latent variables. The model became even more complex when we introduced the structure among latent variables in the *strategy* and *network* domains and additional theoretically relevant mediation effects were introduced, e.g., what types of partner networks lead to global versus national innovation systems. Given this *ex-ante* imposed structure we refined the model by removing the statistically non-significant causal arrows one by one to arrive at a clearer, more parsimonious model.

3.1. The quality of the measurement and structural models

To assess the convergent and discriminant validity, we conducted item and construct level analysis. As the measurement model was based on EFA, we do not expect large cross-loadings across latent variables or very low loadings on relevant latent variables. However (Table 1), three manifest variables do not conform to the rule that for exploratory analysis, loadings should be at least 0.60 (for confirmatory research 0.70), as well, in four manifest variables the second largest cross-loading fails to be less by 0.20 as compared to the loading on the relevant latent variables (although close to the threshold). High cross-loadings among the latent variables representing types of partners were expected, therefore we do not see a problem here given that loadings are higher by at least 0.20 from the highest cross-loadings. That said, we have used this configuration of latent variables for our analysis for the reasons of content validity and then rechecked the calculations with the problematic mediating variables removed: the results were substantially the same as path coefficients changed by 0.05 at most and their statistical significance in the structural model remained the same.

At the construct level, the Fornell-Larcker criterion requiring the square rooted average variance extraced (AVE) to exceed a correlation with any other construct is established, as the largest correlation coefficient is below 0.70 and the minimum square rooted AVE is above 0.70 (Appendix A).

Analysing the quality of measurement model at the latent variable level, the internal consistency reliability of the scales is above the 0.70 threshold, and the AVE of latent variables stands above 0.50 (Table 2) which are within the threshold recommended by Hair et al. (2011). For the final structural model, the quality measures are coefficients of determination (R-squared), redundancy (product of AVE and R-squared: the amount of variance in an endogenous construct explained by its independent latent variables, see Sanchez, 2013: 68–69) show that in average 19 % of variance in latent variables is explained (R square values) and MVs explain in average 13 % of variance of endogenous latent variables (redundancy estimates).

Predictive relevance scores (Stone-Geisser's Q2 value) for different omission distances (d) values show that the construct of international business networks and alliance is negative which indicates that for this latent variable the path model is not relevant in terms of predictive accuracy (Hair et al., 2014: 183–184) and its data cannot be reconstructed by using the PLS model parameters (Fornell and Cha, 1994; Shmueli et al., 2019). Therefore, this latent variable is included into our final model for presentation purposes but could as well be excluded from the model as no other latent variable predicts it adequately. Other than this construct, all values are positive and within the prescribed threshold required for predictive relevance.

Furthermore, the Goodness of Fit measure (GoF) that is based on communalities (AVE's) and R-squares is 0.36, which is a threshold value for a large effect size (based on Cohen, 1988 suggested effect sizes of R-square). Thus, the final model has a good fit with the data.

4. Key findings

Given that the measurement model is valid we can turn to the results of the structural model, i.e. statistical significances and sizes of the path coefficients (Table 3 and Fig. 2).

In general, if we relax our expectations regarding statistical significance level, Innovation development strategy (IDS) does have a direct effect (0.39) on Technological learning and trust (TLT) (0.15). Further, TLT exerted a positive impact (0.38) on International competitors and foreign lead user networks (ICUN). Also, a positive impact of TLT on International user networks (IUN) (0.24), and on National R&D networks (NRD) (0.23) is found. However, Global innovation systems (ISN) (0.2) and International business networks & alliances (IBNA) (0.14) are not reasonably influenced by TLT. Interestingly, ISN mediated TLT with National innovation system network (NIS) at comparatively higher levels (0.43) than other networks. Likewise, IBNA also mediated this relationship at a comparatively low amount (0.21). As ICUN were highly impacted (0.38) by TLT, however, they surprisingly failed (−0.34) to mediate it with NIS network. IUN and NRD network mediated TLT and NIS network at 0.25 and 0.31 respectively. As expected theoretically, no direct impact (0.11) of IDS is found on TLT, and the variety of international networks mediated between TLT for improving NIS network.

From the analysis of the measurement model, we may expect the types of partner networks to be highly interrelated (but not too high, as the VIF's are not higher than 2) and therefore most of the direct path coefficients relating these types are statistically significant ($p < 0.05$). Within this linear view of the process that was set out in our initial model, some mediating effects are observed and should be given a substantial interpretation. First, TLT do not directly relate to NIS network as both path coefficients are close to zero and non-significant, but are mediated by other types of networks including ICUN, IUN, and NRD networks. Second, IDS does not directly impact NIS network. This relationship is mediated by TLT and a variety of networks. The modelled relationships are shown below in structural model Fig. 2.

Table 1
Intercorrelations among latent variables (Spearman's rho cor. coef., $n = 131$) versus square root of AVE.

Labels/variables	AVE sq. root	Max correlation	IDS	TLT	ICUN	IBNA	ISN	NRD	NIS	IUN
Innovation strategy - IDS	0.742	0.568	1.000							
Technological learning and trust - TLT	0.768	0.496	0.213*	1.000						
International competitors and foreign lead users based networks - ICUN	0.831	0.643	0.253**	0.090	1.000					
International Business based networks and alliances - IBNA	0.860	0.676	0.177*	0.108	0.643**	1.000				
International innovation system based network - ISN	0.806	0.676	0.247**	0.097	0.605**	0.676**	1.000			
National R&D based network - NRD	0.837	0.629	0.206*	0.290**	0.482**	0.462**	0.298**	1.000		
National Innovation System based network - NIS	0.819	0.629	0.089	0.170	0.519**	0.394**	0.413**	0.629**	1.000	
International User based networks - IUN	0.721	0.501	0.276**	0.214*	0.350**	0.404**	0.501**	0.429**	0.391**	1.000

* $p < 0.05$.
** $p < 0.01$.

Table 2
Quality characteristics for latent variables.

Labels	Number of reflective MVs	Communality (AVE)	CR (Dillon-Goldstein's rho)	R-squared	Redundancy	Q-squared, d = 5	Q-squared, d = 10
Innovation development strategy - IDS	4	0.55	0.83	0.293	0.170	0.152	0.148
Technological learning and trust - TLT	4	0.59	0.85	0.145	0.085	0.062	0.058
International competitors and foreign lead users based networks - ICUN	7	0.69	0.94	0.032	0.022	0.009	0.011
International Business networks and alliances - IBNA	5	0.74	0.93	0.042	0.031	−0.009	−0.001
International/global innovation system-based network - ISN	6	0.65	0.92	0.562	0.367	0.315	0.324
National R&D network - NRD	3	0.70	0.87	0.141	0.098	0.035	0.043
National Innovation System based network - NIS	3	0.67	0.86	0.435	0.293	0.230	0.254
International User based networks - IUN	3	0.52	0.76	0.285	0.149	0.123	0.125

Table 3
Estimates and confidence intervals for path coefficients in the structural model.

Path	Estimate	Bias	Std. Error	90 % lower	90 % upper	Sig. 90 %	95 % lower	95 % upper	Sig. 95 %
IDS → TLT	0.39	0.03	0.09	0.182	0.501	*	0.182	0.516	*
TLT → ISN	0.20	0.01	0.12	−0.025	0.369		−0.048	0.398	
TLT → IBNA	0.14	0.02	0.08	−0.025	0.246		−0.041	0.263	
TLT → ICUN	0.38	0.02	0.09	0.138	0.480	*	0.122	0.508	*
TLT → IUN	0.24	0.01	0.11	0.038	0.417	*	0.020	0.472	*
TLT → NRD	0.24	0.02	0.09	0.018	0.337	*	0.012	0.357	*
IDS → NIS	0.11	−0.01	0.07	0.009	0.239	*	−0.007	0.261	
ISN → NIS	0.43	−0.01	0.09	0.302	0.591	*	0.287	0.648	*
IBNA → NIS	0.21	0.01	0.09	0.069	0.344	*	0.046	0.372	*
ICUN → NIS	−0.34	0.01	0.11	−0.576	−0.202	*	−0.605	−0.173	*
IUN → NIS	0.25	0.00	0.10	0.081	0.436	*	0.059	0.466	*
NRD → NIS	0.31	0.00	0.07	0.200	0.450	*	0.170	0.482	*

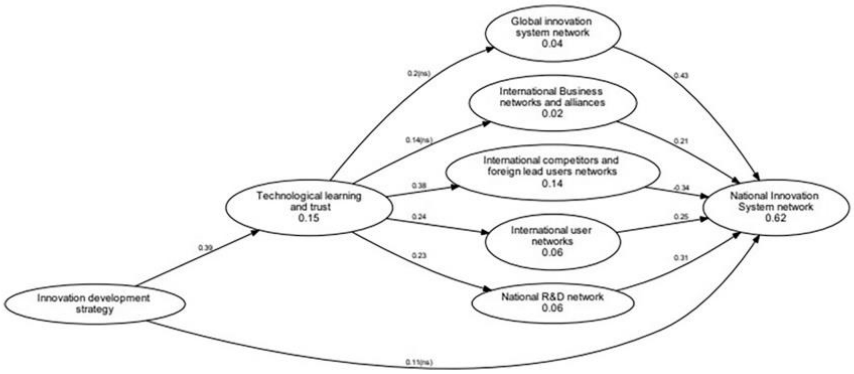

Fig. 2. Structural model: the mediating role of international networks in upgrading national innovation systems capabilities.

5. Discussion and conclusions

The hypotheses tested are based on the typology of firms' innovation development strategy, technology learning and interfirm trust, and underpinning engagement in innovation networks that lead to the success of NIS based networks. PLS-SEM is used to explain the evolving technological learning patterns within and across the complexity of innovation systems and variety of stkeholders.

The modelling revealed that innovation development strategy leads firms towards different approaches in network formation in order to achieve innovation development goals resulting in different innovation networks' constellations. In this interplay, the innovation development and internationalization strategy of firms combined with the strong internationalisation focus directly influenced the pattern of technological learning network formation within the global innovation systems through international user networks, national R&D networks, global innovation system networks, and international business networks and alliances that mediate the engagement within the national innovation

system at the final step. No direct effect of internationalization and innovation development strategy was found on the NIS network.

Surprisingly, technological learning and trust only insignificantly impacted the global innovation system based networks. However, it further mediated the engagement of technological learning and trust development within the NIS network at the highest level compared to other networks studied. It indicates the inherent ability of the global innovation system networks to improve domestic innovation systems, a finding which echoes the results of Laursen and Salter (2006) and Nieto and Rodríguez (2011). Likewise, international business networks & alliances were only marginally affected by technological learning and trust. Still, it reasonably mediated with the NIS network, which is in line with the study of Tojeiro-Rivero and Moreno (2019), who contemplated the role of international business networks to develop the local or national innovation network. International user networks and national R&D networks also mediated technological learning and trust within NIS networks with the amount of stimulus they received from technological learning and trust. In this particular context, we may refer to these as appropriate variables (mediators) that transmit their influence to develop a national innovation system in line with the view of Musiolik et al. (2012).

The key findings highlight a few vital firm behaviour patterns informing technological and innovative capabilities in Central and Eastern European country transitions towards innovative economies:

1. Technological learning and trust are critical organizational capabilities for executing innovation strategies within networks to succeed in national innovation systems. Trust is a capability which (indirectly through the mediation of international networks) improves innovation in NIS networks.
2. While technological learning and trust are critical factors in forming complex innovation networks, they impact national R&D and innovation systems mostly in the context of global innovation systems, international user networks, national R&D networks, international competitors & foreign lead users, and international business networks & alliances.
3. Internationalization and innovation development strategies do not directly drive or improve the domestic innovation system. They achieve this objective through the mediation of technological learning, trust, and various innovation networks.
4. The effects to national innovation system based networks have to be fully mediated by either international business networks, global innovation systems based networks, or international competitor and user networks, depending on innovation strategy and organizational capability employed.
5. User-driven innovation network engagement is the only factor directly impacting and also fully mediating innovation success. There is no direct impact on innovation success from any other innovation network analysed. However, its effects need to be amplified via complex knowledge and learning interactions mediated via national innovation systems or international lead user and competitor networks.

6. Limitations and future research directions

The limitations of the research stem from the research scope and focus, i.e. the entire study has specifically targeted innovative firms from small open economy that faces innovation driven growth challenges, namely Lithuania. In addition to that, the study encompassed R&D intensive SMEs only that shape a specific behavioural patterns and demonstrate higher innovation capabilities, including open innovation as compared to the general sample. We would like to draw the attention to the small size of economy that in combination with the diversity of the technological knowlede desired and the pressure of rapid internationalisation due to limited or absent domestic demand force firms to develop international networks at the very early development stages. The similar tendency has been approached at the level of regional innovation systems and cluster studies (Radziwon and Bogers, 2019). The studies have highlighted the importance of soft skills, especially trust for technological learning across domains, where geographical and cultural proximity plays and important role. Still, technolgical proximity remains dominant variable, and our study did not explicitly addressed it. Therefore the role of technological proximity in combination with the mediating role of international innovation networks in upgrading national innovation systems shall be further studied. The role of societal trust in open innovation has been proven to be of critical importance for innovation driven economies (Brockman at al., 2018), however in the domain of internationally embedded R&D intensive SMEs it can be replaced by the innovation network based trust that reaches outside of national borders. Central Eastern European economies still feature some similarities as it relates to societal trust, however the landscape is rapidly changing in CEE and Europe at large, and the interfirm trust component in relation of societal trust shall be further studied for deepening the understanding of technological learning and upgrading at the NIS level.

7. Implications of study

Technological learning within national innovation systems is defined by the quality and diversity of networks of an innovation. This implies the need at the policy level to draw higher attention to the facilitation of diversity of innovation networks, including user driven innovation networks, international innovation alliances, global innovation systems, value chain based networks, and other more traditional international R&D networks. As the success of the upgrading of national innovation systems depends on the success and direction of international innovation network embededness, technological learning at the global scale should be facilitated by direct and indirect policy measures, and include direct support to network formation, but also multinational and multicultural collaborative innovation skills. These extends far behind team diversity management, as institutional components play an important role as well, including informal and formal institutions. Foreign network formation requires a diferent set of open innovation and networking skills (Podmetina at al., 2018) that needs to be developed at the firm level in order to enable succseeful international network based technological learning. Knowledge transfer to SMEs is meaningful only when it is thoroughly connected to the innovation activities taking place within a smaller business. Hence, any meaningful knowledge transfer for SMEs requires a better understanding of innovation activities and capabilities within these organisations. The SMEs' innovation activities are an amalgamation of technology adoption, product and process development, and intensive marketing activity. Moreover at the firm level, innovation capabilities development should focus on strategic innovation partnership management and networking capabilities along with the development of dynamic capabilities, as well as trust management. Together with innovation absorptive capabilities, larger attention needs to be given to relational and transformative dimensions of technological learning, the networks of innovation, innovative culture, innovation behaviour, dynamic capabilities, intellectual capital, and several others. In addition, these capabilities should be investigated in the variety of collaborative innovation networks including open innovation networks, digital networks, multisided platform based networks, etc. The development of such capabilities will not only increase technological learning within these networks but also lead to further improvement of national or domestic innovation system networks of a country.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.techfore.2022.121873.

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Paper 2

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Industry 4.0 technologies, digital trust and technological orientation: What matters in open innovation?

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ABSTRACT

The fourth industrial revolution, termed Industry 4.0, offers a vital and valuable opportunity to drive social and technological innovations. It has state-of-the-art cyber-physical systems and related technological architecture, which can drastically increase a firm's productivity and innovation performance. Nevertheless, Industry 4.0 is also significantly shortening the product life cycles and demanding the pace of innovation to be accelerated. A firm, however, cannot accelerate the pace of its innovation by exclusively relying only on its internal resources. This is the reason firms are increasingly adopting open innovation strategy through collaboration with external stakeholders. The critical challenge that firms are facing while managing open innovation is trust among the stakeholders. Digital trust, attained through Industry 4.0 technologies, can play an instrumental role in promoting open innovation. Against this backdrop, the present study investigates the impact of digital trust on open innovation performance. The study investigates the role of technological orientation and technological absorption capacity in the association between digital trust and open innovation. Cross-country data of 324 electrical and electronics firms of three major Asia-Pacific countries, namely Malaysia, Indonesia, and Thailand, were collected using a close-ended questionnaire. The study employed partial least square-structural equation modeling (PLS-SEM) and PLS-multi group analysis (PLS-MGA) to analyze the modeled relationships. The results reveal that digital trust, composed of trust and Industry 4.0 technologies, has a significant positive impact on a firm's open innovation. Likewise, results also depict a strongly positive moderating role of technological orientation in the association between digital trust and open innovation. Finally, results also exhibit a significant mediating role of both potential and realized technological absorptive capacities in the association of digital trust and open innovation. It is the first-ever study discussing the linkage of digital trust with open innovation. The findings of this study suggest development of technology strategy to adopt Industry 4.0 technologies for accelerating the pace of open innovation.

1. Introduction

The Industry 4.0 with robotics, digitalization, and cyber-physical systems at heart, profoundly influences technological innovations. The production and innovation processes have now become more intelligent because of Industry 4.0 technologies (Rajput and Singh 2019; Koh et al., 2020). Specifically, Industry 4.0 technologies such as artificial intelligence, big data, blockchain, cyber-physical systems, internet of things, etc. have accelerated the pace of technological transformation and internationalization of businesses (Sung, 2018) with its state-of-the-art cyber-physical systems and related technological architecture, which can greatly increase a firm's productivity and innovation performance. Therefore, global business networks are increasingly adopting these cyber-physical systems, digital platforms, and virtual networks (Frank et al., 2019).

At one end, Industry 4.0 is accelerating the pace of innovation. At the other end, it is shortening products' life cycles, thus forcing firms to accelerate the speed of their innovation processes. However, firms cannot accelerate the pace of innovations solely relying on internal resources and operating in their silhouettes; they need to acquire external knowledge resources. Previous research work (e.g., Chesbrough, 2006; Chesbrough, & Bogers, 2014; Salampasis, 2019; Chesbrough, 2020) has urged to undertake this process of innovation through linking internal experience with external knowledge. For such collaboration and cooperation within business networks, trustworthy and reliable stakeholders (partners, suppliers, etc.) are essential. However, owing to geography, cultural differences, language variations, values differentiation, and some other factors, many actors have

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expressed their concerns, and distrust on other stakeholders in the network (S Salampasis et al., 2014a; Salampasis and Mention, 2019). It implies that adoption of open innovation as a solution to speed up the pace of innovation requires trust among various stakeholders. To enable smooth cooperation for innovations, the presence of the Industry 4.0 technologies in combination with traditional trust measures can be used to form digital trust among the stakeholders, thus improving a firm's open innovation performance. Despite the significant role of digital trust in open innovation, it is hard to see research that comprehensively investigates the dyad of digital trust and open innovation.

Further, anecdotes reveal that digital trust can profoundly improve an organization's capacity to absorb technology-related knowledge, which further enhances the firm's open innovation. Although the concept of absorptive capacity is almost two decades old, it's the role it plays for the digital technologies and open innovation dyad is yet to be investigated (Rajput and Singh, 2019).

Against this backdrop, the present study has three primary objectives. First, to investigate the role of digital trust in promoting open innovation; second to examine the role of technology absorptive capacity (realized and potential) in the association between digital trust and open innovation; and third, to investigate the role of technological orientation in the association between digital trust and open innovation. We take electrical and electronics sector of three Asia-Pacific countries, Malaysia, Thailand, and Indonesia, as the context for this study. First, we review the dispersed literature on digital trust, technological absorptive capacity, and open innovation, and develop a testable framework. Second, by collecting data from three major Asia-Pacific countries, we provide empirical evidence on the role of digital trust in promoting open innovation. Third, we offer policy implications for improving open innovation, particularly in the manufacturing sector.

2. Literature review

2.1. Trust and open innovation: setting the context

In the Industry 4.0 era, firms have no choice but to collaborate and acquire external knowledge due to shortened life cycles of innovation and product (Enkel., et al., 2017). That is why an open knowledge exchange approach that could take place within an innovative setting is inevitable. For Chesbrough et al. (2006, p.1), "open innovation entails the use of purposive inflows and outflows of knowledge to accelerate internal innovation and expand markets for external use of innovation." Open innovation strategies, adopting the premise of open system theory, stresses the interaction of a firm with external stakeholders to improve its innovation performance (Salampasis and Mention, 2019; McGee et al., 1995; Pisano, 1990). Thus, it can be a source of sustainable competitive advantage. These strategies enable a firm to integrate organizational capabilities with externally sourced knowledge that further improves its innovation performance (Sen and Rubenstein, 1989; Kodama, 2005a, 2005b; Hartmann et al., 2014; West and Gallagher, 2006).

Nevertheless, this strategy requires a comprehensive management of trust among the interacting parties and developing trust requires shared values, knowledge sharing, mutual regard, and respect. In this regard, Cheng. et al. (2008, pp. 450–452) offer a model illustrating associations among trust, knowledge sharing, and firm performance. They denote that trust could be a significant determinant of firm performance, particularly of its innovation performance. In the context of open innovation, the role of trust increases manifold. Researchers (e.g., Schneider et al., 2011; Salampasis, et al., 2014a; 2014b; Salampasis and Mention, 2019) assert that management of trust is a significant precursor for successful open innovation. In the presence of digital technologies and virtual environments, the need for trust among networks is critical as the actors in business networks do not meet physically to perform business transactions. Instead, interaction with suppliers, vendors, partners, and other stakeholders is carried out through online platforms and cyber-physical networks in order to share knowledge and information. Consequently, a novel model of trust is necessary in the new modus operandi caused by Industry 4.0 (Rajput and Singh 2019).

2.2. Open innovation

In the context of Industry 4.0 technologies and their execution and integration, open innovation appears to be the most suitable system to promote a firm's activities for knowledge exploration and exploitation. Open innovation is also described as "systematically relying on a firm's… capabilities of internally and externally carrying out the major technology management tasks … along the innovation process" (Lichtenthaler, 2011, p.77). According to Trap (2014, p.1), "open innovation as a model enables businesses to build a structured innovation ecosystem that uses networks of external partners and focuses on developing core internal competencies." It can be interpreted as an inter-firm knowledge transaction that helps a firm to sustain and develop new knowledge (Lichtenthaler and Lichtenthaler, 2009). Although the term open innovation was coined in the last decade, the concept is not new. Terms like open source, user co-creation, user-centered innovation, and distributed innovation, partially reflecting the concept of open innovation, could be found in the literature (Sawhney and Prandelli, 2000; Feng et al., 2020; Franke and Piller, 2004; West and Gallagher, 2006).

Nevertheless, the influx of Industry 4.0 technologies has brought open innovation under the limelight. It is considered as the new way to create value for firms through open collaboration, cooperation, and coopetition in contrast to the conventional closed innovation framework (Trott and Hartmann, 2009; Viskari et al., 2007; Chesbrough 2020). Open innovation has three major types, namely outbound, inbound, and coupled processes. The outbound process (inside-out) represents the usage of a firm's internal knowledge and information, which can also be called surplus research to generate external value. This inside surplus research could have been wasted in the absence of open innovation, which now the firm can sell to external stakeholders (Savitskaya et al., 2010).

The inbound process (outside-in) entails the utilization of outside knowledge, acquired through spinning in, licensing in, and collaboration within value chains to generate value inside the firm (Savitskaya et al., 2010). Coupled process is defined as "linking outside-in and inside-out by working in alliances with complementary companies during which give-and-take is crucial for success" (Gassmann and Enkel, 2004, p.1), such as joint-venturing and co-creating a project with external partners. The essence of open innovation lies in collaboration with external stakeholders to source outside knowledge, which plays an instrumental role in developing mutual competence. This competence helps a firm to improve the efficiency and effectiveness of its innovation activities (Chesbrough and Crowther, 2006; Gassmann and Enkel, 2004; Lichtenthaler, 2011; Podmetina, D. et al., 2018; Petraite, 2020). In doing so, firms are required to disclose only the most relevant information, thus avoiding sharing of confidential information and R&D that could compromise a firm's core competency (Spithoven et al., 2011). It is evident from the brief illustration that the very foundation of open innovation is based upon the principles of trust, transparency, openness, and sharing (Chesbrough, 2003).

Open innovation effectively leads toward a trust-driven-open culture, which is based on the interactions of multiple stakeholders with diverse backgrounds, locations, and expertise who come together for mutual gains. Such interaction requires long-lasting relationships, win-win concerns, and trust for the shared goals (Lichtenthaler and Lichtenthaler, 2009; Spithoven et al., 2011; Vanhaverbeke and Peeters, 2005; Vanhaverbeke et al., 2008). The effectiveness of open innovation depends upon the transformation from a closed system of innovation to an open innovation paradigm. Helfat says that "closed innovation springs entirely from internal company innovation activity, largely in

the form of organized R&D" whereas the open innovation model relies upon "sources external to the company in combination with supplementary internal company innovation activity" (Helfat, 2006, p.86). The key to improve the open innovation performance relies on the way an organization manages its trust with varied stakeholders and the way it interacts with them (Dahlander and Gann, 2010). If a firm can connect its business processes and externally available knowledge in a synergetic way, it can significantly leverage its innovation performance through an open innovation model (Von Zedtwitz, M., & Gassmann, O., 2002; Oliveira and von Hippel, 2011; Salampasis, 2015).

This brief review of literature illustrates a radical transformation in businesses from a conventional close innovation system to open innovation. The review also underscores the role of trust, relationship management, and information management in managing open innovation. Likewise, it also reveals that open innovation as an emerging paradigm and as a concept greatly relies upon the technological context of Industry 4.0. Finally, the above discussion also shows that the inherent element which belongs to the DNA of open innovation Industry 4.0, is trust, which has been merely discussed in the literature. It posits a critical gap in the existing literature.

2.3. Digital trust: a composition of industry 4.0 technologies

In Industry 4.0, technology is increasingly used, accessed, and configured in businesses. Possibly when the fifth industrial era would begin, we will be able to fundamentally alter how information is organized and exchanged to foster formal or informal and business relations. This requires serious adjustments in the norms and culture of business conducts whereby firms nowadays trust their partners in good faith. It is the right time to contemplate on and advance such business norms in the context of growing technological settings and dynamics. Businesses nowadays are managing relationships that are based on trust formulated on human behavior, which makes it more human-centric. However, managers and researchers are increasingly expressing their concerns over this human-centric trust behavior, which is vulnerable to the situation of distrust. The underlying problem is the role of humans in trust formation, which could be replaced or at least managed with the help of technology. Conventional business undertakings involving the human-centric approach of trust has already started to evolve towards a technology-centric approach (Mubarak et al., 2019). This approach is considered more secure, more reliable, and less risky, which are the critical needs of any business relationship, either in the form of collaboration or partnership. For the very purpose, firms and business networks are required to form a technology-embedded trust which entails the inclusion of Industry 4.0 technologies such as big data, internet of things, blockchain, cyber-physical systems, etc. with the existing dimensions of trust, which we call *digital trust*.

As already suggested by scholars such as Bhattacharjee et al. (2006) and Victor, P. et al. (2009), technological advancement and maturity have been realized enough to a level where fostering such setting is possible, rather inevitable. Digital trust can be referred to as the confidence of stakeholders on the competence of actors, technologies, and processes for establishing reliable and secure business networks. Hence, we further argue that trust and Industry 4.0 technologies have a synergistic potential to enhance the cooperation and collaboration amongst firms in an innovation network that could accelerate open innovation while strengthening the business relationships based on digital trust. From this point further, we explain the conventional trust and then discuss Industry 4.0 technologies as fundamental components to develop digital trust.

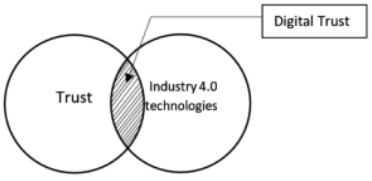

Fig. 1. Digital trust.

Trust is deemed as a multidimensional phenomenon that cannot be defined in a singular way (Brattström et al., 2012; Mubarik, Chandran & Devadason 2016). As it incorporates numerous elements and functions which have individual existence, they do not act autonomously nor consistently (Tyler, et al., 2007), which also portrays that trust is a process rather than a status. Trust tends to be widely talked about and it is assumed to be suitable for organizations to have as well to develop. When it comes to specifying just what it means in an organizational context, however, vagueness lurks in (McAllister, 1995-p.24).

Existing research (Fawcett et al., 2012; Salampasis et al., 2014a; Gulati and Sytch, 2008; Schoorman et al., 2007; Mayer et al., 1995; Mujahid, et al., 2019) shows that trust functions at an interpersonal level among individuals; among organizations at an inter-organizational level; and between individuals and various information systems.

"Trust is generally associated with willing, not forced, cooperation and with the benefits resulting from that cooperation" (Hosmer 1995, p. 390). Therefore, by definition, trust is "the willingness of a party to be vulnerable to the actions of another party based on the expectation that the other will perform a particular action important to the trustor, irrespective of the ability to monitor or control that other party" (Mayer et al., 1995-p.712). This action is linked with trustworthiness and expectation that the other party will behave bona fide and in a credible way. Another perspective of trust is "the confidence that no party to exchange will exploit another's vulnerabilities" (Parkhe, 1998-p.221). All these definitions reflect the dependence of trust purely on human-being or human-centric perspective, which clearly shows the high vulnerability of trust to human error, either intentional or unintentional.

Trust is perceived as a crucial factor for cooperation, collaboration (Lee, Wong, and Chong, 2005), and a sound base to discover new strategic directions (Rios et al., 2018; Zahra et al., 2008). Cooperation embraces the risk of failed cooperation, which may lead to the collapse of business relationships or even the whole business model such as digital businesses, which inevitably require a robust system of trust (Son et al., 2006). The stakeholders in a particular network become trustworthy and the other actors trust them (Gössling, T., 2004). Yet how to be trustworthy or what constitutes trustworthiness remains ambiguous.

A firm should invest in promoting the autonomy of organizational trust to enable cooperation with other companies (Gulati and Sytch, 2008), at least collaboration with those organizations that are similar in products portfolio, functions, or interests. Organizational similarities are vital factors and two firms belonging to similar operational scope and networks can have an effective cooperation and creation of inter-organizational trust. It is also argued that "great companies assume they can trust people and can rely on relationships, not just rules and structures" (Kanter, 2011, p.75). In such settings, a subsequent relationship due to organizational similarities and assortments of organizational whereabouts can be observed, which is not uncommon in global business networks.

Although such connections can enhance creativity, it may also lead to certain communication dilemmas and conflicts (Salampasis, et al., 2014b). In an open innovation setting, the inter-firm collaboration is focused on a firm-centric view that contemplates how firms create value through collaborations and alliances rather than separately through owning the assets jointly (Salampasis et al., 2015). Dyer and Singh (1998) argue that "as a supernormal profit jointly generated in an exchange relationship that cannot be generated by either firm in isolation and can only be created through the joint idiosyncratic

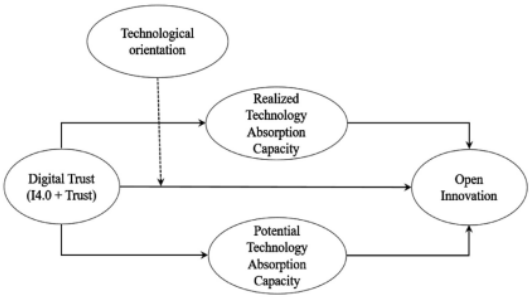

Fig. 2. Conceptual framework.

contributions of the specific alliance partners" while referring to the term "relational view" (p.662). However, Salampasis (2019) highlighted the deficiency of co-creation and value enhancement, which is due to lack of a robust trust system in business networks. From this point further, we discuss Industry 4.0 technologies, which could enhance and shape the phenomenon of trust.

As mentioned earlier, the current era with sophisticated technologies and innovations is called the fourth industrial revolution, or Industry 4.0. The leading technologies of Industry 4.0 include big data, cyber-physical systems, internet of things, and blockchain. These technologies should be integrated with the conventional (human-centric) trust in order to strengthen the existing structure of business networks through technology-oriented trust.

Big Data: Big data is a prominent technology of Industry 4.0 which can handle vast amounts of data and information including capture, transmission, storing, and analysis of structured and unstructured data into meaningful information patterns (Vidgen, 2020) for decision making. In doing so, it undertakes a systematic approach to identify and interpret data as novel ideas (Hartmann et al., 2014; Mubarak et al., 2019). Therefore, by applying big data analytics, reputation and trustworthiness of suppliers, partners, and other stakeholders could be assessed by analyzing the information of their past performance, business portfolio, and collaborations. In this way, it can enhance the open innovation process to select the right supplier, partner, co-creator, or collaborator.

Cyber-Physical Systems (CPS): It is an advanced system with integrated computational and physical devices that can interact with humans through interactive modalities. Using CPS, firms can communicate and collaborate with potential partners or suppliers to carry out open innovation processes without physical supervision or evaluation (Lee, et al., 2019; Nawanir, 2016; Kuo, 2013). Indeed, CPS could be an effective system to streamline the open innovation network in order to co-create, collaborate, and partner where data sharing, communication, and computation are considered as key features.

Internet of Things (IoT): Numerous industries are increasingly adopting IoT. It is considered as an emerging theme, an established plan, and an enormous technology along with as a buzzword in academia and business (Lee, I., 2019; Linstone, 2010). In the beginning, IoT is about recognizable objects connected with the help of radio frequency identification or RFID, which can transform the businesses. However, now experts have specified IoT as a network of connected devices through internet or satellite. IoT is already used in multiple industries such as transport sector, health sector, smart home management, and many self-propelled industries. The prominent technologies used by IoT include RFID, software and hardware applications, middleware, and cloud computing (Chang et al., 2020 ;Le, D. N. et al., 2019; Koh et al., 2019). A firm can streamline its internal as well external collaboration process by utilizing IoT through which they can store, share, and disseminate their precious knowledge in a smart way without involving human interaction. This could foster an efficient open innovation network while enhancing digital trust.

Blockchain: A blockchain is a distinct kind of data storage that records information in a manner that enables various stakeholders to confidentially share and access to similar information and data (Koh, L., 2020). The data entered in the blockchain can neither be changed nor deleted. Moreover, it works both as a secure and integrated way as well as a network and a database as it functions based on defined rules programmed mathematically and enforces them automatically through sophisticated technology (Chang, Y., 2020). Blockchain can be called a digital database-cum-enterprise system, which firstly records all sorts of transactions, all of which can be simultaneously utilized and shared within a vast and decentralized network and can be accessed efficiently by authorized stakeholders (Feng et al., 2020). It is also defined as an incorruptible digital ledger that is just not limited to financial or economic transactions but virtually for everything, including tangible and intangible products and processes (Viriyasitavat, W., & Hoonsopon, D., 2019). Blockchain, when combined IoT, robotics, and cyber-physical systems, could become a highly sophisticated platform to improve the quality of business performance (Accenture 2015) which is critical for technological innovation. In doing so, firms can cultivate their collaboration platforms through blockchain, where they can share real-time research, developments, and knowledge in a swift, secure, and uninterruptible manner.

In a nutshell, Industry 4.0 technologies in combination with conventional characteristics of trust could form a digital trust, which can play an instrumental role in upgrading the performance of open innovation.

2.4. Hypothesis development

2.4.1. Impact of digital trust on open innovation

Industry 4.0 technologies profoundly shape digital trust. Trust is a relationship between various parties rather than feelings or a mental disposition (Castelfranchi, 2004). Hence, it will improve the context upon which it can exert an influence (Möllering, 2005). As better and improved relationships between partners will ultimately enhance their collaborative or shared performance. Digital trust, formed with the fusion of conventional trust and digital technologies, is a powerful organizational capability to keep the networks intact and trustworthy. Nevertheless, it forms a technology-oriented trust which will foster an improved and sophisticated relationship through digital trust.

In open innovation research (Kosonen et al., 2014; Koh et al., 2020;

Latusek-Jurczak and Prystupa-Rzadca, 2014), trust has been prominently discussed as an ignition to start collaborations and partnerships. These collaborations and partnerships are predominantly undertaken to enable purposive inflow and outflow of knowledge to innovate, where success is mainly dependent on trust among the partners and cross-organizational teams (Chesbrough & Bogers, 2014). Further, Hardwick et al. (2013) argued that trust is continuously shaped and gradually improves as collaborations in an open innovation network are undertaken. However, the question remains what constitutes such collaborations in an open innovation network successfully, because most of the collaborations fail due to distrust and doubts among the stakeholders. For virtual and non-physical networks of innovation too, trust is essential for internationalization of innovations (Huizingh, 2011;Hardwick et al. 2013).

The notion of open innovation illustrates the purposive inflow and outflow of knowledge to expand the market (Chesbrough, 2003). Trust has a critical interplay in shaping and assisting the process to enable knowledge to flow smoothly. It is an essential factor to develop inter-firm connections that help inter-firm knowledge exchange (Fukuyama, 1995). Nowadays, such knowledge flows and exchanges take place in an advanced environment where technologies like big data, blockchain, IoT, and CPS are utilized by firms to carry out their business operations. Hence, firms should think of technology to improve the trust among entities, which may lead to form a digital trust. Digital trust can enhance collaboration through the effective infusion of advanced technologies towards open innovation processes.

Thus, we argue that trust equipped with digital technologies will enhance the open innovation process through smooth and swift co-operation, collaboration, and knowledge flows, which could give exceptional competitive advantages in the form of the synergistic output of innovations. Nevertheless, removing digital trust from this equation would undoubtedly restore some of the swaying balance between the collaboration partners and stakeholders, if such a balance is considered worth preserving. Against this backdrop, we draw the following hypothesis:

Hypothesis 1. Digital trust significantly improves open innovation

2.4.2. Digital trust and open innovation: the role of technology absorptive capacity

An essential part of open innovation model is the effective integration of external or acquired knowledge into internal knowledge and routines, which depends upon an organizations absorptive capacity (Cohen and Levinthal 1990). This focuses on the firm's ability to absorb and exploit the externally acquired knowledge in its internal processes. Putting into perspective, researchers have suggested that the acquired knowledge can be absorbed and cultivated smoothly when the structure and culture of firms are open enough to compliment and facilitate the open innovation process (Dahlander and Gann, 2010). Firms therefore should have the competence for knowledge augmentation, and to develop a modern structure and an open culture, which will lead to a successful implementation of the open innovation process.

The connection between open innovation and absorptive capacity is established. Researcher (Christensen and Lægreid, 2005)rgued that absorptive capacity had addressed the organizational competence to absorb external knowledge, so Chesbrough did not present a novel phenomenon. In comparison, Chesbrough (2003) suggested the purposive inflow and outflow of knowledge as an open innovation process. We disagree and rebut the viewpoint of Christensen & Lægreid (2005) by arguing that absorptive capacity posits the capabilities and abilities of firms to absorb acquired knowledge, and open innovation entails the absorption of internal as well externally acquired knowledge. Moreover, open innovation refers to a 'process' of opening innovation. So, we view these two models as a novel in their distinct characteristics.

Many studies in connection with absorptive capacity have only discussed the knowledge augmentation inside the firm, either it is generated internally or acquired from external partners. Hence, we consider and extend this phenomenon by presenting insights from Chesbrough (2003; 2020) that for effective innovation process, the conceptual gates of organizations should be opened to the outside knowledge. The outcome of the innovation process and open innovation can be obscure if the absorptive capacity is missing in the firm; even knowledge is acquired outside or created inside. As an analogy, both a sponge and a sieve can "attract" fluids, but only a sponge can retain them for a later use. Thus, we adopt the notion of technological absorptive capacity (TAC) which we assume has a two-way flow of knowledge for open innovation to enable synergistically smooth innovations. We focus on open technical innovation rather than on economic performance because economic success per se does not help firms to capture value from innovations.

García-Morales et al. (2007, p.531) define absorptive technology capacity as the process that "involves acquisition (through which the firms obtain so-called technological stock), assimilation and transformation (the capacity to develop and refine routines to facilitate combining existing technological knowledge with that acquired, and to assimilate this knowledge and to exploit technological knowledge)," TAC helps a firm to increase, expand, and utilize existing capabilities and technologies to innovate, incorporating the technological knowledge acquired and transforming the firm's operations to increase the productivity of the goods and capital employed. A firm can reinforce its technological competence by importing external technologies and technological knowledge and then diffusing, assimilating, communicating, and absorbing them in the firm operations(Kostopoulos et al., 2011 ; Chang et al., 2020; Zahra et al., 2015; Cheng et al., 2008). In the presence of a shared objective, this two-way sharing of information will foster an amicable relationship with external firms where trust amongst the parties would also be enriched (Salampasis et al., 2015). Identifying, transforming, acquiring, exchanging, and exploiting the technological know-how can only be done based on the knowledge and learning processes already mastered by the firm.

TAC is considered as an essential organizational capability to embrace Industry 4.0. It appears to be a profound influencer of the activities related to technology and innovation in organizations. It is closely linked with technology-embedded trust and is considered a prime enabler of the open innovation process. Researchers (such as Zahra and George (2002) argue that organizations need to improve their capacity to absorb outside technological knowledge, or their TAC, for increaseing their (open) innovation processes (Lund Vinding, 2006; Zahra & George, 2002; Enkel et al., 2017; Lin et al., 2002) whereby the internal knowledge also travels outside correspondingly.

Open innovation also entails the development of the firm's systems and capabilities to identify, assimilate, and exploit external know-how from its strategic environment and successfully integrate it into its internal knowledgebase; it also entails the flow of internal technological know-how to outside. Such cooperation that involves risk arising from cooperation failures, such as cooperation needed for many digital business transactions (Son et al. 2006; Moorman et al., 1993), requires trust. Notably, participants in a particular community become trustworthy so that other people will trust them (Zaheer et al., 1998). Trust has long been viewed as an antecedent of cooperation (Lee, Wong, and Chong, 2005) and a supportive condition for firms to explore new strategic options (Zahra et al., 2008). Therefore, firms functioning with Industry 4.0 technologies foster digital trust in order to smoothly carry out the open innovation process through collaborations and co-creation.

Drawing on the premise of knowledge management theory and social exchange theory, we argue that digital trust directly contributes to a firm's open innovation process, improves a its TAC in Industry 4.0 settings (Mubarik, 2015). In a nutshell, TAC can be instrumental in improving the open innovation of organizations. We further segregate TAC into realized absorptive capacity and potential absorptive capacity.

Table 1
Respondents demography (n = 324)

Size	*n*	%
SMEs	125	39%
Large	199	61%
Geographical dispersion		
Malaysia	124	38%
Thailand	109	34%
Indonesia	91	28%
Firm Age		
1 to 5 years	49	15%
6 to 10 years	105	32%
11 to 15 years	99	31%
16 years ≤	71	22%
Employees		
50 > 150	72	22%
151 > 250	101	31%
251 > 350	86	27%
≥ 351	65	20%

2.4.2.1. Potential and realized technology absorptive capacity. Potential absorptive capacity (PTAC) comprises the acquisition and assimilation of knowledge and capturing the efforts employed to identify, acquire, and assimilate the new knowledge acquired from external partners or sources. (Zara and George 2002; Flatten et al., 2011). We extend this conception to include that acquiring external knowledge occurs in reciprocity whereby the firm opens and exchanges its internal knowledge and research with external partners and collaborators (Chesbrough, 2006; 2019). Realized absorptive capacity (RTAC) caters to the transformation and exploitation, deriving new directions or ideas by combining the existing and newly generated knowledge from within the organization and its application in its operations further to enhance the innovation process (Zahra et al., 2015). Both subsets of absorptive capacity fostering technological and innovation capability we refer to as TAC.

PTAC and RTAC act differently yet complement each other to facilitate the open innovation process. All the times, both these subsets of TAC co-exist to cultivate innovation performance; however, insufficiency and adequacy still exist with the segregation of both from each other. Thus, high PTAC does not imply high performance, neither higher RTAC in isolation. They vary in their functionalities when combined; they fulfill the core objective by acting synergistically, which is the notion of open innovation too. Zahra and George (2002) explained that the segregation of both could cause an efficiency error, which could deteriorate the knowledge absorption and augmentation process. Having said that, we draw the following hypotheses:

Hypothesis 2. Realized absorptive capacity mediates the relationship between digital trust and the open innovation of a firm

Hypothesis 3. Potential absorptive capacity mediates the relationship between digital trust and the open innovation of a firm

2.4.3. Role of technological orientation in digital trust and open innovation

Technological orientation (TO) is an essential factor to succeeding firms' innovation activities (Gatignon & Xuereb, 1997) which are encapsulated in open innovation paradigm as well. According to Roth, Gaimon, and Krajewski (1991), it is a learning process for a firm to acquire the latest technologies or at least their knowledge. Technological orientation is a foremost firm-level paradigm that shows the firm's ability regarding the technological knowledge, adoption, and implementation of innovative technologies for the firm's success (Chen, Tang, Jin, Xie, and Li, 2014).

In the Industry 4.0 times, to ensure a competitive advantage, firms need to continuously update their learning about new technologies. Such technological learning is significantly linked with knowledge assimilation, exploration, and exploitation (Roth et al.,1991) as technological learning occurs in open innovation. In short, technological orientation has the potential to enhance the relationship between digital trust and open innovation. Digital trust integrates advanced technologies with conventional trust elements and open innovation focuses on the purposive inflow and outflow of knowledge, to which technological orientation also has to deal with as its ordinary course of action in many contexts. Thus, we formulate the following hypothesis:

Hypothesis 4. Technological orientation positively moderates the relationship between digital trust and open innovation

3. Material and methods

3.1. Population and sampling

This study has adopted a quantitative method in which data is collected through a structured questionnaire. For the purpose of data collection, we have focused on the Electrical and Electronics sector of three pacific Asian countries, namely Malaysia, Indonesia, and Thailand. There are two primary reasons to select the Electrical and Electronics (E&E) sector. First, this sector is one of the leading contributors to the GDP of these countries. Likewise, companies in the E&E sector could be seen proactive in the adoption of industry 4.0 technologies like bock chain, IoT etc., and are also involved in innovation-related collaborations. The data is collected from 324 E&E firms of various sizes (including small, medium, and large) in December 2019. Table 1 exhibits the demographic details of the respondents. The firms have been selected by using purposive sampling and selected those companies which are practicing in the open innovation process and using any technology of industry 4.0 in their processes.

3.2. Data collection and analysis

The data was collected by using a close-ended questionnaire adopted from the previous studies. The constructs of digital trust, composed of trust and industry 4.0 technologies (*big data, IoT, cyber-physical systems and blockchain*), open innovation, technological orientation, realized absorptive capacity, and potential absorptive capacity was adopted from the previous studies. The taxonomy of the

Table 2
Constructs and Sources

Construct	Sub-Construct	Items	Source(s)
Digital Trust	Trust	4	F. Zhang et al. (2018), Zaheer, et al. (1998)
	Industry 4.0 technologies	4	Imran, M. (2018)
		5	Imran, M. (2018)
		4	Imran, M. (2018)
		6	Kim et al. (2019), Shin (2010)
Open Innovation		15	Mina, Bascavusoglu & Hughes (2014); Enkel et al. (2011)
Absorptive Capacity	Realized Absorptive Capacity	7	George and Zara (2002), García-Morales et al. (2007)
	Realized Absorptive Capacity	7	George and Zara (2002), García-Morales et al. (2007)
Technological Orientation		14	Gatignon, Hubert, & Xuereb, Jean-Marc. (1997)

construct is shown in Table 2. The data was collected by using the online form as well as the physical questionnaire. After data collection, we employed partial least square-structural equation modeling (PLS-SEM) in order to assess the impact of digital trust composed of Trust and Industry 4.0 technologies on Open Innovation. PLS-SEM is considered a highly robust modeling approach, which is applied in two steps. Firstly, it adopts a threefold approach to ensure the appropriateness of the measurement models for qualifying. Then, It includes an assessment of reliability, validity (convergent and discriminant), and model fitness. Finally, the started model is analyzed to test the hypothesized relationship. The overall strength and predicted relevance of the model is analyzed by analyzing the coefficient of determination (R square) and blindfolding (Q square). We employed PLS-Multi Group Analysis (MGA) to examine the cross-country differences.

4. Results and discussion

To examine the impact of digital trust (composed of industry 4.0 technologies and conventional measures of trust) on open innovation, we employed PLS-SEM and PLS-MGA on the firm-level cross-country data, collected from 324 Electrical and Electronics firms of Malaysia, Indonesia, and Thailand. In order to test the reliability of the data, we assessed the values of Cronbach alpha (CB), composite reliability (CR), and factor loadings. The reliability results in Table 3 show that all measurement model has sufficient reliability as the values of their CB alpha, CR and FL are well above the desired threshold of 0.70, 0.60 and 0.50 respectively (Hair et al.,2016). Further, we tested the convergent and discriminant validities of the measurement model to ensure the overall validity. For convergent validity, the value of the average variance extracted (AVE) of each measurement model was checked, which should be greater than 0.50. Results, in Table 3, show that each measurement model has AVE value higher than the threshold value of 0.50. In order to evaluate the discriminant validity, we adopted the Fornell-Larcker criteria. Results of the Fornell-Larcker criteria appear in Table 4, showing the square rooted values of AVE, in diagonal, are higher than inter-construct correlation, thus ascertaining the discriminant validity of all measurement models.

Additionally, to check the fitness of measurement model results, NFI and GFI values have been computed and checked. The results in Table 3 show that the values of GFI and NFI are higher than 0.90, ensuring the model fitness of all measurement model. The results of CB alpha, FL (factor loadings), CR, AVE, and FL-criteria ensure the reliability, validity, and fitness of the measurement models, thus allowing us to proceed for structural model analysis.

The results of the structural model hypotheses testing appear in Tables 5, 6, and 7. Results show that digital trust ($\beta = 0.33$, $p < 0.05$) has a profound effect on the open innovation of a firm in the overall sample and also by country. Further, results show a significant mediating role of realized technology absorptive capacity(RTAC) ($\beta = 0.52$, $p < 0.05$) and potential technology absorptive capacity(PTAC) ($\beta = 0.44$, $p < 0.05$) in the juxtaposition between digital trust and open innovation in the total sample. These results are also stable in country-wise disaggregated analysis, exhibited in the last three columns of Table 5. Nevertheless, the strength of the relationships marginally differs across countries. The results also show a significant decisive moderating role of technological orientation ($\beta = 0.35$, $p < 0.05$) in the association between digital trust and open innovation. It implies that increasing technological orientation can augment the impact of digital trust on open innovation. These results support all four hypotheses of the study, denoting a significant direct and indirect impact of digital trust on open innovation of firms. The values of adjusted R-square, i.e., 0.67, show that the model is moderately strong. Likewise, the values of blindfolding represented by Q-square, i.e., 0.42, confirm the strong predictive relevance of the model. We employed Multi-Group analysis (MGA) to test the possibility of any statistically significant difference in the direct and indirect (through PTAC and RTAC) effect of digital trust on open innovation, by country.

Table 3
Reliability, Consistency and Validity

Construct	Sub-Construct	Items	Loadings	CB alpha	CR	AVE
Digital Trust	Trust	DT1	0.76	0.78	0.83	0.56
		DT2	0.78			
		DT3	0.73			
		DT4	0.71			
	Industry 4.0 technologies	DT5	0.78	0.83	0.89	0.57
		DT6	0.72			
		DT7	0.83			
		DT8	0.74			
		DT9	0.71			
		DT10	0.66			
		DT11	0.88			
		DT13	0.77			
		DT14	0.72			
		DT15	0.73			
		DT17	0.83			
		DT118	0.7			
		DT9	0.68			
		DT22	0.69			
		DT23	0.72			
Absorptive Capacity	Realized Absorptive Capacity	RAC1	0.85	0.77	0.88	0.58
		RAC3	0.79			
		RAC4	0.71			
		RAC5	0.75			
		RAC7	0.72			
	Realized Absorptive Capacity	PAC1	0.85	0.78	0.87	0.57
		PAC2	0.79			
		PAC4	0.71			
		PAC6	0.66			
		PAC7	0.75			
Technological Orientation		TO1	0.72	0.86	0.92	0.56
		TO2	0.73			
		TO3	0.79			
		TO5	0.81			
		TO6	0.74			
		TO7	0.72			
		TO9	0.79			
		TO12	0.68			
		TO14	0.73			
Open Innovation		OI1	0.83	0.91	0.92	0.57
		OI2	0.79			
		OI3	0.82			
		OI4	0.77			
		OI5	0.72			
		OI6	0.75			
		OI7	0.68			
		OI8	0.71			
		OI9	0.73			

Note: DT12, DT16, DT20, DT21, RAC6,PAC3,PAC5,TO4, TO8, TO10,TO11, TO13 have been deleted due to factor loading lower than 0.40.

Table 4
Fornell-Larcker Criteria for Discriminant Validity

	VIF	DT	PAC	RAC	TO	OI
Digital Trust (DT)	2.08	***0.75***				
Potential Absorptive Capacity (PAC)	1.84	0.33	***0.74***			
Realized Absorptive Capacity (RAC)	2.56	0.39	0.53	***0.76***		
Technological orientation (TO)	1.97	0.27	0.32	0.44	***0.75***	
Open Innovation (OI)	2.07	0.31	0.42	0.26	0.45	***0.75***

Note: Diagonal values are square root of AVE

Grossly results do not show any significant difference across the country, except for two glaring cases. First, the results in Table 6 show that the effect of digital trust on open innovation differs while comparing Malaysia and Thailand. The difference in the magnitude ($diff = 0.16$, $p < 0.05$) shows that digital trust has a stronger influence in the case of Malaysia as compared to Thailand. Likewise, the effect of potential technological absorptive capacity differs while comparing

Table 5
Hypotheses Testing

Hypotheses		Total Sample β-value	Malaysia (n = 124) β-value	Indonesia (n = 109) β-value	Thailand (n = 91) β-value
Hypothesis 1	Digital Trust → Open Innovation	0.33* (3.462)	0.36* (4.095)	0.28* (4.252)	0.52* (3.852)
Hypothesis 2	Digital Trust → RTAC → Open Innovation	0.52* (4.281)	0.48* (5.958)	0.38* (5.805)	0.61* (3.795)
Hypothesis 3	Digital Trust → PTAC →Open Innovation	0.44* (5.761)	0.39* (4.165)	0.11*** (1.751)	0.096** (1.872)
Hypothesis 4	Digital Trust × TO → Open Innovation	0.35* (6.64)	0.28* (4.642)	0.22* (6.015)	0.36** (1.981)
	Adj R-square	0.67	0.64	0.59	0.61
	Q-square	0.42	0.39	0.32	0.35

Note values in parenthesis are t-values
Q Square (Total Sample) 0.37 for the whole mode; SMEs 0.21; Large 0.35
*,**, and *** show level of significance at 1%, 5% and 10% level

Malaysia with Indonesia. The difference of the magnitude shows that role of PTAC is higher in the case of Malaysia than Indonesia. Despite these two differences, overall results support the direct and indirect effect of digital trust on open innovation in all cases. Likewise, results also support the positive moderating role of technological orientation in all cases. We also employed PLS-MGA (Multi-Group Analysis) for checking the possibility of any difference in results by the size of the firms, i.e., SMEs and large firms.

The results are exhibited in Table 7. The results [diff (L-SMEs) = 0.25; $p < 0.05$] denotes that the effect of digital trust on open innovation differs by the size of the firm. Results [diff (L-SMEs) = 0.26; $p < 0.05$] also shows the significant difference in the indirect effect (through potential absorptive capacity) of digital trust on open innovation. In the case of the other two hypotheses, we do not see any statistically significant difference. Putting together findings of this study reveal a significant role of digital trust on open innovation; however, the strength of the effect may differ by country. Further, our findings reveal a significant mediating role of RTAC and PTAC in the association between digital trust and open innovation. Results also show the moderating role of technological orientation in all cases.

The findings of our study concur with the literature on the Industry 4.0 technologies, trust, and open innovation. Our first hypothesis, which confirms the significant effect of digital trust on open innovation, echoes the findings of Zheng and Holtmanns, 2008, Salampasis (2019), Imran (2018), Kim et al. (2019) and Macs (2019). These researchers, among others, argue that trust embedded with digital technologies does not only increases the reliability of the communication channels but can significantly build trust among stakeholders. The primary reason for improving trust among stakeholders could be the capabilities of Industry 4.0 technologies to trace and verify the shared information. Further, Industry 4.0 technologies like blockchain, through their comprehensive system of single-entry recording, ensure the confidentiality of the information (Frank, 2019). This system also ensures the availability of the information to the right party in the right format at the right time (Mobarik and Zuraida, 2019) without any alteration.

The results of the second and third hypotheses of the study, confirming the role of potential and realized absorptive technology capacity, concur with the studies of Tariq and Mubarik (2020), Laudante (2017), and Frank (2019). According to Mahmood and Mubarik (2020), the TAC of a firm determines its capacity to identify, assimilate, acquire, and apply the outside technology-related knowledge to the organizational processes and strategies. Improving digital trust helps a firm to connect with the external partners and work closely with them (Ayentimis and Burgess, 2018). This connectivity improves firms' collaboration with external stakeholders as it does a firm's TAC, which further improves the open innovation performance of the firm. The third finding of this study confirms the role of technological orientation in improving the association between open innovation and digital trust and is well in line with the studies of Ayentimi and Burgess (2018) and Ayentimi (2018). These studies argue that improving technological orientation augments the effect of technologies and digital trust on innovation. For adopting technological capabilities, firms' first need is to know about the technology. This knowledge, when acquired and updated regularly, leads technological orientation (Schweisfurth et al., 2011; Miao et al., 2018; Kogut & Zander, 1992). It can be defined as "a firm's openness to new ideas, and it is a proclivity to adopt new technologies during product development" (Hurely & Hult, 1998, p. 24). These studies imply that technological orientation can play an instrumental role in reinforcing the effect of digital trust on open innovation. It also acts as a catalyst for enhancing the outputs of the firm's entrepreneurial and innovation activities (Li, 2005; Kim, 2019).

5. Conclusion

Digital technologies like internet of things, blockchain, and cyber-physical systems are bringing a paradigm shift in the way business processes are executed and innovations are being made. Industry 4.0 technologies, integrated with the conventional organizational capabilities, can become a critical success factor to compete in the highly technology-driven markets. Industry 4.0 technologies, when combined with the human-centric trust, form a digital-trust, which can be

Table 6
Inter-country Comparison

Hypotheses		Thai vs. My diff (T-M)	p-value	Thai vs. Ind diff (T-I)	p-value	My-Ind diff (M-I)	p-value
Hypothesis 1	Digital Trust → Open Innovation	0.16*	0.001	0.24	0.061	0.08	0.115
Hypothesis 2	Digital Trust → RTAC → Open Innovation	0.13	0.132	0.23**	0.041	0.1	0.062
Hypothesis 3	Digital Trust → PTAC→Open Innovation	-0.3	0.000	-0.024	0.432	0.28*	0.002
Hypothesis 4	Digital Trust × TO → Open Innovation	0.08	0.168	0.14	0.131	0.06	0.164

*,**, and *** show level of significance at 1%, 5% and 10% level

Table 7
Multi Group Anaysis (By size)

Hypotheses		Large	SMEs	|L-SMEs|	(WS) p-value	(P) p-value
Hypothesis 1	Digital Trust → Open Innovation	0.53	0.28	0.25*	0.031	0.029
Hypothesis 2	Digital Trust → RTAC->Open Innovation	0.38	0.33	0.05	0.460	0.492
Hypothesis 3	Digital Trust → PTAC->Open Innovation	0.57	0.31	0.26*	0.002	0.003
Hypothesis 4	Digital Trust × TO → Open Innovation	0.36	0.32	0.04	0.250	0.238

WS: Welch-Satterthwait
P: Paramteric

instrumental in improving the technological and open innovation performance of firms.

Against this backdrop, this study aimed to examine the impact of digital trust on the open innovation performance of a firm. By collecting data from three major Asia-Pacific countries and applying PLS-SEM and PLS-MGA, this study analyzed the modeled relationships. The findings of the study reveal the profound role of digital trust in improving the open innovation of a firm. The findings of this study also reveal an important role of realized and potential TAC in the association between digital trust and open innovation. Finally, the results confirm the moderating role of technological orientation in improving the association between digital trust and open innovation.

In a nutshell, these results show significant both direct and indirect effects of digital trust (technology-embedded) on the open innovation of a firm. It implies that Industry 4.0 technologies, when combined with conventional capabilities, can significantly improve an organization's innovation abilities.

6. Implications and future research

The findings of this study offer some profound policy implications. The first implication of this study is the adoption of Industry 4.0 technologies in improving the conventional organizational challenges and capabilities. Traditional firms try to stick with the conventional technologies due to the innate distrust and uncertainty for new technologies (Kim 2018). Our findings not only dispel this conventional fear but also suggest an organization to adopt digital technologies to improve digital trust. Adoption of digital technologies cannot be immediate; the organization needs to develop a comprehensive technological adoption strategy. Development of such a strategy not only allows a firm to evaluate the suitability of the latest technologies for implementation in the organization but also helps the organization to adopt contemporary technologies.

The results imply that an organization should deliberately make efforts to improve its technology-related absorption capacity to improve the orientation of technology-related knowledge to facilitate innovations. Integrating human resource development strategy with the technological strategy of a firm can play a vital role in improving its TO and TAC.

Based on our findings, we suggest large organizations to adopt Industry 4.0 technologies to improve their open innovation performance. However, we recommend SMEs to first focus on improving their TO and RTAC. In doing so, SMEs should focus on improving their TO and TAC in order to prepare a necessary ground for adopting the Industry 4.0 digital technologies, which further can augment an organization's open innovation.

In a small organization, it is suggested to develop and integrate human development and technology strategies as they have potential to enhance technology absorptive capacity which help to adopt digital technologies to further enhance open innovation practices. Lastly, we recommend the involvement of top management in developing and linking the technology strategy with HRD strategy and its execution.

Our study has some suggestions for future researchers. First and foremost is the collection and analysis of time series data. As we have collected cross-sectional data in two phases from three countries, if a researcher could get the same data longitudinally, it can depict a comprehensive picture. Second, future researchers can extend their sample by including firms from other industries in order to see the stability of the results across both manufacturing and service sectors. Moreover, the high-tech firms and growth firms should be undertaken to exam the interplay of digital trust and open innovation, as those firms have reputation of accomplishing productive innovation outputs. Last but not least is the role of organizational structure, which researchers can include in order to see the heterogeneities across various styles of organizational structures .

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No

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Paper 3

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Intellectual capital, blockchain-driven supply chain and sustainable production: Role of supply chain mapping

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ABSTRACT

The production and consumption of products are held responsible for most environmental challenges and climatic changes, which adversely affect human lives and compromise the future of generations to come. Sustainable production appears as a strategic route to combat these adversities, the pursuit of which is highly challenging. In this study, we argue that Intellectual capital (IC), featured by human capital, relational capital, and structural capital, can play a dual role in improving the sustainable production of a firm. We put forward that IC contributes to sustainable production directly and indirectly through the adoption of blockchain-driven supply chain management (BCSCM). In this context, the objective of this study is to examine the impact of intellectual capital (IC) on sustainable production. The study also investigates the role of SC mapping and BCSCM in the association between IC and sustainable production. Data were collected from 289 textile firms of Pakistan and Bangladesh with the help of a designed questionnaire. The study employed CB-SEM to examine the modeled relationship. Further, PLS-Multi-group Analysis (MGA) was used for cross-country comparison of the results. The results diverge from the conventional wisdom exhibiting an insignificant direct impact of IC in sustainable production. Nevertheless, the results show a meaningful indirect effect of IC through BCSCM and SC mapping on sustainable production. Results also exhibit a significant direct impact of BCSCM on the sustainable production of a firm. The results call for consideration of IC and BCSCM in improving the sustainability of a firm.

1. Introduction

Industry 4.0 (I4.0), conceived in 2011 as a future business strategy in Germany, is now a hardcore reality, disrupting conventional business processes and market dynamics. It has triggered massive digitalization of manufacturing processes, automating the end-to-end value chains with minimal human interactions (Sprovieri, 2019; M.S. Mubarik et al., 2021; Fragapane et al., 2020). Equipped with technologies including Cyber-physical systems (CPS), Industrial Internet of Things (IIoT), autonomous vehicles, cloud and cognitive computing, and many more, it is pushing the business process digitalization and automation to unprecedented levels. Further, I4.0 facilitates the applications of advanced analytics and business-intelligence capabilities, resulting in new forms of human-machine interaction such as advanced robotics and 3-D printing (Baur and Wee, 2015; Khan et al., 2021). These staggering digital advancements are transmuting the traditional supply chains (O'Marah 2017; Mubarik and Naghavi 2020). According to Stank et al., p.957). "*If industry observers and scholars are to be believed, we are on the cusp of an age where conventional supply chain processes will soon dramatically change, or alternatively, become completely usurped by electronic information streams.*"

In order to amicably adopt the new paradigm, the key challenges faced by the present supply chains need to be well understood. The first challenge among them is sustainable production. Rapidly changing climatic conditions and increased awareness about social and environmental issues have brought sustainable production to the center point

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(Mahmood and Mubarik 2020; Khan et al., 2021; M.S. Mubarik et al., 2021b). Firms are increasingly being pushed both externally and internally to ensure the sustainability of their production processes. Firms are looking for developments in supply chains that can contribute to their sustainable production.

A second critical challenge, intertwined with sustainable production, is related to traceability. It is puzzling to find an appropriate tool(s) available for manufacturers to ensure the sustainability of the production processes. The absence of such tools is creating problems of supply chain visibility in the extended supply chains. It is important for the businesses to have visibility of products in every stage of the supply chain, such as the identity, location, and other tracking information (Ganesan et al., 2016). Blockchain-driven supply chain and supply chain mapping appear to be a natural fit to simultaneously cater to SC traceability and sustainability (Mubashar and Zuraida 2019). Nevertheless, how SC mapping can influence the sustainability of the production process is vague and calls for much-needed research (Wichmann et al., 2020). Likewise, the impacts of blockchain-driven supply chains on sustainable production are inconclusive.

Furthermore, the implementation of blockchain-driven supply chain and supply chain (SC) mapping requires well-integrated organizational processes, strong relationships with stakeholders, and high levels of human capital, collectively known as intellectual capital (IC) (Secundo et al., 2020). M.S. Mubarik et al. (2021) argued that IC is an indispensable organizational asset for incorporating technological developments like blockchain-driven supply chain and supply chain mapping. They continued to argue that a firm's strategic initiative may turn into a disastrous situation without a strong IC. Although the fundamental link between IC, technological adoption, and sustainable production is on the whole persuasive, more remains to be understood about its precise nature. Our study attempts to address this issue by refining and extending the understanding of the IC-BCSCM-sustainability paradox.

We draw upon the IC-based view and develop new insights on the role of IC in increasing BCSCM and SC mapping. We argue that IC—*in the form of human capital, relational capital, structural capital*—can play an instrumental role in improving a firm's SC mapping and BC-BSC, enhancing sustainable production of a firm. More specifically, from studies on IC, we construe how human, organizational, and social capital enable organizations to adopt a blockchain-driven supply chain and its impacts on sustainable production thereof. Further, drawing upon dynamic capabilities theory, we argue that SC mapping and BCSCM can be instrumental in increasing sustainable production.

We collected data from 289 firms of 02 South Asian nations, Pakistan and Bangladesh, to empirically examine our argument. In doing so, the study contributes to the literature in at least three ways. First, drawing upon the dynamic capabilities theory and IC-based view, we propose a new framework, modeling the IC, blockchain-driven supply chain, SC mapping, and sustainable production together. Second, the study provides empirical evidence on the role of BCSCM and SC mapping in the association between IC and sustainable production. Thirdly, the study provides empirical evidence on the impact of IC on sustainable production.

The study proceeds with the following structure. Section 2 discusses the literature, including the theoretical exposition and hypotheses development. The methodology is presented in Section 3, covering the data, data collection instrument, and analytical technique. In Section 4, the findings of the study are presented and are discussed in Section 5. Finally, the study concludes by suggesting the implications, limitations, and future research directions in *Section 6.*

2. Literature review

2.1. Theoretical exposition

The study takes its theoretical basis from the Intellectual Capital-based view (ICV) and dynamic capabilities theory (DCT). ICV, according to Reed et al. (2006), asserts that the combination of three dimensions of IC, i.e., human capital, relational capital, and structural capital, leads toward a unique, indivisible resource endowment, which can significantly influence the performance of a firm. ICV is closely linked with Knowledge-Based View (KBV), as both stem from Resource-based view. Nevertheless, both differ in focus as KBV's primary focus is "evaluating the effectiveness of a firm's use of knowledge-management tools as knowledge-generating mechanisms, such as its information technology systems and information management systems" (Reed et al., 2006, p. 869). Whereas the prime focus of ICV is "on the stocks and flows of knowledge capital embedded in an organization and is posited to have direct associations with its financial performance." We argue that sustainable production is an integral part of a firm's performance; hence, IC can profoundly influence it.

We model the blockchain-driven supply chain (BCSCM) by taking the lead from the dynamic capabilities theory. For Teece et al., p.529), "*The capabilities approach places emphasis on the internal processes that a firm utilizes, as well as how they are deployed and how they will evolve.*" For the DCT to sustain long-term competitive advantage, a firm's resources should have the dynamism to encounter the rapidly changing business environment. The development of such dynamic capabilities can help the organization attain performance objectives. We argue that BCSCM is a dynamic capability of an organization, which can play an instrumental role in augmenting the sustainable production of the firm. Likewise, BCSCM also enables firms to attain the dynamic capabilities (e.g., SC mapping) to effectively integrate suppliers, customers, and other related players in the supply chain. Drawing on dynamic capabilities and ICV, we propose that BCSCM enhances the capability of the supply chain by enabling SC mapping and creates value for the organization by improving the sustainable production and visibility of a firm. Further, taking the lead from ICV, we argue that IC enables a firm to attain BCSCM and to develop SC mapping capabilities.

2.2. Hypotheses development

2.2.1. Intellectual capital and sustainable production

Intellectual capital (IC) represents an organization's intangible resources, which can profoundly influence a firm's sustainable production. It considers the organizational relationships with its suppliers, customers, and employees, the organization's processes and routines, and technical know-how, expertise, and knowledge rooted in an organization's human resources (Secundo et al., 2017; M.S. Mubarik et al., 2021). There is a broad consensus by scholars (e.g. Bontis, 1998; Han and Li 2015, 2015; Ahmed et al., 2019,209; Mahmood and Mubarik 2020; Salvi et al., 2020; M.S. Mubarik et al., 2021) on the fact that IC has three major interrelated dimensions namely human capital, relational capital, and structural capital.

Human capital (HC) encapsulates the knowledge, skills, abilities, and resilience of employees of an organization, which can be directly or indirectly instrumental in uplifting organization performance partly or as a whole (Li et al., 2021; Wang et al., 2021). For M.S. Mubarik et al. (2021, p.3), "human capital [is] the knowledge, skills, multi-tasking ability, commitment, engagement, attitude, experience, intelligence, and creativity of employees of an organization". *Relational capital (RC)* is defined as the sum of an organization's relationship with its stakeholders. In other words, it is the associations and collaborations of an organization with its customers, suppliers, and other stakeholders. *Structural capital (SC) refers to as the organization processes, routines, and* non-human knowledge rooted in the organizational processes and data basis. The knowledge remains with the organization, unlike human capital (Ahmed et al., 2019; Mubarik et al., 2019). For M.S. Mubarik et al. (2021, p.3), "SC represents the institutional memory and codified knowledge base of the firm even when employees come and go." Put together, HC, RC, and SCL are three important constituents that form the intellectual capital of a firm.

Researchers (e.g. Bontis 1998; Mahmood and Mubarik, 2020) argue that all three cords of IC play a crucial role in improving sustainable production. Some of the researchers, clubbing sustainable production as pert of the normal firm performance, conclude IC as the major factor influencing firm performance. In view of such scholars, uplifting IC directly or indirectly contributes to sustainable production. Nevertheless, substituting sustainable production with performance may not be entirely true as in some of the cases, conventional performance parameters could be altogether different and, in some cases, even conflicting to the concept of sustainable production. Therefore, according to Khalique et al. (2020), IC's impact on performance may not be generalized to the other performance aspects like sustainable production. According to Mubarik et al., 2021b; Mubarik et al., 2021a, sustainable production considers the systems and processes that are green, energy-efficient, and economical. It can be taken as the subset of corporate sustainability (Ahmed et al., 2019).

The notion of sustainable production was introduced at United Nations Conference on Environment and Development in 1992. According to US-EPA(2021, p.1), "Sustainable manufacturing [production] is the creation of manufactured products through economically sound processes that minimize negative environmental impacts while conserving energy and natural resources." US-Environmental Protection Agency (US-EPA) further claims that sustainable production can significantly improve the safety of the employees, products, and community. It is well interlinked with the concept of sustainable development. Primary resource conservation (energy and material use), greenness (environment sinks), social justice, community development, and economic performance are important facets of sustainable development. According to Veleva and Ellenbecker (2001), sustainable production requires work on six major facets, namely i) usage of material and energy, ii) natural environment, iii) community development and societal justice, iv) financial/economic performance, v) employees and vi) products. These parameters are closely linked with the triple bottom lines (TBL) model of the helix, where the people, planet, and profit are considered as the center of an organization. For the sake of this study, we are taking a company's environmental performance, economic performance, and social performance as major indicators to gage sustainable production.

Although a clear-cut demonstration of the relationship between IC and sustainable production may not be available in the literature, several studies indirectly highlight the impact of IC on the various aspects of organizational sustainability (Mahmood and Mubarik 2020; Khan et al., 2021). For example, Eisenstat (1996) argued that the development of human capital through effective HR practices directly contributes to the sustainability of an organization. Similarly, Rayner and Morgan (2018) showed a significant impact of human capital—measured as employees' green behavior—on the knowledge about sustainability.

Regarding the effect of relational capital on sustainability, some studies (e.g., Bansal 2002; Khan et al., 2021; M.S. Mubarik et al., 2021) highlighted the instrumental role of structural capital –organizational processes, routines, databases, and systems—in augmenting the sustainability of an organization. Previously, Prajogo and Mc Dermott (2011) also showed the impacts of structural capital in improving environmental compliance. Further, studies (e.g., Chung et al., 2012; Khan et al., 2020) demonstrated a significant role of relational capital in sustainability performance, including sustainable production. Against this backdrop, we draw the following hypothesis:

Hypothesis 1: IC positively contributes to sustainable production.

2.2.2. Intellectual capital and BCSCM

We also argue that a strong intellectual capital can play a significant role in adopting and implementing the blockchain-driven supply chain, which can further influence sustainable production. Starting from the human capital, the first cord of IC, it is argued that high quality human capital—*equipped with employees with right experience, skills, and understanding of the customer market*—have higher capability to identify, adopt and implement the technological developments taking place in the business environment (Subramaniam and Youndt, 2005; Mubarik et al., 2018). Critical knowledge and information about technological processes learned from supply chain partners can be applied to manufacturing processes more effectively and efficiently with a high level of HC. Further, firms with high-quality human capital can have a higher tendency to learn the technological developments from their suppliers and customers. BCSCM, being the key technological development, can be better understood and adopted by firms possessing high-quality human capital.

Relational capital, represented by the firm's relationship with its stakeholders, can also play a profound role in understanding and adopting block chain-based supply chain management. A firm having collaborative relationships with external stakeholders has more access to the knowledge embedded in the external networks. Such knowledge can be related to the process technologies like BCSCM or product or network innovation. In short, the stronger relational capital enhances access to the latest knowledge and helps in adopting it. The technological knowledge obtained from external resources could be exploited by making it part of the organization routines. A strong structural capital can help a firm assimilate and institutionalize technological developments effectively and efficiently (Mahmood and Mubarik 2020; M. S. Mubarik et al., 2021).

Hypothesis 2a: IC positively contributes to the application of blockchain-based supply chain management

2.2.3. Blockchain-based supply chain management and sustainable production (SP)

Blockchain has appeared as a cutting-edge technology has enormous potential to improve the performance of supply chain management. Unlike other technologies, block technology uses a decentralized database for the storage of information. Researchers (e.g., Zhou et al., 2020) argue that blockchain follows a distributed ledger system recording data into timestamped blocks. It stores data in distributed ledger among a particular group of participants. An individual member can not change the data. This makes blockchain ledger trustworthy. Further, data stored on BCT is immutable as the record of complete transaction history is maintained on the blockchain ledgers. This technology has immense potential to transform the conventional SC to a high-performing blockchain-based supply chain (BCSCM). Primarily, it can be used for SC traceability, transparency, verifiability, and security. The unique architecture of blockchain also helps to improve the efficiency of the transaction. BCSCM can influence sustainable production as the implementation of BC greatly help firm to realize the knowledge and information sharing among the supply chain partners. The improved sharing of information helps the firm identify the waste in the supply chain processes and reduce the cost of production (Yeoh, 2017). One of the major challenges to incorporating sustainable production is information transparency, security and traceability. The decentralized databases, having distributed ledger technology, enable blockchain-driven supply chains to be comparatively safer, trustworthy, and traceable (Orji et al., 2020). They can also play a key role in detecting and preventing any unsustainable process (s) and practice(s) in the supply chain, which is the very essence of SC mapping (Mackey and Nayyar, 2017). For M.S. Mubarik et al. (2021), BCSCM can profoundly influence the sustainability of a firm's production as it develops a firm's capability to better monitor and evaluates the sustainability of its business processes. According to Xue et al. (2020), "blockchain is a cutting-edge technology that can transform and remodel the relationships between all members of the supply chain system". They further mention, *"The application of blockchain in the supply chain is still in the trial stage. But practical facts tell us that the use of blockchain in the supply chain will have a significant impact*

on its operation and will reshape the relationship among the members" (p.2). Based on the literature discussed above, we draw the following hypothesis:

Hypothesis 2b: The application of BCSCM contributes to sustainable production.

2.2.4. IC and SC mapping

SC mapping refers to "the process of engaging across companies and suppliers to document the exact source of every material, every process and every shipment involved in bringing goods to market" (Ivanov, and Dolgui, 2020). It represents the supply network relationships, flows, and dynamics in a simplified yet realistic manner by capturing the essence of the environment in which the supply chain operates (Farris, 2010). SC mapping assists an organization in visualizing "the network that connects the business to its suppliers and its downstream customers and allows the identification of problematic areas and support process decisions." SC mapping is a stringent and challenging process that requires close collaboration with internal and external stakeholders and demands a high level of human knowledge, skill, and expertise—human capital—to drive it. SC mapping requires employees to have a solid knowledge of a firm's supply chain processes and how they are linked with the upstream and downstream partners (M.S. Mubarik et al., 2021). SC mapping greatly depends on how a firm closely interacts with its suppliers and customers— relational capital. SC mapping projects could not succeed due to the weak relational capital of a firm (M.S. Mubarik et al., 2021; Ali et al., 2021). According to Khan et al. (2021), an organization with a stronger and well-documented process has higher chances of mapping its supply chain. As a matter of fact, SC mapping efforts can not be initiated without having standardized supply chain processes and routines. The above literature reveals the connectivity of all three cords of IC i.e. human, relational, and structural capital with SC mapping and allows us to draw the following hypothesis:

Hypothesis 3a: IC positively contributes to the SC mapping

2.2.5. SC mapping and sustainable production

In order to ensure the sustainability of the supply chain processes, they must have traceability, visibility and verifiability. SC mapping can make the processes traceable by linking the processes with technologies and providing a stand-in of the actual environment. Researchers (e.g. Cooper et al., 1997; Christopher and Lee, 2004; Childerhouse and Towill 2006; Carvalho and Machado 2007; Doorey, 2011; Achilles, 2013; Barros et al., 2011; Choi et al., 2020) mention that SC mapping improves the visibility of the processes by providing the real-time data from the various interface points (Mubarik et al., 2021). It also helps to ensure that trust exists among the supply chain partners as information shared could be verified through distributed ledgers. In contrast, an ill-mapped supply chain can reduce the extent of information sharing and can result in unsustainable production. For M.S. Mubarik et al. (2021, p.15), "it is important to note that SC mapping cannot only be effective in adopting SC resilience, sustainability, and cleaner production but also play a very instrumental role in controlling the supply chain losses and chaos. The case of Tesco is a stunning example in this regard. In 2013, the company lost nearly 300 million euros when horse meat was found in beef products at some of its stores. The complexity of its food supply chain, having various layers of suppliers, made it extremely challenging for Tesco to identify and separate the origin of the horse meat". SC mapping in this regard can help the firm to cope-up with such situations. Based upon the above discussion, we draw the following hypothesis.

Hypothesis3b: SC mapping improves sustainable production.

Based upon the above discussion, we have derived a conceptual framework of the study as exhibited in Fig. 1. It provides a snapshot of the hypotheses of the study. Fig. 1 demonstrates the mediating roles of Supply Chain Mapping (H3a and H3b) and BlockChain Based Supply Chain Management (H2a and H2b) in the association between IC and sustainable production. Likewise, it is also reflecting the direct impact of IC on sustainable production (H1).

3. Methodology

3.1. Data

Data were collected from 289 textile firms from Pakistan and Bangladesh. The Textile sector in Pakistan is one of the major contributors to the country's GDP and exports. This sector also falls among the top 10 leading exporters of the world. The majority of the textile factories in Pakistan are located in Karachi, Lahore, and Faisalabad. Likewise, Bangladesh's textile sector is a major contributor to the country's export and employment and is considered the backbone of the country's economy.

Data were collected from June 2019 to January 2020. Initially, it was planned to collect data from June 2019 to May 2020 from at least 300 firms for each country. However, due to the COVID, data collection was stopped in the month of January 2020. A total of 800 firms (400 from each country) were selected for the data collection and were sent the questionnaire through email. A total of 160 firms responded to the questionnaire from Pakistan, among which 08 questionnaires were incomplete. After excluding the incomplete questionnaires, the total number of responses from Pakistan was 152. From Bangladesh, we received 143 filled questionnaires; however, six questionnaires were incomplete/wrongly filled and were excluded from the final count. Hence, a total of 137 complete responses were received from Bangladesh. The total sample of 289 questionnaires were processed for

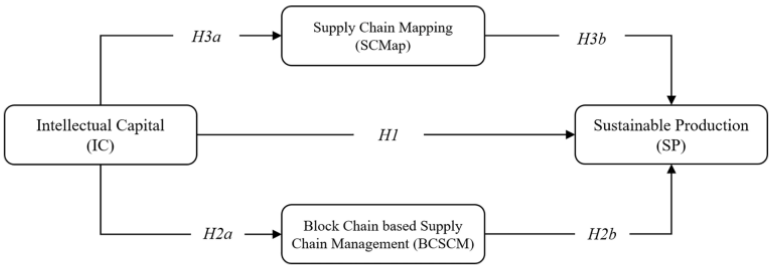

Fig. 1. Conceptual framework.

analysis.

3.2. Instrumentation

A close-ended questionnaire was developed using a 5-Point Likert scale. All the constructs were adopted from the previous studies. The details of the construct are exhibited in Table 1. The construct of IC was adopted from M.S. Mubarik et al. (2021). They recomposed the construct by taking dimensions from various studies. Further, the construct of BCSCM was adopted from Mobashar et al. (2020).

3.3. Analytical technique: covariance based -SEM (CB-SEM)

The study employed covariance based-structural equation modeling (CB-SEM) to estimate the modeled relationships. The CB-SEM is considered the most suitable approach for theory testing. This approach is employed in two steps. In the first step, measurement models internal consistency, reliability, validity (convergent and discriminant), and fitness (GFI, CFI, RMSEA) is evaluated. After confirmation of the measurement model's validity, reliability and fairness, path analysis is done to test the hypotheses of the study. It is important to note that CB-SEM does not allow to compare the groups based on the observed heterogeneity. Therefore, to compare the difference by country, we employed PLS-MGA (Partial Least Square-Multi Group Analysis)

4. Findings

4.1. Respondents demography

Data from 289 textile firms at Pakistan and Bangladesh were collected for the analysis. Table 2 below exhibits the brief demography of respondents. Medium firms constitute 56% of the total sample whereas large firms constitute 44%, followed by firms aged 20 years or above(30%). Further, firms with an average age between 11 and 19 years were highest in the sample with 44% percent of the total. Interestingly, around 19% of the firms were found to have foreign ownership whereas 42% of the firms had joint ownership. Some of the firms were owned by expatriate Pakistanis and/or Bangladeshi, who have claimed the nationality of other countries. Demography of the respondent's firms shows a fairly equal distribution of the sample size by country, age, size, and ownership.

4.2. Internal consistency, reliability, and validities of the scales

The first step for employing CB-SEM is to ensure the construct's internal consistency, reliability, and validity using a confirmatory factor analysis approach. Internal consistency of the constructs was assessed by confirming the CR and factor loading values, which should be greater than 0.60 for each construct. The results in Table 3 exhibit that all the constructs have CR values and factor loadings value greater than 0.60. It ensures the internal consistency of all constructs. The reliability of the construct, which measures the extent to which a construct could be dependable, is gauged by checking the CB alpha value. Results in Table 3, depict that value of CB alpha values of all constructs are greater than 0.70, confirming the reliability of all the constructs.

Table 1
Constructs and their sources.

SC mapping	Upstream mapping Midstream mapping Downstream mapping	Subramaniam and Youndt (2005); Ahmed et al., (2019); Wang et al., (2019); Al-Jinini et al., (2019)
BCSCM	Information Transparency Data and Information Immutability Smart Contract	Kim and Shin (2019)
Sustainable Production	Environmental Social Economic	Veleva and Ellenbecker (2001); M.S. Mubarik et al. (2021)
Intellectual Capital	Human Capital Structural Capital Relational Capital	M.S. Mubarik et al. (2021)

Table 2
Profile of respondent firms.

Size	Pakistan	Bangladesh	Total	%
Medium*	87	76	163	56%
Large**	65	61	126	44%
Firm Age(years)				
1 – 10	33	42	75	26%
11 – 19	67	59	126	44%
≥20	52	36	88	30%
Ownership				
Foreign	21	34	55	19%
Local	89	78	167	58%
Joint	42	25	67	23%

*, &** show the employment size between 75 and 200 and >200.

Further, validity is gauged from two aspects i.e., convergent validity and discriminant validity. The convergent validity is gauged by computing the AVE values of each construct, which should be greater than 0.50. Results show that all the constructs of this study possess AVE values greater than 0.50, thus confirming the convergent validity. The discriminant validity of the constructs was checked by employing the Fornell-Larcker criteria, which compares the square rooted values of AVE with inter-construct correlation. As exhibited in Table 4, the square rooted AVE values are greater than the inter-construct correlation. It confirms the discriminant validity of the constructs. Further, the fitness of all measurement models (constructs) were ascertained from three aspects i.e., parsimonious, incremental, and absolute, using the values of CFI, GFI, RMSEA, and PNFI. The values of CFI, GFI, and PNFI are greater than 0.80, and the values of RMSEA for all constructs are lower than 0.08. It reflects the satisfactory fitness of all the measurement models.

After confirming the consistency, reliability, validity, and fitness of all measurement models, the subsequent section construes the results of path analysis.

4.3. Path analysis

The estimated model for all firms appears in Fig. 2. The complete results of the path analysis are exhibited in Table 5. Before explaining the individual hypotheses, it is essential to explain the overall model fit, its predictive relevance and the significance of the modeled variables. Starting from the value of adjusted R-square, which shows that a considerable variation (53%) in sustainable production is being explained by SC mapping and IC. We also computed Q-square and F-square values of the model using the same mathematical equation used in PLS-SEM. Square values show the high predicted relevance of the model. Likewise, f square values—*measurement of variance explains each exogenous variable in the models*—show the considerable contribution of each variable in the model. Putting together, the results of adjusted R-square, Q-square, and f-square confirm the model robustness, predictive relevance, and significance of individual variables. It enables us to proceed with the hypotheses testing.

First, the path relationship tests the impact of IC on sustainable production in the aggregate sample and then by country. The results reveal a highly significant and large impact of IC on sustainable production in the overall sample (*β 0.41, t-value 2.16*) and in the country-wise analysis [Pakistan *β 0.23, t-value 2.27*; Bangladesh *β 0.37, t-value 4.25*]. The PLS-MGA *(p-value 0.125)* results do not reflect any difference between Pakistan and Bangladesh results, thus confirming the stability of the relationship across the country. These results provide significant support to accept the first hypothesis of the study that denotes a

Table 3
Reliability, validity and fitness.

Construct	Sub-construct	Convergent validity and reliability				Model fitness			
		AVE	CR	CB alpha	Loadings	CFI	GFI	RMSEA	PNFI
Supply Chain Mapping	Upstream Mapping Midstream Mapping Downstream Mapping	0.51	0.89	0.78	*Floats between 0.67 to 0.89. Items deleted: USM1, USM2 DSM4*	0.89	0.91	0.07	0.82
BCSCM	Information Transparency Data and Information Immutability Smart Contract	0.53	0.88	0.81	*Between 0.81 to 0.69 Items deleted: DI 2*	0.94	0.92	0.041	0.85
Sustainable Production	Environmental Social Economic	0.52	0.79	0.91	*Between 0.89 to 0.72 Items deleted: ESP 1, SSP 2, EES 2*	0.88	0.87	0.05	0.83
Intellectual Capital	Human Capital Structural Capital Relational Capital	0.51	0.82	0.85	*Between 0.68 to 0.82 Items: deleted: HC1, SC4, RC3*	0.94	0.92	0.078	0.81

Note: Acceptable threshold value of factor loading is 0.50 subject to the value of AVE>0.50.
Threshold values of AVE, CR, and CB alpha are 0.50.060, 0.70 respectively.
The acceptable threshold values of CFI, GFI, and PNFI is 0.80. Whereas the upper acceptable value of RMSEA is 0.08.

Table 4
Fornell-Larcker criteria.

	SCMap	BCSCM	SP	IC
Supply Chain Mapping (SCMap)	***0.71***			
BCSCM	0.54	***0.73***		
Sustainable Production (SP)	0.49	0.24	***0.72***	
Intellectual Capital (IC)	0.31	0.37	0.41	***0.71***

significant role of IC in improving sustainable production.

The study's second hypothesis is the significant and positive mediating role of the application blockchain-driven supply chain (BCSCM) in the juxtaposition of IC and sustainable production. The overarching argument is that IC helps in the effective and efficient adoption of BCSCM, which further significantly influences sustainable production. The results of H2a *(β 0.37, t-value 3.67)* in the aggregate sample support the positive impact of IC on BCSCM. Likewise, H2b is also supported by results *(β 0.29, t-value 2.98)*, confirming the significant impact of BCSCM on Sustainable Production. The results are stable in inter-country comparison, and MGA results do not reveal any significant difference in H2a *(0.062)* and H2b *(p-value 0.091)*.

The third hypothesis of the study models the mediating role of SC mapping in the association between IC and sustainable production. Our results depict a significant impact of IC on SC mapping at 5% *(β 0.31, t-value 4.54) at 5%*. Likewise, the results also show a significant positive impact of SC mapping on sustainable production *(β 0.42, t-value 3.43)*. These results support H3a and H3b, confirming an SC mapping as a mediator in the association between IC and sustainable production. It implies that IC improves the SC mapping, which further improves sustainable production. The results are stable in country-wise comparison

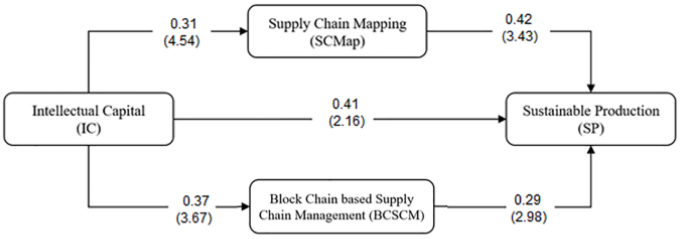

Fig. 2. Estimated model (overall).

Table 5
Path analysis.

Hypothesis	Path	Overall		Pakistan		Bangladesh		Pak vs.BD
		β-value	t-value	*β*-value	t-value	*β*-value	t-value	P-value
H1	IC→ SP	0.41**	2.16	0.23**	2.27	0.37**	4.25	0.125
H2a	IC→ BCSCM	0.37***	3.67	0.19***	4.08	0.29**	2.99	0.091
H2b	BCSCM → SP	0.29**	2.98	0.31***	5.19	0.18**	5.01	0.062
H3a	IC → SC Mapping	0.31***	4.54	0.22***	3.56	0.39***	3.86	0.431
H3b	SC Mapping → SP	0.42***	3.43	0.38***	4.54	0.44***	4.91	0.74
Adj R square		0.53						
Q-Square		0.28						
f-square		0.45						

*** and ** show the rejection of null hypothesis at 1% and 5% respectively.

Table 6
It enables us to proceed for hypothesis testing.

	Hypothesis	Decision
H1	IC positively contributes to the sustainable production.	Supported
H2	SC mapping positively mediates the relationship between IC and sustainable production	Supported
H3	BCSCM positively mediates the relationship between IC and sustainable production	Supported

with marginal difference in the coefficient values. The MGA results have also supported the same, which does not reveal any statistically significant difference in the inter-country results (*p-value 0.431; 0.74*). In condensed form, all three major hypotheses of the study have been supported in the aggregate sample and in country-wise comparison, as exhibited in Table 4.

5. Discussion

The findings of the study illustrate overwhelming support to all three hypotheses, revealing the direct and indirect impact of IC on sustainable production. Likewise, results also support the significant mediating role of BCSCM and SC mapping in the association of IC and Sustainable Production. The results on the impact of IC on Sustainable production are found to be consistent with the M.S. Mubarik et al. (2021), Mahmood and Mubarik (2020) and Khan et al. (2021). These studies consider IC as a precursor for incorporating sustainability in the organizational processes, including production processes. Ahmed et al. (2019) construed that IC plays a significant role in increasing an organization's commitment to the environment, community welfare, employee health, and safety. Likewise, Khan et al. (2021) argued that firms with higher levels of IC could have comparatively higher levels of sustainability in the production processes. A higher level of IC implies a higher level of human capital, relational capital, and structural capital. Employees with a higher level of human capital are considered more aware of the triple bottom lines, i.e., economic, social, and environmental performance. They tend to be more careful about the sustainability of their actions (Mubarik and Naghavi, 2020). It has been further supported by Khan et al. (2021), who argued that a higher level of human capital help incorporate sustainability into the production processes of organizations. Yusliza et al. (2020, p. 30) mentioned IC as knowledge and argued, "*knowledge is an asset that can become a unique source of competitiveness among competitors and an important contributor to cleaner production strategies*".

The findings on the role of BCSCM also concur with the studies of Saberi et al. (2019), Wang et al. (2019), Mubarik et al. (2019), and M.S. Mubarik et al. (2021b). For Wang et al., 1), "intellectual capital efficiency (ICE) and its sub-dimensions (i.e., human capital efficiency, organizational capital efficiency and capital employed efficiency (CEE)) have significantly positive impacts on dynamic technology capability." They construed that IC can be instrumental in acquiring and implementing the latest process technologies, e.g., blockchain technology (Wang et al., 2019). Given that blockchain technologies can enhance traceability and improve integrations, it can significantly improve the sustainability of production (Mahmood and Mubarik 2020; M.S. Mubarik et al., 2021). In a nutshell, the literature supports the fact that blockchain technology positively reinforces the impact of IC on sustainable production.

Literature on the role of SC mapping in the association of IC and sustainable production is scant; thus, it is challenging to compare and contrast our results with it explicitly. Nevertheless, a recent study by M. S. Mubarik et al. (2021) highlights an influential role of SC mapping in improving sustainable production. An effectively mapped supply chain helps a firm zoom into its business processes to visualize unsustainable business processes. This further leads toward the replacement or enhanced such processes to make them more sustainable. Likewise, SC mapping improves integration among internal and external stakeholders, reducing the duplication of efforts and suppressing waste. They argued that an effectively mapped supply chain enables a firm to improve the sustainability of its processes. Whereas enabling SC mapping requires the development of IC, an improvement of IC improves BCSCM, which further helps to attain sustainable production.

6. Conclusion, implications and limitations

A majority of the production processes emit pollutants into the soil, air and water during the production process and along the entire supply chain. To remedy this situation, production processes need to be transformed towards the "sustainable production" paradigm. Sustainable production aims to ensure that the production of goods conserves resources and preserves the regenerative capacity of the environment. Against this backdrop, the central argument of the paper is the use of IC to build SC mapping and BCSC to improve and sustain production. The study argued that IC plays a key role in the adoption and implementation of BCSCM, which further contributes to sustainable production. Likewise, the study also asserted that IC enables a firm to institute SC mapping, further affecting sustainable production. Following the IC Based View and Dynamic Capitalizes theory, the study hypothesized the direct impact of IC on sustainable production. Despite the critical role of IC both in building SC mapping and improving sustainable production, there is a void of literature on this conception. Present study bridges this gap.

The findings of the study illustrate that IC yield three major benefits to the organization. First, it directly contributes to the sustainable production of a firm. Second, it significantly improves the efficiency and effectiveness of BCSCM. Third, it enhances the visualization and monitoring of the processes across the value chain by enabling supply chain mapping. The findings also reveal that SC mapping plays a phenomenal role in elevating the sustainable production of a firm.

The study has some profound implications for managers. First and foremost is the need for strategic retreat considering the IC-Sustainable production and BCSCM-Sustainable production dyads. The findings reveal that IC can significantly improve the sustainability of production. Nevertheless, it raises questions as to how the IC can be developed and managed to reap its multitude of impacts. Based on our findings, we suggest a three-stage sequential strategy to be adopted in three stages. First is gaging the level of IC to identify where the firm is standing in terms of the strength of its IC. This could be done by adopting the process suggested by Mubarik et al. (2018). The study of Mubarik et al. (2018) demonstrated that the level of intellectual capital could be gauged on a scale of 1 – 5, with 1 being the lowest and 5 the highest. If a firm's IC level is low (less than 3), then the first thing for them to do is to improve the level of its IC to the moderate level for adopting the next strategy. Second, it must focus on mapping its upstream, midstream and downstream value chain processes. The stronger level of IC will play an instrumental role in mapping the firm's supply chain processes. The SC mapping will also enable the firm to visualize the flow of products and services across the supply chain. It will also help the firm to zoom in on various business processes to analyze their conformance to the sustainability standards. In short, the SC mapping will significantly contribute to sustainable production. This strategy may be labeled as the SC mapping-led sustainable production. Third, once the business processes have been mapped, the firm may opt to adopt the BCSCM. The adoption of BCSCM will contribute to the sustainable production of the firm and improve the effectiveness of its SC mapping. That is why some of the practitioners often argue that the simultaneous adoption of SC mapping and BCSCM can enhance sustainable production. However, keeping in mind the strategic nature of BCSCM and its impacts on the business processes, it is advisable to adopt a sequential rather than simultaneous strategy. The adoption of BCSCM for improving production sustainability may be labeled as "BCSCM-led-sustainable production." Both SC mapping-led-sustainable production and

BCSCM-led-sustainable production require a stronger level of intellectual capital.

As in the case of every study, this study has some limitations. However, these limitations provide ample grounds for future research. First, the above recommendation to adopt SC mapping and BCSCM can be one of the strategic approaches. We suggest future research to look into the appropriate strategic routes to capitalize on IC, SC mapping, and BCSCM for attaining sustainable production. Second, the use of cross-sectional design for testing the basic hypotheses of the study is another principal limitation. Using the case study approach and considering the case of firms that have already implemented the SC mapping and BCSCM can provide an in-depth understating of this paradox. Additionally, the case-based approach can play an instrumental role in clarifying SC mapping and BCSCM effects on sustainable production.

7. Credit author statement

All authors have checked the manuscript and have agreed to the submission

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Appendix: questionnaire

	1. Intellectual Capital
	a. Human Capital
1	Employees in our company are highly skilled in their respective jobs.
1	Employees in our company are considered among the best people in our industry
1	Employees in our company are experts in their particular jobs and functions
1	Our employees can find simple solutions for more complex problems.
1	Our employees are well-educated compared with their peers in the industry
	b. Relational Capital
1	Employees from different departments feel comfortable while calling each other
1	Our employees apply the knowledge leaned from one area of the company to the other area when they face any problem.
1	Our company is keen on developing long-term relationships with its suppliers and customers.
1	We collaborate extensively with external parties (e.g., customers and suppliers) to develop new solutions
1	Customer feedback guides our company activities
	c. Structural Capital
1	Much of our company's knowledge is contained in manuals, archives, and databases.
1	We usually follow the sequence of written rules and procedures
1	Our company embeds much of its knowledge and information in structures, systems and processes
1	Our company uses intellectual property rights (patents/registered software, and copyrights)as a way to store knowledge
1	Our company protects knowledge and key information to avoid loss of key people left the company
	2. Supply Chain Mapping
	a. Upstream Supply Chain
1	We are able to visualize our upstream SC processes, and activities.
1	The mapping of our SC processes depicts geographical relationships with supplier, allowing spatial visualization.
1	Our firm is able to capture the real time information about the products and materials sourced, their quantities, and replenishment lead time.
1	SC mapping provides real time information sharing of suppliers.
1	We are aware of the tier-2 suppliers of the critical components and raw material.
1	We have documented processes for dealing with suppliers.
1	We are able to visualize the real time flow of material from the suppliers.
1	We have a system for real time sharing of information with suppliers.
1	Our SC mapping provides us a simplified representation of our upstream SC by capturing the essence of the environment in which the SC operates.
1	We have mapped the flow of products, and information in the upstream SC.
	b. Midstream
1	We have mapped processes showing the flow of material within the company.
1	We can track the flow of goods within our company in real time from one department to other.
1	We have a system of real time sharing of information within the company, across several departments.
1	We can identify the SC processes inefficiencies in real time.
1	Due to the mapping of midstream processes, we can monitor the effectiveness of our SC strategy.
1	The mapping of our SC helps to catalog and distribute key information for survival in a dynamic environment.
1	Our SC mapping alerts our concerned managers to possible constraints in the system.
1	We have mapped the flow of products and information in the midstream SC.
	c. Downstream
1	We have mapped the geographical dispersion of our customers.
1	We have mapped the geographical dispersion of our tier-2 customers.
1	We have a system of real time sharing of information with customers.
1	We can visualize the flow of goods from our company to customers' customers.
1	The mapping of our downstream processes plays an essential role in providing guidance in the quantum changes in the downstream SC.
1	We have mapped the flow of products and information in the downstream SC.
1	The mapping of our downstream SC processes permits our company to identify areas for further analysis.
	3. Sustainable Production
	a. Environmental
1	Products and packaging are designed to be safe and ecologically sound throughout their life cycles; services are designed to be safe and ecologically sound.
1	Wastes and ecologically incompatible byproducts are continuously reduced, eliminated, or recycled

(*continued on next page*)

(*continued*)

1. Intellectual Capital
1 Energy and materials are conserved, and the forms of energy and materials used are most appropriate for the desired ends
1 Chemical substances, physical agents, technologies, and work practices that present hazards to human health or the environment are continuously reduced or eliminated
1 Workplaces are designed to minimize or eliminate physical, chemical, biological, and ergonomic hazards
b. Economical
1 Management is committed to an open, participatory process of continuous evaluation and improvement.
1 Work is organized to conserve and enhance the efficiency and creativity of employees
1 Management is committed to focus on the long-term economic performance of the firm
c. Social
1 The continuous development of employees' talents and capacities is a priority of our organization
1 The security and well-being of all employees is a priority
1 The communities around workplaces are respected
1 The communities around workplaces are enhanced economically.
1 The communities around workplace are enhanced socially, culturally and physically.
4. Blockchain based Supply Chain Management
a. Information Transparency
1 Information transparency has become a critical element to maintain a strong partnership
1 Our firm would be willing to make further investment in importing information transparency to facilitate communication with the partner firm
1 "Information transparency" technology is highly applicable to our firm and may be considered to replace the current contractual relationship with a partner.
b. Data and Information Immutability
1 Data and information immutability have become a critical element for maintaining a strong partnership.
1 Data and information immutability ensure that change and removing information on a private or permissioned blockchain requires notifying the network members and follows certain agreements and approval requirements.
1 Our firm can count on the partner to be sincere based on data and information immutability
1 "Data and information immutability" technology is highly applicable to our firm and may be considered to replace the current contractual relationship with a partner.
c. Smart contracts
1 Smart contracts in the form of digital contracts remove human judgment from transactions and rather follow pre-determined conditions including rules and penalties that are agreed upon with a partner
1 Smart contracts have become a critical element to maintaining a strong partnership
1 "Smart contract" technology is highly applicable to our firm and may be considered to replace the current contractual relationship with a partner.

Note: All the items were measures at 5 points Likert scale.

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Paper 4

Ghobakhloo, M., Iranmanesh, M., Mubarak, M. F., Mubarik, M., Rejeb, A., & Nilashi, M. (2022). Identifying Industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values. *Sustainable Production and Consumption*. 33, 716–737.

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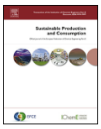

Research article

Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values

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ABSTRACT

Scholars believe that the newly introduced Industry 5.0 has the potential to move beyond the profit-centered productivity of Industry 4.0 and to promote sustainable development goals such as human-centricity, socio-environmental sustainability, and resilience. However, little has been done to understand how this ill-defined phenomenon may deliver its indented sustainability values despite these speculative promises. To address this knowledge gap, the present study developed a strategy roadmap that explains the mechanism by which Industry 5.0 delivers its intended sustainable development functions. The study first developed and introduced the Industry 5.0 reference model that describes the technical and functional properties of this phenomenon. The study further conducted a content-centric synthesis of the literature and identified the sustainable development functions of Industry 5.0. Next, the interpretive structural modeling (ISM) technique was employed to identify the sequential relationships among the functions and construct the Industry 5.0-enabled model of sustainable development. The ISM involved collecting the opinions of 11 Industry 5.0 experts through expert panel meetings. Results revealed that Industry 5.0 delivers sustainable development values through 16 functions. Circular intelligent products, employee technical assistance, intelligent automation, open sustainable innovation, renewable integration, and supply chain adaptability are examples of the functions identified. These functions are highly interrelated and should be developed in a specific order so that the synergies and complementarities among them would maximize the sustainable development value gains. The roadmap to Industry 5.0-driven sustainability developed in this study is expected to provide a better understanding of ways Industry 5.0 can contribute to sustainable development, explaining how the development of its functions should be managed to maximize their synergies and contribution to the intended sustainability values. The study also highlights important avenues for future research, emphasizing the potential enablers of Industry 5.0 development, such as Government 5.0 or Corporate Governance 5.0.

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1. Introduction

The Industry 5.0 concept has recently emerged as the vision of a future industry that values protecting the environment and society. The advocates of Industry 5.0 believe that Industry 4.0 is not the proper framework for achieving sustainable development. The literature acknowledges that Industry 4.0 centers around technology-driven productivity (Ghobakhloo et al., 2021a). Although the internal productivity mechanism of Industry 4.0 inadvertently improves some micro-environmental sustainability metrics such as production efficiency or emission reduction (Ng et al., 2022), it cannot move past the profit-centricity of the contemporary production and consumption economic models (Sindhwani et al., 2022). Critiques argue that Industry 4.0 aligns with the long-lasting neoliberal capitalism models that emphasize profitability and shareholder primacy, intensifying some of the prevailing socio-environmental concerns such as regional inequality, environmental degradation,

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Nomenclature

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
BPM	Business process monitoring
CADM	Computer-aided design and manufacturing
CAI	Cognitive artificial intelligence
CCPS	Cognitive cyber-physical systems
CIP	Circular intelligent products
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DST	Data sharing and transparency
ERP	Enterprise resource planning
ETA	Employee technical assistance
HIRT	Human interaction and recognition technologies
INA	Intelligent automation
ILB	Logic-knowledge base
IoE	Internet of everything
ISM	Interpretive structural modeling
MICMAC	Matrice d'Impacts Croisés Multiplication Appliqués à un Classement
ORE	Operational and resource efficiency
OSI	Open sustainable innovation
RIN	Renewable integration
RTC	Real-time communication
SCA	Supply chain adaptability
SCM	Supply chain modularity
SII	System integration and interoperability
SOP	Service-orientation and personalization
STH	Sustainable thinking
SUD	Sustainable development
UPR	Upskilling and reskilling
VUI	Value network integration

and fragility of the global economy (Grybauskas et al., 2022; Renda et al., 2022). Indeed, Industry 5.0 represents a transformative model that draws on the Industry 4.0 experience and Covid 19 disruptions to develop a hyperconnected and data-driven industrial ecosystem that values sustainable development goals (Javaid et al., 2020). Consistent with the European Commission's 2022 Industry 5.0 agenda, the sustainable development objectives of Industry 5.0 include the inclusive development of economic, environmental, and social pillars of sustainability and their underlying micro-objectives (Renda et al., 2022). In particular, this phenomenon aims to promote resilience, socio-environmental sustainability, and human-centricity under the sustainable development agenda (Saniuk et al., 2022). The human-centricity micro-objectives of Industry 5.0, for example, consist of employment growth, workplace dignity, employee autonomy, and job satisfaction (Breque et al., 2021). Despite these contributions, introducing Industry 5.0 as a new paradigm for achieving competitive sustainability is associated with two significant controversies. First, the boundaries, core principles, and functionality of Industry 5.0 are vastly understudied. Second, it is practically unclear how Industry 5.0 can contribute to promoting sustainable development. The present study strives to address these knowledge gaps.

Nowadays, some general agreements exist on the core values of Industry 5.0, at least on the three pillars of economic resilience, environmental sustainability, and human-centricity (Akundi et al., 2022). However, academic and industry experts offer diverse perspectives on the definition, functionality, and boundaries of this phenomenon. Scholars such as Longo et al. (2020) and Lu et al. (2022) believe that Industry 5.0 centers around human-centric manufacturing, and technological advancements should promote human well-being in social smart factories. Viewed from the environmental sustainability perspective, Sindhwani et al. (2022) explain that Industry 5.0 represents the vision of human-robot collaboration for a smart business ecosystem that promotes resource efficiency and bioeconomy. According to Sindhwani et al. (2022), the scope of Industry 5.0 expands beyond the manufacturing industry, involving other business sectors such as agriculture or healthcare. Alternatively, the European Commission builds on the Society 5.0 concept and considers Industry 5.0 a socio-economic structural shift toward a sustainable future industry. European Commission proposes that Industry 5.0 is not the chronological continuation of Industry 4.0. Instead, Industry 5.0 complements and, in many instances, extends its predecessor, adding socio-environmental dimensions to Industry 4.0 paradigm (Breque et al., 2021).

Besides the ambiguity surrounding the definition, functionality, and boundaries of Industry 5.0, the literature falls short in holistically explaining how this phenomenon can deliver its sustainable development values. Comparatively, Industry 4.0 is significantly well-studied, and the literature provides valuable insights into the underlying mechanism by which Industry 4.0 delivers its intended values, such as manufacturing productivity (Hughes et al., 2022), supply chain innovation (Hahn, 2020), sustainable manufacturing (Ng et al., 2022), or sustainable energy (Ghobakhloo and Fathi, 2021). Although scholars have recently made important contributions to understanding the values of Industry 5.0, these early contributions have addressed the micro implications of this phenomenon. For example, Sharma and Arya (2022) described how Industry 5.0 could improve smart city monitoring systems, whereas Fatima et al. (2022) showed how Industry 5.0 could lead to production and warehousing automation. Scholars argue that Industry 5.0 should equitably contribute to various aspects of sustainable development (Grabowska et al., 2022; Renda et al., 2022). Nonetheless, little has been done to understand how a transformative phenomenon such as Industry 5.0 and its underlying sustainability functions can interact with various micro and macro economic, environmental, and social sustainability objectives.

Referring to the knowledge gaps discussed above, the present study attempts to answer the following research questions:

RQ1. What are the underlying components and sustainability values of Industry 5.0?

RQ2. How can Industry 5.0 deliver sustainable development values?

To address the first research question, the study introduces the Industry 5.0 reference model that provides a description of this phenomenon, explaining its underlying technologies, techno-functional principles, smart components, and values. Concerning the second research question, the study conducts the content-centric synthesis of the literature and identifies the Industry 5.0 functions for sustainable development. The study further draws on ISM to explore how these functions should interact to deliver Industry 5.0 values such as resilience, socio-environmental sustainability, and human-centric operations. The resulting strategy roadmap for Industry 5.0-enabled sustainable transformation and the underlying findings are expected to offer notable implications for research and practice. Besides introducing the sustainable development functions of Industry 5.0, the study explains how their development should be managed so that the synergies resulting from precedence relationships and complementarity among the functions could maximize the intended sustainability values.

2. Literature review

This section describes the Industry 5.0 phenomenon and identifies the functions through which it might align with sustainable development, particularly in terms of resilience, sustainability, and human centricity.

2.1. Industry 5.0 definition and background

The Industry 5.0 concept has caused many controversies among academics and industrial communities. Researchers have offered various

reasons for the prevalence of Industry 5.0. For example, Özdemir and Hekim (2018) defined Industry 5.0 as an evolutionary yet incremental upgrading of Industry 4.0 that can offer symmetrical innovation to address the limitations of the Industry 4.0 innovation ecosystem. Alternatively, scholars such as Nahavandi (2019) and Kumar et al. (2021) have criticized the productivity-centricity of Industry 4.0, proposing that Industry 5.0 denotes the emergence of human-centric industrial operations, pushed by a new wave of disruptive technologies that promote synergetic human-machine integration while improving working conditions, employment, and productivity. While providing diverse perspectives on this phenomenon, these early studies agreed on two fundamental features of Industry 5.0. First, early studies unanimously acknowledged that Industry 4.0 and the underlying industrial transformation had been associated with notable shortcomings such as the digital divide or technology-centricity (Longo et al., 2020). Indeed, recent studies, such as the work of Grybauskas et al. (2022), clearly outline such limitations or adverse sustainability impacts of Industry 4.0. Second, scholars widely believe that while Industry 5.0 builds on the technological constituents of Industry 4.0 (Xu et al., 2021), it associates with radical technological advancements in cognitive artificial intelligence (CAI), energy transitions technologies, and smart materials, to name a few (Maddikunta et al., 2022).

The development of the Industry 5.0 paradigm took a new turn when the European Commission released the perspective of Europe's technology leaders on Europe's future industry agenda under the label of Industry 5.0. While discussing the challenges of the term 'Industry 5.0,' this report proposed that "Industry 5.0 should not be understood as a replacement nor an alternative to, but an evolution and logical continuation of the existing Industry 4.0 paradigm" (Müller, 2020, p. 6). While acknowledging that Industry 5.0 is centered around human and ecological values, this report proposed that this phenomenon should ensure that novel technological innovation should be shaped toward supporting socio-environmental development (Müller, 2020). In 2021, European Commission released its Industry 5.0 agenda for resilient, sustainable, and humancentric European Industry. According to this agenda, Industry 5.0 is a complementary exercise, extending the Industry 4.0 paradigm to prioritize emerging socio-environmental needs (Breque et al., 2021). In early 2022, European Commission took a stronger position against Industry 4.0, arguing that this paradigm cannot be considered the proper framework for addressing the prevailing climate crisis and social tensions (Renda et al., 2022). This policy document proposes that Industry 5.0 represents a new vision for the industry, redefining the role and functionality of value chains, business models, and digital transformation in the hyperconnected business environment. According to this policy document (Renda et al., 2022) and very recent academic contributions (e.g., Grabowska et al., 2022; Maddikunta et al., 2022), Industry 5.0 differs from Industry 4.0 in the following manners:

- Industry 5.0 values both productivity-driven competitiveness and sustainable development;
- Industry 5.0 empowers the human workforce via promoting human-centric approaches to technological development;
- Industry 5.0 advances technological innovation (such as smart renewable systems) in the realm of environmental sustainability;
- Industry 5.0 promote stakeholder primacy in technology governance, innovation growth, and sustainability performance management;
- Industry 5.0 draws on certain technologies and functional principles to expand the scope of corporate responsibility to the entire value chain.

Nowadays, there is a general agreement that Industry 5.0 diverges from previous industrial revolutions as it represents a stakeholder-pulled socio-technological phenomenon that systematically shifts classic profit and consumption-driven economic models to circular, regenerative, sustainable, and resilient value-creating economic models.

2.2. Industry 5.0 reference model

Industry 5.0 is vastly understudied, and the early studies offer varying conceptualizations of this phenomenon and its underlying components. To address the ambiguity and complexity of this phenomenon, we develop and present the reference model of Industry 5.0 in Fig. 1. This reference model offers a holistic overview of this phenomenon, describing the technological constituents, principles, components, and core value objectives of Industry 5.0. Consistent with the European Commission agenda (Breque et al., 2021; Müller, 2020), we consider Industry 5.0 a socio-technological phenomenon. Industry 5.0 is a technological phenomenon, given that it centers around technological advancements and the digitalization of industrial value networks. Industry 5.0 is also a social phenomenon because it builds on the culture of social dialogue among stakeholders to manage and steer technological innovation to promote fundamental sociocultural values such as human dignity, equality, privacy, and autonomy (Renda et al., 2022).

Fig. 1 explains that the enabling technologies constitute the fundamental layer of the Industry 5.0 reference model. This layer consists of technologies that have emerged and matured since the third industrial revolution and have become commercially affordable and applicable since the emergence of Industry 4.0. Smart computer-aided design and manufacturing (CADM) tools (e.g., 3D printers), cloud computing, big data analytics, and enterprise systems are examples of the enabling technologies that deliver the primary production and efficiency growth objectives of digitalized business ecosystems under Industry 5.0 (Xu et al., 2021). The enabling technologies are also critical to the proper functioning of emerging technologies of Industry 5.0. For example, enterprise resource planning (ERP) is an indispensable enabling technology of Industry 5.0. ERP has its story started with the introduction of material resource planning more than half a century ago in the 1960s. ERP systems evolved to support manufacturing resource planning in the 1980s and became internet-enabled to support more complex functions such as human resource and customer relationship management in the early 2000s (Ghobakhloo et al., 2019). Modern ERPs integrate with cloud data, IoT, and artificial intelligence to provide real-time insights into various business and supply chain operations. Under Industry 5.0, smart ERPs are responsible for integrating with operations and information technologies such as process controllers, execution systems, or data abstraction tools to extract actionable business intelligence from raw data. ERP is essential to several micro-objectives of Industry 5.0, such as industrial productivity or product circularity (Wang et al., 2022).

Industry 5.0 also relies on the most disruptive technological innovations listed under the emerging technologies of the reference model to deliver its core objectives of human centricity, resilience, and sustainability (Müller, 2020). Fig. 1 shows that cognitive cyber-physical systems (CCPS), CAI, and smart wearables are among the emerging technologies of this phenomenon. Extant literature, such as the recent studies by Alvarez-Aros and Bernal-Torres (2021), Duggal et al. (2022), and Maddikunta et al. (2022), provide early insight into the properties of these technologies. For instance, CCPS involves integrating machine consciousness into CPS and operating on the novel sense-analyze-compute-act cycle (Alohali et al., 2022). The self-awareness and self-monitoring features of CCPS allow it to recognize the role of human cognition in offering safer and smoother man-machine symbiosis (John et al., 2021). To take a human-centric approach to the manufacturing environment, Industry 5.0 draws on adaptive robots, CCPS, and human interaction and recognition technologies to develop a human-centric solution that prioritizes core human worker needs while maintaining or improving industrial productivity (Maddikunta et al., 2022; Xu et al., 2021). For example, adaptive robots, complemented by edge computing, CAI, and cognitive computing, alleviate the limitation of traditional robots (restricted safety for human collaboration) and collaborative robots (limited load and speed) to offer high productivity while ensuring the safety and

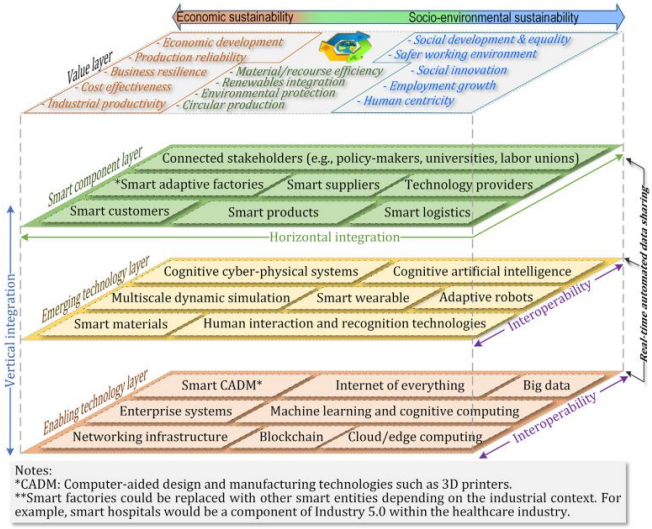


Fig. 1. The reference model of Industry 5.0.

convenience of the collaborating human operators (Lu et al., 2022). Recent advancements in smart wearable technologies also offer important implications for developing more human-centric industrial operations. For example, smart bio-inspired protective tools or head-worn intelligent wearables can significantly improve the information capacity, intelligence, stability, and productivity of the human workforce in industrial settings (Niknejad et al., 2020). Under Industry 5.0, smart wearables should integrate with CCPS, edge computing, and IoT to seamlessly communicate with various components of the smart working environment to function as intended (Duggal et al., 2022; Kubiak et al., 2022).

Concerning the resilience objective of Industry 5.0, businesses can draw on dynamic simulation, CAI, and big data to develop a digital replica of supply chain operations and identify bottlenecks, weak links, risks, and imminent disruptions to improve the adaptability and responsiveness of supply networks. Alternatively, modern supply chains can use the internet of everything (IoE), blockchain, smart materials, and smart CADM to increase operational agility and move toward new business models supporting product personalization and servitization (Frederico, 2021; Sindhwani et al., 2022).

The third layer of the reference model represents the essential components of this phenomenon. Like its predecessor, Industry 5.0 represents a paradigm shift entailing the digitalization of industrial value chains (Javaid et al., 2020; Rupa et al., 2021). Nevertheless, Industry 5.0 differs from Industry 4.0 as it holds the stakeholder perspective, taking a stakeholder-centered approach to defining the impact scope of this phenomenon and the expected value delivery mix (Madsen and Berg, 2021). Consistently, the smart component layer of the reference model consists of smart customers, suppliers, logistics, technology providers, and adaptive factories, which collectively create the hyperconnected and data-driven business ecosystem (Renda et al., 2022). More importantly, connected stakeholders such as policy-makers, universities, and labor unions are indispensable components of Industry 5.0. Integration of connected stakeholders is critical to Industry 5.0 because it is primarily a technology-driven phenomenon, and the majority of socio-environmental values cannot be delivered without systemic technology governance imposed by stakeholders to push its intended objectives (Saniuk et al., 2022). The European Commission even believes that Industry 5.0 requires Government 5.0 to respond to this phenomenon's policy, regulatory, funding, and innovation management needs (Renda et al., 2022). The reference model in Fig. 1 is primarily applicable to the manufacturing industry, yet its component can adjust to any industrial setting, given that the ripple effects of Industry 5.0 expand beyond the manufacturing sector. For example, Industry 5.0 would have important implications for the healthcare industry (Sharma et al., 2022), and the components can tailor to the particularities of this sector, for example, by adding smart hospitals and adjusting the smart adaptive factory component to the production of personalized healthcare products (Maddikunta et al., 2022).

The double-headed arrow on the top of the value layer in the reference model proposes that Industry 5.0 is not merely economic-productivity driven as it systematically pursues balancing economic and socio-environmental sustainability. The Industry 5.0 reference model acknowledges that various aspects of economic, environmental, and social sustainability within the value layer are interrelated, and synergetic complementarity among them requires Industry 5.0 stakeholders to simultaneously pursue various sustainable development objectives. Business, supply chain, and economic resilience are the most emphasized economic sustainability objectives of Industry 5.0 (Akundi et al., 2022; Nahavandi, 2019). Under environmental sustainability, Industry 5.0's intended values involve preserving Earth's ecological and resource integrity via promoting the circular economy, carbon neutrality, renewable integration, and resource efficiency (Breque et al., 2021). Social sustainability values of Industry 5.0 involve promoting human-centric approaches to place fundamental human needs and rights at

the heart of the industrial economy, promoting social development, employment, equality, and human agency (Carayannis and Morawska-Jancelewicz, 2022; Sindhwani et al., 2022).

Besides the enabling and emerging technologies, Industry 5.0 relies on certain techno-functional principles to deliver the intended digital transformation aspect of this phenomenon. These principles represent essential technical conditions that enable Industry 5.0 components, such as smart factories or customers, to leverage the underlying technologies and function properly according to this phenomenon's core objectives. As shown in the reference model, vertical integration, horizontal integration, interoperability, and real-time data sharing are among the fundamental techno-functional principles of Industry 5.0. When appropriately developed, techno-functional principles facilitate the development of the sustainable development functions of Industry 5.0, conditions that allow smart components efficiently leverage emerging and enabling technologies to deliver the sustainable development values of this phenomenon. For example, the real-time automated data sharing principle allows smart objects and modules of Industry 5.0 components to vertically or horizontally communicate in real-time when needed. This condition enables the real-time communication (RTC) sustainable development function of Industry 5.0 (Sharma et al., 2022). The RTC function allows real-time analysis and monitoring of supply chain nodes, providing real-time insight into supply chain operations and improving visibility and agility (Saniuk et al., 2022). The literature has diverse perspectives on this type of function. The study systematically reviews the literature to identify sustainable development functions of Industry 5.0, the results of which are reported in the following section.

3. Industry 5.0 sustainable development functions

The study conducted a content-centric synthesis of the literature to identify functions through which Industry 5.0 might promote sustainable development, especially in the three well-known goals of resilience, environmental sustainability, and human centricity. For this purpose, the research team followed the existing guides within the literature (e.g., Watson and Webster, 2020; Webster and Watson, 2002). Fig. 2 describes the steps undertaken to conduct the content-centric synthesis of the Industry 5.0 literature. Step A1, as explained in Fig. 2, involved conducting a systemic search of the Scopus and Web of Science, which identified 210 documents. In step A2, the research team defined three exclusion criteria to shortlist the most relevant documents. The 210 documents identified in step A1 were subjected to the exclusion criteria in step A3, leading to the initial pool of 24 eligible documents. The backward review was conducted across step B1, in which the reference section of the 24 eligible documents was analyzed to pinpoint potentially relevant documents not previously identified. This step led to identifying 26 new documents. These documents were subjected to the exclusion criteria in step B2. As a result, 23 documents were excluded, and three new eligible documents were shortlisted, leading to the extended pool of 27 (24 + 3) eligible documents. Step C1 involved conducting the forward review procedure, in which Google Scholar and the Web of Science platforms were used to review the title of documents that had cited the 27 eligible articles identified across steps A3 and B2. Throughout this step, the research team identified 19 new documents (not previously identified) that had important keywords such as Industry 5.0 or human-centricity explicitly mentioned within the title. In step C2, the exclusion criteria were applied to the newly identified 19 documents, excluding 15 documents and shortlisting four new eligible documents. Step C2 led to the final pool of 31 (24 + 3 + 4) eligible documents.

In step D, two research team members performed the conceptual content analysis of the eligible articles. Conceptual content analysis is the suitable synthesis technique in the present study, given that the main objective here is to identify, quantify, and count the occurrence of the terms of interest within the textual data (Krippendorff, 2018). The study developed and followed a detailed content analysis protocol to ensure the reliability and validity of the conceptual analysis findings. This protocol involved defining the necessary steps, such as the coding scheme of implicit terms, codification of text into controllable content categories, defining content assessment levels (e.g., themes vs. terms), coding systems of the concepts (e.g., existence vs. frequency), and denoising procedures for distinguishing concepts. Two content analysts independently conducted the conceptual content analysis while

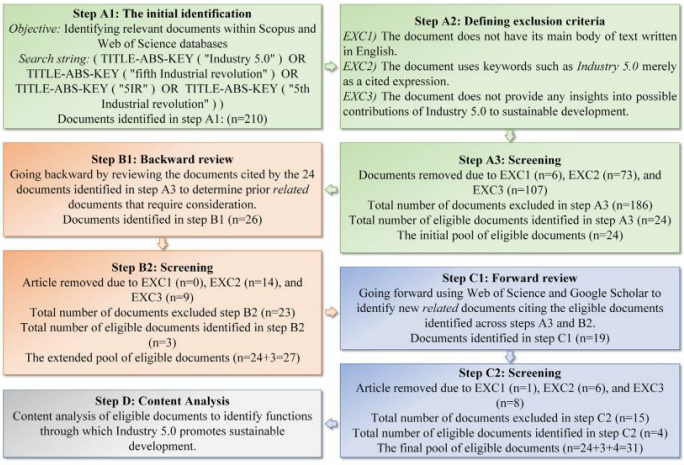


Fig. 2. The methodology applied for identifying the sustainable development functions of Industry 5.0.

adhering to the protocol to minimize the threat of assessor bias. After performing the content analysis independently, the two assessors shared their results and collaboratively performed the reexamination and reassessment of the text in the case of disagreements. Accordingly, the assessors collaboratively crosschecked their results, interpreted the conflicting findings, and reached a shared consensus on the functions through which Industry 5.0 might promote sustainable development, as perceived by the eligible documents. Step D led to identifying 16 functions of Industry 5.0 for promoting sustainable development, primarily in terms of resilience, sustainability, and human-centricity. Table 1 lists these functions and their acknowledgment strength within the eligible documents.

4. Methods

There are several well-established methods and techniques for dealing with complex decision problems and systems, examples of which include the Analytic Network Process (ANP), Analytic Hierarchy Process (AHP), ISM, and Decision-Making Trial and Evaluation Laboratory (DEMATEL). ISM was used as the most appropriate technique for addressing the objectives of this study. As with any decision modeling technique, ISM comes with advantages and limitations. Following, we explain our reasoning for using ISM in the present study and how we have dealt with the limitation of this technique. In general, ISM is associated with the following significant benefits (Sushil, 2012; Vimal et al., 2022):

- ISM can draw on qualitative data collection methods such as in-depth interviews or group decision-making techniques to capture the experts' collective opinion and knowledge base;
- ISM can systematically use conceptual, judgmental, and computational resources to provide an in-depth understanding of the pattern of contextual relations among elements of a complex system;
- ISM allows the interpretation of the contextual relationships among each pair of elements. ISM can also pair with an interpretive logic-knowledge base (built on experts' opinions) to interpret the functionality of each pair of relationships.

ISM allows scholars to draw on expert opinions and develop visual representations of poorly explored and complex systems. The present study is exploratory because Industry 5.0 is in its embryonic stage and significantly understudied. Thus, ISM is employed to explore the sustainable development functions of Industry 5.0 and structure them into a comprehensive interpretive model.

More importantly, the study aims to develop a strategy roadmap that identifies the interrelationships among Industry 5.0 sustainable development functions and describes the internal mechanism through which Industry 5.0 can deliver sustainability, resilience, and human-centricity based on the experts' collective opinion. The development of such a strategy roadmap has two requirements. The first requirement is to identify the precedence relationships among system elements, which is supported by most decision modeling techniques such as ISM, DEMATEL, and their fuzzy variants. The second requirement relates to expert-based group decision-making, where experts should engage in live discussions to produce a shared consensus regarding each pairwise relationship and its detailed functionality. To our knowledge, the original ISM offers the best compatibility of the two requirements of strategy roadmapping, as also highlighted by prior studies comparable to the present work, for example, to roadmap Industry 4.0 implications for sustainable innovation (Ghobakhloo et al., 2021a), energy sustainability (Ghobakhloo and Fathi, 2021), and sustainable manufacturing (Ng et al., 2022). ISM is prone to two major limitations when used for strategy roadmapping. The first limitation pertains to the experts' knowledge bias or unequal expert participation in collaborative decision-making. We have applied

Table 1
Sustainable development functions of Industry 5.0 and their acknowledgment within the literature.

Authors	BPM[a]	CIP	DST	ETA	INA	ORE	OSI	RIN	RTC	SCA	SCM	SII	SOP	STH	UPR	VUI
Özdemir and Hekim (2018)							x									
Demir and Cicibaş (2019)		x		x			x	x						x		
Demir et al. (2019)				x			x	x							x	
Haleem and Javaid (2019)			x		x								x			
Nahavandi (2019)	x			x	x	x								x		
Aslam et al. (2020)				x			x						x			
Gorodetsky et al. (2020)			x				x						x			
Javaid and Haleem (2020)		x			x		x			x			x		x	
Javaid et al. (2020)	x		x		x	x					x	x				x
Longo et al. (2020)		x	x											x	x	
Doyle Kent and Kopacek (2021)					x										x	
ElFar et al. (2021)		x					x	x						x		
Fraga-Lamas et al. (2021a)						x		x	x							x
Fraga-Lamas et al. (2021b)	x		x						x			x				
Johri et al. (2021)					x		x					x	x			
Kumar et al. (2021)		x	x		x	x						x				
Margherita and Braccini (2021)				x		x										
Mladineo et al. (2021)	x			x	x	x								x		
Thakur and Kumar Sehgal (2021)									x			x				
Xu et al., 2021		x	x	x		x				x		x			x	x
Akundi et al. (2022)	x			x	x	x		x			x				x	
Carayannis and Morawska-Jancelewicz (2022)							x							x	x	x
Dautaj and Rossi (2022)				x										x		
Fatima et al. (2022)	x		x		x	x	x			x	x					x
Gürdür Broo et al. (2022)															x	
Lu et al. (2022)	x			x	x	x			x						x	
Maddikunta et al. (2022)		x				x				x	x	x	x			x
Patera et al. (2022)		x							x			x				
Saniuk et al. (2022)						x			x	x		x	x	x		x
Sharma et al. (2022)		x				x	x		x			x	x			x
Sindhwani et al. (2022)		x		x			x	x					x			

[a] Note: BPM, business process monitoring; CIP, circular intelligent products; DST, data sharing and transparency; ETA, employee technical assistance; INA, intelligent automation; ORE, operational and resource efficiency; OSI, open sustainable innovation; RIN, renewable integration; RTC, real-time communication; SCA, supply chain adaptability; SCM, supply chain modularity; SII, system integration and interoperability; SOP, service-orientation and personalization; STH, sustainable thinking; UPR, upskilling and reskilling; VUI, value network integration.

rigorous measures to minimize such bias threats, such as moderating expert panel meetings in a structured manner or using a self-assessment questionnaire for identifying eligible experts. The second limitation relates to the ISM's weakness in interpreting the identified contextual relationships (Sushil, 2012). We have addressed this limitation by developing a knowledge base and recording experts' collective opinions concerning the functionality of each pairwise relationship identified. Fig. 3 describes the process of conducting ISM in the present study and its underlying steps, which follow the standard ISM methodology widely accepted within the literature (e.g., Huang et al., 2021).

4.1. Collecting expert opinion

ISM uses experts' opinions and insights to determine the contextual relationships among elements of a system. Accordingly, the present study collected the Industry 5.0 expert opinion to determine the relationships among the sustainable development functions of this phenomenon. The research team followed the widely acknowledged expert identification and selection guides (e.g., Hertzum, 2014) to develop and implement a reliable expert selection protocol. The research team mainly targeted European experts because of two reasons. First, Industry 5.0 and its predecessor primarily originate from Europe. Second, the present study was directly funded by a European Commission H2020 ERA Chair program, providing the necessary resources to contact and collaborate with top European Industry 5.0 expert group advising the Commission or other European policymaking bodies on how to devise forward-looking digital transformation policies for Europe's future industry.

Following the expert selection protocol, the research team collaborated with partners (e.g., academic, industry, or executive collaborators) and identified 24 experts potentially knowledgeable about and conversant with Industry 5.0. These experts were contacted and requested to fill in a simple self-assessment questionnaire measuring their familiarity with the Industry 5.0 phenomenon. The self-assessment questionnaire consisted of six open-ended questions (Please refer to Appendix A). Out of 24 experts contacted, 21 answered the self-assessment questionnaire. The research team collectively assessed the 21 self-assessment questionnaires returned, based on which 17 experts were identified as eligible to participate in the expert panel meetings. Out of the four experts identified as ineligible, one showed a lack of familiarity with the Industry 5.0 concept, one highlighted the lack of necessary English proficiency to engage in expert panel discussions effectively, and two declared an inability to commit to all expert panel meetings fully. After sending the invitations and follow-ups to the 17 eligible experts, 11 experts agreed to participate. Although ISM background does not provide any robust sample size rules, most studies agree on having 5 to 13 experts (e.g., Ng et al., 2022; Sarabi et al., 2020), mainly when using qualitative data collection methods like in-depth interviews or group brainstorming. Thus, the sample of 11 experts deems reliable in the present study.

The 11 experts consisted of four females and seven males, all academicians who had experienced collaborating with the European Commission as policy advisors, members/consultants of executive boards, or senior collaborators of the European Union's research and innovation funding programme in the areas of digitalization and sustainability. In terms of academic background, the expert team consists of two professors of sustainable development, a professor of complex systems and spatial planning, an associate professor of sustainability leadership, a professor of logistics and operations management, an associate professor of production engineering, senior research flow of innovation and digital economy, an associate professor of political science, a professor of digital technologies, an associate professor of applied computer science, and an associate professor of sustainable and secure digital transformation.

Experts' opinions and insights were collected across six online expert panel meetings organized via the nominal group technique. Using the nominal group technique-based expert panel meeting is a reliable and widely accepted method for capturing expert opinion within the ISM literature (Ghobakhloo et al., 2021a; Ng et al., 2022). Using nominal group technique for organizing expert panel meetings and capturing experts' opinions involved four standard septs: (1) clarification step explaining intended goals of each meeting, (2) expert silent ideation, (3) round-robin expert insight recording, and (4) collaborative opinion discussion. Using these standard steps, the experts evaluated, refined, and validated the 16 sustainable development functions of Industry 5.0 across the first two meetings. Overall, the experts acknowledged the categorization of functions yet recommended minor revisions to

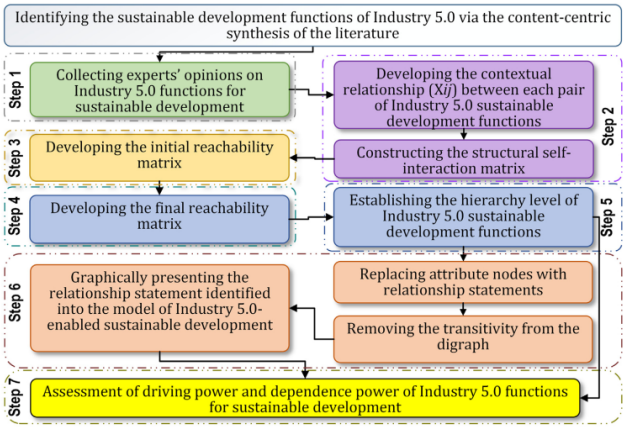


Fig. 3. The ISM methodology for the present study.

their titling. Experts collaboratively identified the contextual relationships among each pair of the sustainable development functions of Industry 5.0 across meetings 3 to 6. Besides the four standard steps, these meetings included three additional steps: (1) pilot voting on interrelationships among sustainable development functions, (2) discussing the preliminary relationships identified, and (3) final voting on the interrelationship between each pair of Industry 5.0 sustainable development functions. The research team followed the widely accepted guides to execute, moderate, and manage the meetings systematically to prevent bias and ensure the validity of outcomes.

4.2. Developing contextual relationships

This step involves using the following widely accepted coding system to identify the contextual relationships among system elements based on expert opinion and constructing the structural self-interaction matrix.

V: Sustainable development function *i* causes (determines) sustainable development function *j*;

A: Sustainable development function *i* is caused (determined) by sustainable development function *j*;

X: Sustainable development functions *i* and *j* mutually cause (determine) each other;

O: Sustainable development functions *i* and *j* are unrelated (independent).

Drawing on the expert opinions captured across expert panel meetings and building on the coding system explained above, the structural self-interaction matrix for the present study is developed and presented in Table 2. For example, the ETA-SII entry is symbolized as A in this table, meaning employee technical assistance (ETA) is determined by system integration and interoperability (SII).

4.3. Developing initial reachability matrix

Developing the initial reachability matrix entails subjecting the structural self-interaction matrix to the following transition coding scheme. Applying this coding system to the structural self-interaction matrix of the study, the initial reachability matrix is developed and presented in Table 3.

When the entry (i, j) in structural self-interaction matrix is symbolized by V, the entries (i, j) and (j, i) in initial reachability matrix are, respectively, set to 1 and 0;

When the entry (i, j) in structural self-interaction matrix is symbolized by A, the entries (i, j) and (j, i) in initial reachability matrix are, respectively, set to 0 and 1;

When the entry (i, j) in structural self-interaction matrix is symbolized by X, the entries (i, j) and (j, i) in initial reachability matrix are both set to 1;

When the entry (i, j) in structural self-interaction matrix is symbolized by O, the entries (i, j) and (j, i) in initial reachability matrix are both set to 0.

4.4. Developing final reachability matrix

This step involves developing the final reachability matrix by subjecting the relationships identified within the initial reachability matrix (Table 3) to the transitivity rule (Vimal et al., 2022). This rule implies that if element A causes element B and element B causes element C, then element A inadvertently causes element C, regardless of their relationships identified within the initial reachability matrix. Table 4 presents the final reachability matrix of the study. The '1*' values in Table 4 represent the application of the transitivity rule to individual relationships. The DST-INA value in Table 4, represented by 1*, can be exemplified to explain this rule better. The DST-INA entry in initial reachability matrix (Table 3) is 0, which means DST does not cause INA. However, DST directly causes VUI (DST-VUI entry in Table 3 is 1),

Table 2
The structural self-interaction matrix for Industry 5.0 sustainable development functions.

Functions	*j*																				
	Value network integration (VUI)	Upskilling and reskilling (UPR)	Sustainable thinking (STH)	Service-orientation and personalization (SOP)	System integration and interoperability (SII)	Supply chain modularity (SCM)	Supply chain adaptability (SCA)	Real-time communication (RTC)	Renewable integration (RIN)	Open sustainable innovation (OSI)	Operational and resource efficiency (ORE)	Intelligent automation (INA)	Employee technical assistance (ETA)	Data sharing and transparency (DST)	Circular intelligent products (CIP)	Business process monitoring (BPM)
BPM	A	O	O	O	A	A	V	A	O	O	V	A	A	A	V	–
CIP	A	O	A	A	O	O	V	A	X	A	V	O	O	A	–	
DST	X	V	V	O	A	O	V	A	V	V	O	A	V	–		
ETA	O	A	V	O	A	O	V	A	O	A	V	V	–			
INA	A	V	O	O	A	V	V	A	V	O	V	–				
ORE	A	O	O	A	O	A	V	O	O	O	–					
OSI	A	V	A	V	O	O	V	O	V	–						
RIN	A	O	A	O	A	O	O	A	–							
RTC	A	O	O	V	A	O	V	–								
SCA	O	O	O	A	A	A	–									
SCM	O	O	O	V	A	–										
SII	V	O	O	V	–											
SOP	A	V	A	–												
STH	O	V	–													
UPR	O	–														
VUI	–															

Table 3
The initial reachability matrix for Industry 5.0 sustainable development functions.

Functions	Business process monitoring (BPM)	Circular intelligent products (CIP)	Data sharing and transparency (DST)	Employee technical assistance (ETA)	Intelligent automation (INA)	Operational and resource efficiency (ORE)	Open sustainable innovation (OSI)	Renewable integration (RIN)	Real-time communication (RTC)	Supply chain adaptability (SCA)	Supply chain modularity (SCM)	System integration and interoperability (SII)	Service-orientation and personalization (SOP)	Sustainable thinking (STH)	Upskilling and reskilling (UPR)	Value network integration (VUI)
BPM	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0
CIP	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	1
DST	1	1	1	1	0	0	1	1	0	0	0	0	0	1	0	0
ETA	1	0	1	1	1	1	0	0	0	1	0	0	0	1	1	0
INA	1	0	0	0	1	1	0	1	0	1	1	0	0	0	1	0
ORE	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
OSI	0	1	0	1	0	0	1	1	0	1	0	0	1	0	1	0
RIN	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0
RTC	1	0	1	1	1	0	0	1	1	1	0	0	0	0	0	0
SCA	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
SCM	1	0	0	0	0	1	0	0	1	1	1	0	1	0	0	1
SII	1	0	1	1	1	0	0	1	0	1	1	1	1	0	0	0
SOP	0	1	0	0	0	1	0	0	0	0	0	0	1	0	1	0
STH	0	1	0	0	0	0	1	1	0	0	0	0	1	1	0	0
UPR	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
VUI	1	1	1	0	1	1	1	1	1	0	0	0	1	0	0	1

and VUI directly causes INA (VUI-INA entry in Table 3 is 1). Therefore, according to the transitivity rule, DST is assumed to cause INA within the final reachability matrix. Table 4 also represents the driving power and dependence power of functions. The driving power value for a given function equals the number of functions it causes within the final reachability matrix, while the dependence power equals the number of functions caused by. The driving and dependence power values will be used in the MICMAC (Matrice d'Impacts Croisés Multiplication Appliqués à un Classement) analysis.

4.5. Establishing hierarchy level

As the most crucial outcome of ISM, the graphical interpretive model is developed by positioning system elements (functions in this study) into their appropriate placement levels. Identifying placement levels involves establishing the hierarchy level of Industry 5.0 sustainable development functions. This procedure entails using entry values in the final reachability matrix to develop the reachability, antecedent, and intersection sets for each sustainable development function. For a given function, the reachability set consists of the function itself and other functions caused by it, whereas the antecedent set comprises the function itself and other functions that determine it. The intersection set for the given function consists of functions shared across its reachability and antecedent sets (Ghobakhloo et al., 2021a).

Establishing hierarchy levels commences by building each function's reachability, antecedent, and intersection sets in iteration 1. Next, the extraction procedure takes place, in which function(s) with identical reachability and intersection sets are extracted (and removed) from the remaining sets in upcoming iterations. Table A1 represents the process of identifying the hierarchy level of Industry 5.0 sustainable development functions. Iteration 1 of this table identifies SCA for extraction because it is the only function with identical reachability and intersection sets. The extraction process in iteration 1 involves removing SCA from all remaining reachability, antecedent, and intersection sets. Accordingly, the iterative extraction process is continued iteratively until the hierarchy level of each sustainable development function is identified. Table A1 explains that the hierarchy levels of functions in the present study are established across ten iterations. Thus, the graphical interpretive model would consist of 10 placement levels.

4.6. Developing the interpretive model

This step involves positioning the sustainable development functions to their designated placement levels based on their extraction (hierarchy) level and representing the direct relationships between the functions with vector arrows. The interpretive model of Industry 5.0-enabled sustainable development is presented in Fig. 4. Consistent with the ten iterations of extractions in Table A1, the model positions the functions across ten placement levels. Nonetheless, the placement order in this model is the direct opposite of the extraction sequence identified in Table A1. This placement system follows the ISM literature recommending that function(s) with the highest driving power, extracted at the last iteration, should be placed at the beginning of the interpretive model due to their enabling role (e.g., Ghobakhloo and Fathi, 2021; Huang et al., 2021). According to the ISM methodology, the transitivity rule should be ignored while developing the interpretive model (Vimal et al., 2022). It means that vector arrows should only visualize the direct relationships between the functions across successive placement levels. SII → VUI, INA → SCM, and STH → RIN relationships are the exception in this model, extending the relationships over successive placement levels. For example, for the SII → VUI relationship, it is notable that no functions in placement level 2 determine VUI. Thus, the SII, positioned in placement level 1 (two levels lower), has been linked to VUI with the vector arrow. The same logic holds for INA → SCM and STH → RIN relationships.

Table 4
The final reachability matrix for Industry 5.0 sustainable development functions.

Functions	Business process monitoring (BPM)	Circular intelligent products (CIP)	Data sharing and transparency (DST)	Employee technical assistance (ETA)	Intelligent automation (INA)	Operational and resource efficiency (ORE)	Open sustainable innovation (OSI)	Renewable integration (RIN)	Real-time communication (RTC)	Supply chain adaptability (SCA)	Supply chain modularity (SCM)	System integration and interoperability (SII)	Service-orientation and personalization (SOP)	Sustainable thinking (STH)	Upskilling and reskilling (UPR)	Value network integration (VUI)	**Driving power**	*Rank*
BPM	1	1	0	0	0	1	0	1*	0	1	0	0	1*	0	0	0	**6**	*6*
CIP	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	**4**	*8*
DST	1	1	1	1	1*	1*	1	1	1*	1	0	0	1*	1	1	1	**14**	*3*
ETA	1	1*	0	1	0	1	1*	1*	0	1*	0	0	1*	1	1*	0	**10**	*4*
INA	1	1*	1	1	1	1	1*	1	0	1	1	0	1*	1*	1	1*	**14**	*3*
ORE	0	0	0	0	0	1	0	0	0	1	0	0	0	1*	0	0	**2**	*9*
OSI	1*	1	0	1	0	1*	1	1	0	1	0	0	1	1*	1	0	**10**	*4*
RIN	0	1	0	0	0	1*	0	1	0	1*	0	0	1*	0	0	0	**5**	*7*
RTC	1	1	1	1	0	1*	1*	1	1	1	1*	0	1	1*	1*	1*	**15**	*2*
SCA	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	*10*
SCM	1	1*	0	0	0	1	0	0	0	1	1	0	1	0	0	0	**6**	*6*
SII	1	1*	1	1	1	1*	1*	0	1	1	1	1	1	1*	1*	1	**16**	*1*
SOP	0	1	0	0	0	1	0	1*	0	1	0	0	1	0	0	0	**5**	*7*
STH	0	1	0	1*	0	1*	1	1	0	1*	0	0	1	1	1	0	**9**	*5*
UPR	1*	0	0	1*	0	1*	0	0	0	0	0	0	0	1*	1	0	**5**	*7*
VUI	1	1	1	1*	1	1	1	1	1	1*	1*	0	1	1*	1*	1	**15**	*2*
Dependence power	**10**	**13**	**5**	**9**	**5**	**15**	**8**	**12**	**4**	**15**	**5**	**1**	**12**	**9**	**9**	**5**		
Rank	*4*	*2*	*7*	*5*	*7*	*1*	*6*	*3*	*8*	*1*	*7*	*9*	*3*	*5*	*5*	*7*		

4.7. Driving and dependence analysis

MICMAC is a comparative classification and evaluation tool that draws on the driving power and dependence power values identified across the final reachability matrix (Table 4) to visualize and compare enabling role and dependability of functions. Fig. 5 presents the MICMAC analysis of the present study. MICMAC analysis entails classifying the functions into four quadrants: autonomous, linkage, driver, and dependent (Ng et al., 2022). The driver quadrant includes Industry 5.0 sustainable development functions with strong driving and weak dependence power. The driver functions are SII, RTC, DST, INA, and VUI. Functions with weak driving and dependence power are categorized under the autonomous quadrant. SCM is the only autonomous sustainable development function in this study. The linkage quadrant comprises functions with strong driving and dependence power. OSI, ETA, and STH are the linkage functions. It means they play a critical role in transferring the value of driver functions to dependent functions. As linkage functions, OSI, ETA, and STH are unstable, meaning any action on these functions would affect the other functions and, consequently, have a reflexive effect on themselves. For example, OSI would lead to open collaboration on the ETA that improves the human workforce's decision-making and information processing capabilities, from operators to managers. These valuable capabilities allow decision-makers to understand better the value of STH, encouraging them to allocate more resources and trust in open collaboration for sustainable innovation, which creates a loop enabling OSI. Within the ISM background, linkage elements and the resulting feedback loops are undesirable, especially when the outcome of the ISM is planned to serve as a theoretical basis for the regression-based structural model where feedback loops (connection cycles) are not acceptable. The ISM outcome in the present study is used to develop the strategy roadmap in which feedback loops pose no limitations. Overall, the presence of linkage variables in our study indicates that OSI, ETA, and STH are highly interdepended, and feedback loops exist among them. Thus, these functions should be developed simultaneously under the Industry 5.0 framework while considering their mutuality and complementarity. The dependent quadrant includes functions having weak driving power and strong dependence power. These functions are more complicated to develop since they rely upon linkage and driver functions to enable their development. BPM, UPR, RIN, SOP, CIP, ORE, and SCA are the dependent sustainable development functions of Industry 5.0.

5. Results and discussion

The interpretive model of Industry 5.0-enabled sustainable development and the MICMAC analysis collectively reveal that Industry 5.0 and the underlying digital industrial transformation facilitate the core objectives of sustainability, resilience, and human-centricity by first delivering the system integration and interoperability (SII) function. The integration part of the SII function involves combining all micro-modules of the hyperconnected digital ecosystem, such as computing systems, software packages, human operators, or smart devices, vertically and horizontally within and across smart components of Industry 5.0. The interoperability part of the SII function entails the ability of micro-modules of the smart components to communicate with and understand each other seamlessly (Sharma et al., 2022). SII offers important implications for various aspects of sustainable development, as the resulting decentralization provides all Industry 5.0 stakeholders with open, democratized, and pluralistic access to value (Fraga-Lamas et al., 2021b; Sindhwani et al., 2022). Fig. 4 shows that SII directly enables real-time communication (RTC) and value network integration (VUI). SII delivers this enabling role by facilitating data integrity, system access, and semantics clarity (Javaid et al., 2020; Thakur and Kumar Sehgal, 2021).

VUI refers to the vertical integration of all business processes and functions across various organizational layers and the horizontal

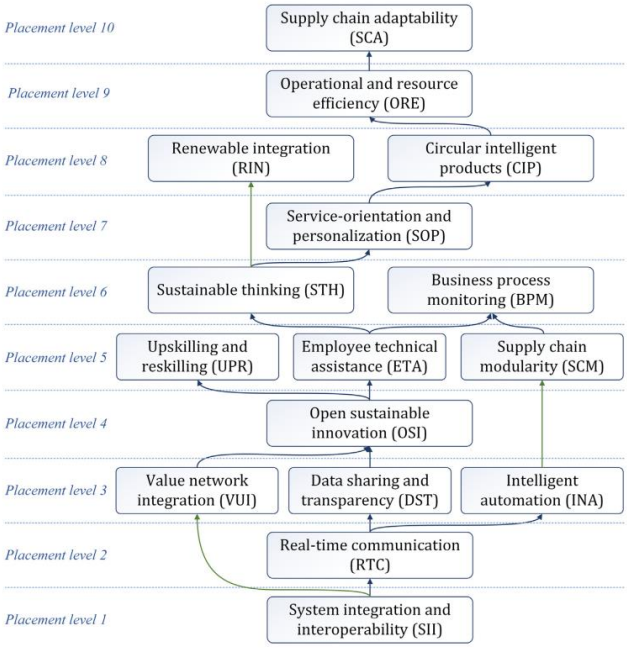
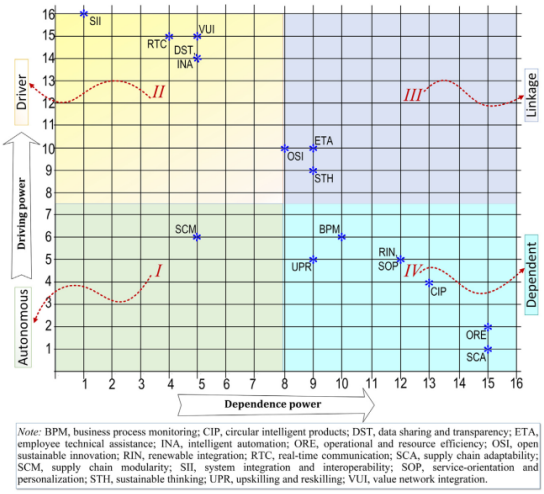


Fig. 4. The interpretive model of Industry 5.0-enabled sustainable development.

integration of supply chain processes involving seamless manufacturing, logistics, and distribution operations (Jabrane and Bousmah, 2021). Consistently, VUI requires the internal and external integration of Industry 5.0 smart components. VUI is closely tied to integrative technological constituents of Industry 5.0, such as CAI, CCPS, IoE, blockchain, and cloud computing (Longo et al., 2020). Product customization, manufacturing agility, process visibility, and improved trust and collaboration are outcomes of VUI essential to the sustainable development objectives of Industry 5.0 (Xu et al., 2021). The RTC function entails the ability of Industry 5.0 micro-modules to communicate and exchange data in real-time when necessary. The RTC function expands beyond the traditional real-time communication of production system components on the shopfloor, involving seamless communication of all value network modules (Javaid et al., 2020). Latest advancements in industrial communication (e.g., 5G or 6G), IoE, and AI-edge computing are crucial to addressing real-time communication requirements under Industry 5.0. RTC serves the sustainable development objectives of Industry 5.0 by improving production reliability, work environment safety, decision processes, risk management, and stakeholder responsiveness at the micro-organizational and value network levels (Saniuk et al., 2022).

Fig. 4 explains that RTC is critical to developing data sharing and transparency (DST) and intelligent automation (INA), functions that significantly rely on data timeliness, reliability, and dependability. DST is indispensable to Industry 5.0 as it addresses the data requirement of this data-driven phenomenon, allowing secure and reliable sharing of valuable data within organizational borders and across value networks (Özdemir and Hekim, 2018). Under the Industry 5.0 environment, DST ensures that the data is always accessible, communicable, and verifiable (Gorodetsky et al., 2020). More importantly, DST entails regulating data ownership and fair value return. IoE, blockchain, big data analytics, and cloud computing are critical enablers of DST under Industry 5.0 (Kumar et al., 2021). RTC supports the sustainable development objectives of Industry 5.0 by improving customer experience, value network visibility, value network collaboration, and environmental performance monitoring (Fatima et al., 2022). The INA function involves using disruptive automation technologies such as cognitive robots, CAI, intelligent business process management, and process automation to scale, automate, and streamline the decision-making processes across value network members (Nahavandi, 2019). Under Industry 5.0, INA's contribution to sustainable development objectives involves process simplification, resource productivity, industrial accident prevention, and environmental compliance (Fraga-Lamas et al., 2021b). More importantly, INA can augment the workforce, improve workplace safety, and enhance employee job satisfaction (Mladineo et al., 2021).

INA, in turn, enables the supply chain modularity (SCM) function. SCM draws on the digital supply network concept and aims to deliver scalable, agile, and customizable value networks. SCM involves decomposing complex value chains comprising smart adaptive factories, distribution channels, and suppliers into reconfigurable modules (Shao and Zavala, 2020). SCM allows industrial value chains to rearrange their modules according to the market needs and environmental circumstances and develop business models that support the core



Note: BPM, business process monitoring; CIP, circular intelligent products; DST, data sharing and transparency; ETA, employee technical assistance; INA, intelligent automation; ORE, operational and resource efficiency; OSI, open sustainable innovation; RIN, renewable integration; RTC, real-time communication; SCA, supply chain adaptability; SCM, supply chain modularity; SII, system integration and interoperability; SOP, service-orientation and personalization; STH, sustainable thinking; UPR, upskilling and reskilling; VUI, value network integration.

Fig. 5. Driving power and dependence power matrix.

objectives of Industry 5.0 through more equitable value distribution, product adaptation, and supply chain responsiveness (Dolgui et al., 2020). SCM relies on Industry 5.0 technologies that facilitate decentralization, allowing value network modules to make independent decisions and operate autonomously (Xu et al., 2021). CAI, CCPS, IoE, and edge/fog computing are examples of technologies vital to the SCM function (Maddikunta et al., 2022).

Through integrating value network operations and enabling transparent data sharing (VUI and DST functions), Industry 5.0 delivers the open sustainable innovation (OSI) function. This function delivery order is expected because OSI is data-intensive and requires close collaboration among value network members (Ghobakhloo et al., 2021b). OSI entails using Industry 5.0 technologies and techno-functional principles that support integrating open innovation into developing more sustainable products, processes, services, and business models (Demir and Cicibaş, 2019). IoE, cloud computing, and big data are essential to OIS since they integrate stakeholders' and consumers' green expectations into innovation processes (Carayannis and Morawska-Jancelewicz, 2022). Alternatively, smart CADM (e.g., additive manufacturing solutions), smart material, and dynamic simulation (e.g., digital twinning) transform the results of collaborative ideation and innovation into sustainable new products and processes (ElFar et al., 2021). Reduced energy consumption, improved societal impact, higher employee morale, and customer satisfaction are among the contributions of OSI to Industry 5.0 sustainable development values (Breque et al., 2021). Fig. 4 explains that OSI is the direct enabler of employee technical assistance (ETA) and upskilling and reskilling (UPR).

ETA entails using emerging technologies such as adaptive robots, smart wearables, and human interaction and recognition technologies (HIRT) that empower workforce-machine symbiosis. Instead of replacing employees with autonomous robots, ETA promotes human-centered approaches to industrial operations, such as the augmented or collaborative operator (Demir et al., 2019). Accordingly, ETA involves automating tedious and unergonomic tasks, providing employees with real-time information for better decision-making, and improving employees' competencies to interact with rapidly advancing digital industrial systems (Kaasinen et al., 2022). ETA mainly contributes to the socio-economic values of Industry 5.0, as it improves employees' productivity, health, work satisfaction, decision performance, and autonomy (Lu et al., 2022). UPR directly addresses the job displacement and unemployment concerns of Industry 4.0. UPR entails drawing on Industry 5.0 technologies and principles to devise and implement new human resource development programs that: (1) allow employees to learn new skills to address the existing talent gaps and (2) teach employees new skills that prepare them for new or alternate jobs caused by the ongoing digital transformation (Gürdür Broo et al., 2022). Industry 5.0 delivers UPR in various ways, such as using extended reality to improve training effectiveness, applying AI to optimize employee career pathing, or improving information and knowledge sharing within and across organizational boundaries (Kaasinen et al., 2022). UPR serves the sustainable development objectives of Industry 5.0 by addressing the ever-worsening skill crisis and improving employee morale, social inclusivity, and workforce performance (Carayannis and Morawska-Jancelewicz, 2022). By delivering ETA and SCM, Industry 5.0 paves the way for developing business process monitoring (BPM) and sustainable thinking (STH) functions.

The BPM function of Industry 5.0 involves analysing and reviewing business processes in real-time to identify existing and emerging critical process problems. BPM is multifaceted, including the functional monitoring of distributed business applications, technical monitoring of systems (e.g., hardware, software, or machinery), and process monitoring of business workflows (Maddikunta et al., 2022). Industry 5.0 delivers BPM via technologies and techno-functional principles that support real-time communication, decentralized decision-making, self-awareness/expressiveness, and human-machine integration (Nahavandi, 2019; Mladineo et al., 2021). Cost-saving, process scalability, improved employee experience, accountability, and customer satisfaction are examples of contributions that BPM can offer to the sustainable development values

of Industry 5.0 (Paschek et al., 2022). The STH function requires businesses to place sustainable operations next to institutional survival as their primary organizational goals. Thus, STH involves drawing on Industry 5.0 technologies such as smart materials, HIRT, CADM, or intelligent product lifecycle management that allow businesses to develop and implement a systemic approach to integrate sustainability and create shared value for stakeholders (Renda et al., 2022). STH serves Industry 5.0 sustainable development goals by empowering businesses to integrate sustainability issues into the core business strategies and develop sustainable management practices that support resilience, environmental preservation, and human centricity (Carayannis and Morawska-Jancelewicz, 2022; Saniuk et al., 2022).

STH plays a critical role in facilitating the renewable integration (RIN) and service-orientation and personalization (SOP) functions of Industry 5.0. RIN refers to decarbonizing the energy sector by implementing and integrating renewable energy technologies into the energy supply chains (Kong et al., 2021). Although the price of these technologies has fallen significantly during the past few years, integrating renewable energy technologies is still challenged by technical barriers (such as energy variability or uncertainty) and administrative barriers such as lack of regulations and policies (ElFar et al., 2021). Industry 5.0 delivers the RIN function using CAI, dynamic simulation, IoE, decentralization, and other technologies and principles to improve energy production/storage capabilities, situational awareness, distribution management, load prediction, and resource generation forecasting. To deliver RIN, Industry 5.0 also facilitates collaboration among renewable energy stakeholders to facilitate supportive regulations and policy interventions (Carayannis et al., 2021). SOP involves developing more service-oriented business models, allowing products and assets of companies such as smart goods, production facilities, innovation capacity, or human capital to be offered to customers as possible services (ElFar et al., 2021; Gorodetsky et al., 2020). SOP also involves the large-scale production of customized (and even individualized) goods and services (Aslam et al., 2020). SOP is an ambitious function that relies on various technologies and techno-functional principles of Industry 5.0, such as horizontal/vertical integration, IoE, smart CADM, and cloud computing, to deliver the necessary value network integration and flexibility of the production processes (Johri et al., 2021; Sharma et al., 2022). SOP offers important implications for Industry 5.0 sustainable development values such as business resilience, customer satisfaction, resource efficiency, and product circularity (Saniuk et al., 2022). More importantly, SOP allows the development of the circular intelligent products (CIP) function.

The circular part of the CIP involves using Industry 5.0 technologies to design products that can function within the circular economy framework. CIP ensures that products are designed and developed to be environmentally friendly across their lifecycles (Fraga-Lamas et al., 2021a). Thus, CIP entails using smart materials, intelligent product lifecycle management, IoE, and smart CADM to develop products that eliminate waste, pollution, and emission and can be longer in use productively (Lenz et al., 2020). The intelligent part of CIP critically relies on materializing the smart product concept. Under Industry 5.0, a smart product can be featured as being sensor-equipped, AI-driven, and made of smart or engineered living materials (Li et al., 2021). Thanks to smart and circular products that can monitor and communicate their environmental footprint throughout the life cycle, CIP boosts Industry 5.0 sustainable development values concerning supply chain resilience, sustainable innovation, economic development, and environmental protection (Kumar et al., 2021; Sindhwani et al., 2022). Building on CIP, Industry 5.0 can deliver the operational and resource efficiency (ORE) function. This function involves using Industry 5.0 technologies and principles for industrial efficiency at various levels. For example, alert-driven IoE and CCPS systems can predict and prevent equipment-related production risks at the smart factory level (Xu et al., 2021). Alternatively, HIRT and smart wearables can empower employees to operate more productively and become more efficient at work. Automation, real-time communication, decentralization, and integrability features of Industry 5.0 further allow the digital supply networks to apply data-driven and actionable improvements throughout supply chain operations, optimizing resource consumption and reducing operational costs (Lu et al., 2022). The ORE function allows businesses to support the sustainable development objectives of Industry 5.0 by improving product accessibility, job creation, business agility, compliance, and circularity (Akundi et al., 2022; Nahavandi, 2019).

Finally, yet importantly, ORE complemented by the preceding functions delivers the supply chain adaptability (SCA) function of Industry 5.0. SCA entails drawing on Industry 5.0 features to proactively identify the structural shifts in the market and adjust the value network design, module compositions, and strategies accordingly (Maddikunta et al., 2022). It is intricate to develop SCA because of its extensive scope of impact and sheer dependence on other sustainable development functions (Renda et al., 2022). For instance, the product adjustment aspect of SCA involves using IoE, CADM, adaptive robots, and dynamic simulation to develop new products or rethink the existing ones according to shifting consumer preferences (Pettit et al., 2019). Alternatively, SCA requires supply chains to draw on CAI, cognitive computing, real-time communication, horizontal integration, and other constituents of Industry 5.0 to sense imminent disruption and proactively devise the best response strategies (Dolgui and Ivanov, 2022). SCA offers various implications for sustainable development values of Industry 5.0, primarily manifested in improving business, supply chain, and economic resilience (Sindhwani et al., 2022).

5.1. The roadmap to Industry 5.0-driven sustainability

The main objective of the study involved developing a roadmap describing how Industry 5.0 can function to enable sustainable development, especially in terms of resilience, environmental sustainability, and human-centricity. We identified the sustainability functions of Industry 5.0 by conducting a content-centric literature review. The interpretive model presented in Fig. 4 describes in which order these functions can best lead to promoting sustainability. These findings offer insights into the functionality of Industry 5.0 for sustainability and the necessary development sequences of functions. Nonetheless, Fig. 4 cannot be considered a sustainability roadmap since it falls short in interpreting the role of each function in promoting sustainable development goals of Industry 5.0 as well as the contextual relationships among each pair of functions. To develop the promised roadmap to the Industry 5.0-driven sustainability, we drew on the Interpretive Logic-knowledge base (ILB) developed based on the experts' opinions during the panel meetings. Fig. 6 represents the roadmap to the Industry 5.0-driven sustainability, which was developed based on integrating the ISM outputs with the ILB. In this figure, the direct relationships shown by vector arrows correspond to the contextual relationships identified within the initial reachability matrix (Table 3). This figure also assumes a direct relationship between each function and sustainable development. Placement levels in Fig. 6 correspond to the placement levels identified in the interpretive model (Fig. 4). Due to the complexity of the roadmap, the interpretation of each relationship has been explained in Table A2. This table corresponds to the ILB that recorded the collective opinions of experts regarding contextual relationships.

In general, the roadmap in Fig. 6 serves as a reference framework for Industry 5.0 actors involved in transforming industries toward sustainable development goals. This roadmap highlights the action plan for capitalizing on Industry 5.0 functions to gain sustainability values. Therefore, this roadmap assists with bridging the gap between the Industry 5.0 sustainability vision and the underlying actions and interactions that allow satisfying the intended sustainability objectives of this phenomenon. Technically speaking, this roadmap outlines the actions, interactions, and vision of Industry 5.0 for the future of the industry. It provides leaders, policy-makers, and Industry 5.0 actors the visual

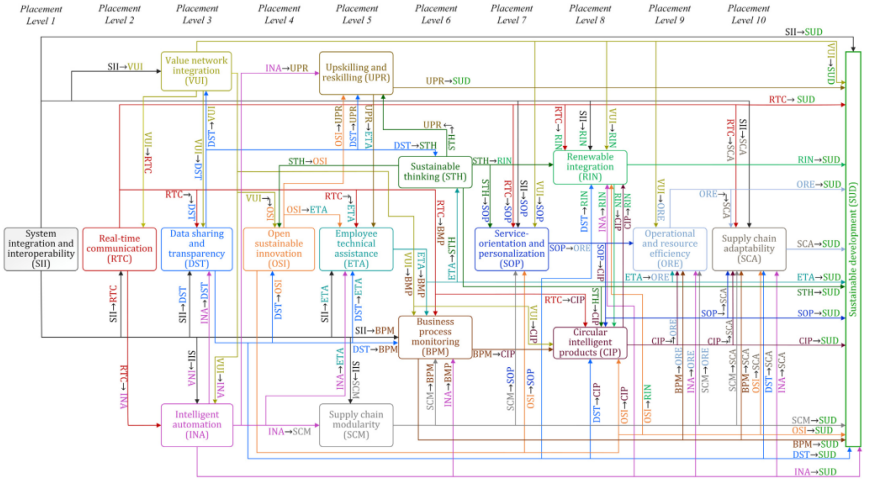


Fig. 6. The roadmap to Industry 5.0-driven sustainability.

representations of how each Industry 5.0 function should be developed or capitalized sequentially to maximize the sustainability values of Industry 5.0. For the present study, the vision is to deploy an industrial transformation framework titled Industry 5.0 to achieve sustainable development in ways that adhere to planetary and societal boundaries. The action part of the strategy roadmap manifests in the 16 sustainability functions of Industry 5.0, developed via consulting with the literature. The roadmap further demonstrates how actions (functions) should be sequentially developed to deliver the intended vision. The ISM methodology allowed us to explore and identify the precedence relationships among actions (16 functions) that collectively deliver the intended vision. More importantly, the strategy roadmap should generally explain the 'how' question related to the role of each action. In the present study, Table A2 and Fig. 6 collectively answer the how question, describing the internal enabling role of each sustainability function concerning other functions.

Results collectively reveal that each of the 16 functions provides essential and, in many cases, exclusive implications for promoting various micro and macro aspects of sustainable development. For example, ETA implications for sustainable development mainly involve promoting the micro-socioeconomic aspects of sustainability, such as enhancing employee productivity or improving workplace safety, satisfaction, and dignity. Alternatively, STH role in progressing sustainability entails improving macro socio-environmental sustainability aspects such as alleviating overconsumption or empowering Industry 5.0 stakeholders (e.g., social actors) to contribute to the circular economy or oversee the transitioning toward sustainable development. Table A2 reveals that while the functions identified provide key contributions to various aspects of sustainable development, their enabling role concerning the three core sustainability objectives of Industry 5.0 can be summarized as follows;

- Functions such as real-time communication, value network integration, intelligent automation, supply chain modularity, business process monitoring, service-orientation and personalization, operational and resource efficiency, and supply chain adaptability facilitate business, supply chain, and economic aspects of resilience;
- The environmental sustainability goals are mainly supported by value network integration, intelligent automation, sustainable thinking, renewable integration, circular intelligent products, and operational and resource efficiency;
- The human-centricity objectives of Industry 5.0 are mainly propelled by system integration and interoperability, data sharing and transparency, open sustainable innovation, upskilling and reskilling, employee technical assistance, and service-orientation and personalization.

Results presented in Fig. 6 and Table A2 reveal that the desirable contribution of Industry 5.0 to sustainable development entails the inclusive and sequential development of all sustainability functions. There are two major reasons for such inference. First, results show that each function can only address a few aspects of sustainable development. Indeed, functions complement each other to offer a broad spectrum of micro and macro-level economic, environmental, and social sustainability implications. Second, complex precedence relationships exist among sustainable development functions of Industry 5.0, and the sequence of their development would define how Industry 5.0 would lead to sustainable development values. For example, Table A2 shows that RTC enables SCA development, meaning supply chain adaptability builds on the foundation of supply chain-wide real-time communication. The enabling role of RTC for SCA involves the elimination of functional silos across the supply network or data-driven forecasting of imminent disruptions. While RTC does not offer direct implications for supply chain resilience, it plays a vital indirect role by increasing the adaptability of supply chains. Thus, collective and sequential development of Industry 5.0 functions, as identified within Fig. 6, is indispensable to sustainable development.

6. Conclusions

Experts believe that Industry 5.0 has emerged to complement Industry 4.0 and address the socio-environmental concerns of the ongoing

digital industrial transformation. Industry 5.0 has been advertised to promote sustainable development. Nonetheless, it is unclear how Industry 5.0 can deliver its intended sustainable development values. To address this knowledge gap, the study conducted a content-centric synthesis of the literature and identified 16 functions through which Industry 5.0 can promote sustainable development values, especially in terms of resilience, environmental sustainability, and human-centricity. Notably, several of the functions identified, such as real-time communication or business process monitoring capabilities, are not exclusive to Industry 5.0, given that they have been associated with technological advancements since the third industrial revolution. However, The technological and regulatory advancements under Industry 5.0 redefines the width (quality) and breadth (scope) of these functions. The hyperconnected business ecosystems of Industry 5.0 and the stakeholder-centric features of this phenomenon allow the integrative development of these functions, building on their complementarities to offer additive values for achieving intended sustainable development goals.

The study further applied ISM and structured the relationships among the function into the Industry 5.0-enabled sustainable development model. This model describes how Industry 5.0 can extend beyond delivering efficiency and productivity to promote socio-environmental development meaningfully. The model and underlying findings are expected to offer theoretical and practical implications for academicians, industrialists, and policy-makers.

6.1. Implications

The study attempted to explain how Industry 5.0 can deliver its intended sustainable development values. For this purpose, the study first addressed the ambiguity surrounding this concept and developed a reference model that provided a holistic understanding of this phenomenon. The reference model showed that Industry 5.0 is a socio-technological phenomenon, which relies on technological advancements and stakeholder collaboration to go beyond economic development and address prevailing environmental and social concerns. Industry 5.0 is pushed by two major classes of technologies, including (1) enabling technologies that have matured since the third industrial revolution and have been vastly commercialized during Industry 4.0 and (2) emerging technologies representing the most disruptive technological innovations such as CAI or adaptive robots. The technological aspect of Industry 5.0 also involves developing the necessary techno-functional design principles, such as real-time capability or decentralization. These principles allow the technological constituents of Industry 5.0 to operate optimally and deliver their intended functionality. Contrary to Industry 4.0, which is often manifested in smart factories, the scope of Industry 5.0 expands well beyond the manufacturing industry and smartization of production facilities. Indeed, the sociocultural part of this phenomenon denotes the shift toward the stakeholder perspective while defining the components and scope of Industry 5.0. Smart customers, stakeholders (e.g., governments or labor unions), suppliers, adaptive production facilities, and technology providers are examples of the components that should digitalize and integrate to create the hyperconnected value ecosystem of Industry 5.0. The particularity of Industry 5.0 components changes according to business and industrial context. For example, smart patients, pharmaceutical firms, physicians, hospitals, and insurance companies constitute the components of Healthcare Industry 5.0, also known as Health 5.0.

The study identified 16 functions through which Industry 5.0 can promote sustainable development goals. These functions are the byproduct of the interaction among technology, principle, and component layers of the Industry 5.0 reference model. Results revealed that each function could independently contribute to some sustainable development objectives of Industry 5.0. For example, the data sharing and transparency (DST) function can promote supply chain visibility, traceability, and transparency features vital to the supply chain resilience objective of Industry 5.0. Nevertheless, there is substantial complementarity among the functions identified, and collective development of all functions and resulting synergies would offer superadditive values for sustainable development objectives of Industry 5.0. Notably, ISM results showed that complex precedence relationships exist among the functions identified, which means these functions are developed sequentially in a specific order. Indeed, the sequence of relationships identified in Fig. 4 and Fig. 6 can be valuable to scholars, policy-makers, and even industrialists, empowering them to strategically govern the technology-driven digital industrial transformation under Industry 5.0 to promote sustainable development.

The interpretive model in Fig. 4 and the MICMAC results show that Industry 5.0 contribution to sustainable development should first involve using system integration and interoperability features of this phenomenon to enable real-time communication among Industry 5.0 micro-components (e.g., operations technologies, information technologies, operators, embedded systems, or processes). These functions should be further leveraged for value network-wide process integration, data sharing, and intelligent automation. By doing so, value networks can integrate, exchange information, and transparently collaborate to promote open sustainability innovation. By introducing sustainability into innovation processes, value network partners should further leverage Industry 5.0 features to modularize the supply chain design, develop smart workspace and employees, and increase the versatility and specialization of human resources to meet Industry 5.0 skill requirements. Meeting these conditions would allow integrating sustainable thinking into business strategies to balance economic gains and socio-environmental commitments. For this to happen, supply partners should proactively monitor core business processes and functions to analyze their economic and socio-environmental performance and risks. Developing these functions should allow businesses to integrate renewable energy (e.g., via AI-driven microgrids) and move toward servitization and product individualization to develop new value streams and improve customer experience. In doing so, businesses should leverage Industry 5.0 technologies, principles, and functions to develop circular intelligent products that allow self-mapping of their entire lifecycle to integrate into the circular economy. These functions would eventually allow businesses to increase their resource and operational efficiency, thus, improving economic growth and reducing waste, energy consumption, and emission. Finally, these functions allow industrial value chains to gain the necessary agility, resources, capabilities, expertise, and innovation capacities to adapt to the structural shifts in the market caused by disruptions and gain the necessary resilience.

The precedence relationships identified across the ISM analysis represent the natural order in which the sustainable development functions of Industry 5.0 should be developed. The driver functions, placed at the lower levels of the structural model, are more critical because businesses should leverage them to develop more dependent functions such as ORE or SCA. Nonetheless, the absolute value of dependent functions cannot be overlooked, given that they are indispensable to the sustainable development objectives of Industry 5.0. Although many of the functions identified are not exclusive to Industry 5.0, this phenomenon draws on its technological constituents, techno-functional design principles, and smart components to build a transition path that allows inclusive development of all functions in the identified order. Therefore, the Industry 5.0-enabled roadmap to sustainable development represents a transformation framework that learns from Industry 4.0 shortcomings and Covid 19 disruption to design a hyperconnected industrial ecosystem that is inherently productive, resilient to future shocks, human-centered, and socio-environmentally sustainable.

To summarize, the roadmap and underlying results are believed to offer the following contributions to the theory and practice:

- Industry 5.0 can contribute to sustainable development via 16 interdependent functions. These functions vary significantly in their purpose and properties, ranging from micro-technical functions like real-time communication to macro-operational functions like supply chain adaptability.
- Each of the functions provides important but exclusive implications for promoting sustainability. These functions complement each other in promoting various aspects of sustainable development. Thus, none of the functions can be overlooked, regardless of their enabling role or dependability.
- Significant precedence relationships were identified among the sustainability functions of Industry 5.0. Therefore, these functions should be developed and capitalized sequentially and in the specific order described within the structural model. The synergies arising from the sequential development of these functions maximize the possible sustainability gain of the Industry 5.0 framework.
- Although some of the identified functions are not exclusive to this phenomenon, Industry 5.0 offers a digital transformational ecosystem that allows the synchronized and conclusive development of these ambitious functions.

6.2. Limitations and future research directions

Overall, the present study identified functions through which Industry 5.0 might potentially deliver its intended sustainable development values. The study modeled the sequence in which these functions should be developed based on the ISM technique and further identified their possible interactions. While we followed the standard methodology to develop our interpretive model and strategy roadmap, the following limitations should be taken into consideration while interpreting the results:

- The roadmap is limited to the contextual properties under which it has been developed, particularly concerning the experts' demographics.
- Although the study identified the sequential relationships between each pair of functions, it could not conclusively determine the strength of the relationships, mainly due to the limitation of the ISM methodology.
- The functions introduced root in the early contributions of the literature to the Industry 5.0 phenomenon. This topic is new and evolving, and literature on Industry 5.0 is equally embryonic. We expect the width and breadth of the Industry 5.0 sustainability functions to grow in the future considerably.
- The study explained how Industry 5.0 could function in promoting sustainable development. Nonetheless, it was unconscionable for the present study to explain how industries and businesses should transform from Industry 4.0 or even older industrial frameworks to Industry 5.0.

In addition, and despite our efforts, much is unknown about how this phenomenon will unfold in the future. Thus, future research is invited to extend our work in the following manners. Due to methodological constraints, we merely drew on the opinions of European experts to identify the contextual relationships among the functions. Although Industry 5.0 is primarily a European initiative, we expect it to become a global reality as Industry 4.0 once did. Using the opinion of a broader spectrum of experts from various socio-economic contexts and resynthesizing the relationships among the sustainable development functions of Industry 5.0 can serve as an important avenue for future research.

While we acknowledge that Industry 5.0 has the capacity to promote sustainable development, it is not a self-propelled phenomenon. Indeed, our model described a hypothetical best-case scenario where all necessary conditions for materializing Industry 5.0 were in place. Although the transition toward this phenomenon has already begun, especially in Europe as well as in Japan (under Society 5.0), the materialization and success of Industry 5.0 rely on several necessary actions and vital requirements. Industry 5.0 requires the implementation of necessary technologies, mainly emerging technological innovations. While industry leaders excel in this area, industrial reports indicate that average businesses, particularly smaller ones, still struggle with implementing basic Industry 4.0 technologies. This condition requires inclusive technology diffusion initiatives across various regions and industries to empower impartial and fair technological advancement of value networks. However, Industry 5.0 is in its infancy, and such a supportive technological development agenda appears to be lacking. Future research is invited to explore how Industry 5.0 technology development and implementation roadmap should be developed to support open innovation, shared research, and collaborative technology diffusion initiatives across regions. In addition, Industry 5.0 is partly a technology-driven phenomenon, which relies on value network-wide integration, interconnectivity, and data-driven operations. The high pace of digital transformation under Industry 5.0 renders cybersecurity a vital enabler of this phenomenon. The width and breadth of cyber risks under Industry 5.0 call for future research on secure and resilient approaches to cybersecurity.

The reference model identified the crucial role of Industry 5.0 stakeholders, explaining that transition into this phenomenon entails supportive policies in several areas, such as society, culture, innovation, education, government operations, energy, economic affairs, environment, and taxation. The collective and synergetic development of these policies falls outside the remit of individual stakeholders (e.g., governments or labor unions), requiring bilateral and, in many instances, multilateral cooperation among Industry 5.0 stakeholders. The underlying mechanism through which stakeholders can collaborate to develop meaningful Industry 5.0 supportive policies and regulations is largely unknown. Therefore, identifying how the power of public-private stakeholder collaboration can be harnessed for shaping Industry 5.0 supportive policies, initiatives, and regulatory frameworks represents an important avenue for future research.

Finally, yet importantly, experts believe that much like the Government 5.0 concept signifying the government's new role in promoting Industry 5.0, this phenomenon requires a new form of corporate governance. Indeed, Corporate Governance 5.0 is indispensable since the Industry 5.0 transition requires corporations to fundamentally change their mindset, strategies, and objectives. Under Industry 5.0, businesses should transition from shareholder primacy to stakeholder capitalism, emphasizing less on short-term economic gains and prioritizing shared value. This requires aligning corporate initiatives with Industry 5.0 sustainable development objectives, deliverable via a transformative corporate governance model. While there is a general agreement on the necessity of Corporate Governance 5.0, there is little to no understanding of how such sustainable corporate governance frameworks could be developed. Future research can address this knowledge gap by conducting in-depth analyses of how businesses can integrate sustainable development values of Industry 5.0 into their corporate strategies and develop measurable indices to assess their progress toward those values.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Self-assessment questionnaire

1. How familiar do you consider yourself with the Industry 5.0 framework proposed by the European Commission?
2. How familiar do you consider yourself with Industry 5.0 scientific and industrial background?
3. How familiar do you consider yourself with the mechanisms through which Industry 5.0 can promote sustainable development?
4. Please briefly explain your past collaboration with the European Commission that might somehow relate to Industry 5.0-driven sustainability (Examples may include collaboration as principal investigator, senior researcher, or advisory board on related topics such as technology governance, digital transformation, Industry 4.0, sustainability, digitally-driven circular economy, or resilient economy).
5. Your contribution would involve participating in six online expert panel meetings. Each meeting would approximately take 70 min. Assuming that the meeting dates would be tailored to your schedule, how likely would it be for you to commit to every single expert panel meeting?
6. How would you rate your English proficiency for engaging in oral and written discussions across the six expert panel meetings?

Table A1
Hierarchy level for sustainable development functions of Industry 5.0.

Function	Reachability set	Antecedent set	Intersection set	Extraction level
Iteration 1				
BPM[a]	BPM, CIP, ORE, RIN, SCA, SOP	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	BPM	
CIP	CIP, ORE, RIN, SCA	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	CIP, RIN	
DST	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCA, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	BPM, CIP, ETA, ORE, OSI, RIN, SCA, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
INA	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, SCA, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
ORE	ORE, SCA	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCM, SII, SOP, STH, UPR, VUI	ORE	
OSI	BPM, CIP, ETA, ORE, OSI, RIN, SCA, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, VUI	ETA, OSI, STH	
RIN	CIP, ORE, RIN, SCA, SOP	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SII, SOP, STH, VUI	CIP, RIN, SOP	
RTC	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCA, SCM, SOP, STH, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCA	SCA	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCA, SCM, SII, SOP, STH, VUI	SCA	*1*
SCM	BPM, CIP, ORE, SCA, SCM, SOP	INA, RTC, SCM, SII, VUI	SCM	
SII	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCA, SCM, SII, SOP, STH, UPR, VUI	SII	SII	
SOP	CIP, ORE, RIN, SCA, SOP	BPM, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	RIN, SOP	
STH	CIP, ETA, ORE, OSI, RIN, SCA, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
UPR	BPM, ETA, ORE, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, STH, UPR	
VUI	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCA, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 2				
BPM	BPM, CIP, ORE, RIN, SOP	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	BPM	
CIP	CIP, ORE, RIN	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	CIP, RIN	
DST	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	BPM, CIP, ETA, ORE, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
INA	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
ORE	ORE	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCM, SII, SOP, STH, UPR, VUI	ORE	*2*
OSI	BPM, CIP, ETA, ORE, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, VUI	ETA, OSI, STH	
RIN	CIP, ORE, RIN, SOP	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SII, SOP, STH, VUI	CIP, RIN, SOP	
RTC	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCM, SOP, STH, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCM	BPM, CIP, ORE, SCM, SOP	INA, RTC, SCM, SII, VUI	SCM	
SII	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCM, SII, SOP, STH, UPR, VUI	SII	SII	
SOP	CIP, ORE, RIN, SOP	BPM, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	RIN, SOP	
STH	CIP, ETA, ORE, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
UPR	BPM, ETA, ORE, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, STH, UPR	
VUI	BPM, CIP, DST, ETA, INA, ORE, OSI, RIN, RTC, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 3				
BPM	BPM, CIP, RIN, SOP	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	BPM	
CIP	CIP, RIN	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	CIP, RIN	*3*
DST	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	BPM, CIP, ETA, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
INA	BPM, CIP, DST, ETA, INA, OSI, RIN, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
OSI	BPM, CIP, ETA, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, VUI	ETA, OSI, STH	
RIN	CIP, RIN, SOP	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SII, SOP, STH, VUI	CIP, RIN, SOP	*3*

Table A1 (*continued*)

Function	Reachability set	Antecedent set	Intersection set	Extraction level
RTC	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SOP, STH, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCM	BPM, CIP, SCM, SOP	INA, RTC, SCM, SII, VUI	SCM	
SII	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, UPR, VUI	SII	SII	
SOP	CIP, RIN, SOP	BPM, DST, ETA, INA, OSI, RIN, RTC, SCM, SII, SOP, STH, VUI	RIN, SOP	
STH	CIP, ETA, OSI, RIN, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
UPR	BPM, ETA, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, STH, UPR	
VUI	BPM, CIP, DST, ETA, INA, OSI, RIN, RTC, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 4				
BPM	BPM, SOP	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	BPM	
DST	BPM, DST, ETA, INA, OSI, RTC, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	BPM, ETA, OSI, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
INA	BPM, DST, ETA, INA, OSI, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
OSI	BPM, ETA, OSI, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, VUI	ETA, OSI, STH	
RTC	BPM, DST, ETA, INA, OSI, RTC, SCM, SOP, STH, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCM	BPM, SCM, SOP	INA, RTC, SCM, SII, VUI	SCM	
SII	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, SOP, STH, UPR, VUI	SII	SII	
SOP	SOP	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, SOP, STH, VUI	SOP	*4*
STH	ETA, OSI, SOP, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
UPR	BPM, ETA, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, STH, UPR	
VUI	BPM, DST, ETA, INA, OSI, RTC, SCM, SOP, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 5				
BPM	BPM	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	BPM	*5*
DST	BPM, DST, ETA, INA, OSI, RTC, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	BPM, ETA, OSI, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	
INA	BPM, DST, ETA, INA, OSI, SCM, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
OSI	BPM, ETA, OSI, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, VUI	ETA, OSI, STH	
RTC	BPM, DST, ETA, INA, OSI, RTC, SCM, STH, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCM	BPM, SCM	INA, RTC, SCM, SII, VUI	SCM	
SII	BPM, DST, ETA, INA, OSI, RTC, SCM, SII, STH, UPR, VUI	SII	SII	
STH	ETA, OSI, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, OSI, STH, UPR	*5*
UPR	BPM, ETA, STH, UPR	DST, ETA, INA, OSI, RTC, SII, STH, UPR, VUI	ETA, STH, UPR	
VUI	BPM, DST, ETA, INA, OSI, RTC, SCM, STH, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 6				
DST	DST, ETA, INA, OSI, RTC, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
ETA	ETA, OSI, UPR	DST, ETA, INA, OSI, RTC, SII, UPR, VUI	ETA, OSI, UPR	*6*
INA	DST, ETA, INA, OSI, SCM, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
OSI	ETA, OSI, UPR	DST, ETA, INA, OSI, RTC, SII, VUI	ETA, OSI	
RTC	DST, ETA, INA, OSI, RTC, SCM, UPR, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SCM	SCM	INA, RTC, SCM, SII, VUI	SCM	*6*
SII	DST, ETA, INA, OSI, RTC, SCM, SII, UPR, VUI	SII	SII	
UPR	ETA, UPR	DST, ETA, INA, OSI, RTC, SII, UPR, VUI	ETA, UPR	*6*
VUI	DST, ETA, INA, OSI, RTC, SCM, UPR, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 7				
DST	DST, INA, OSI, RTC, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
INA	DST, INA, OSI, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	
OSI	OSI	DST, INA, OSI, RTC, SII, VUI	OSI	*7*
RTC	DST, INA, OSI, RTC, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SII	DST, INA, OSI, RTC, SII, VUI	SII	SII	
VUI	DST, INA, OSI, RTC, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	
Iteration 8				
DST	DST, INA, RTC, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	*8*
INA	DST, INA, VUI	DST, INA, RTC, SII, VUI	DST, INA, VUI	*8*
RTC	DST, INA, RTC, VUI	DST, RTC, SII, VUI	DST, RTC, VUI	
SII	DST, INA, RTC, SII, VUI	SII	SII	
VUI	DST, INA, RTC, VUI	DST, INA, RTC, SII, VUI	DST, INA, RTC, VUI	*8*

(*continued on next page*)

Table A1 (*continued*)

Function	Reachability set	Antecedent set	Intersection set	Extraction level
Iteration 9				
RTC	RTC	RTC, SII	DST	*9*
SII	RTC, SII	SII	SII	
Iteration 10				
SII	SII	SII	SII	*10*

[a] Note: BPM, business process monitoring; CIP, circular intelligent products; DST, data sharing and transparency; ETA, employee technical assistance; INA, intelligent automation; ORE, operational and resource efficiency; OSI, open sustainable innovation; RIN, renewable integration; RTC, real-time communication; SCA, supply chain adaptability; SCM, supply chain modularity; SII, system integration and interoperability; SOP, service-orientation and personalization; STH, sustainable thinking; UPR, upskilling and reskilling; VUI, value network integration.

Table A2
Interpretive logic-knowledge base matrix for sustainable development functions of Industry 5.0.

Contextual relationship	Enabling role
System integration and interoperability (SII)	
SII → BPM	Streamlined problem situation detection; streamlined data transfer via various interfaces
SII → DST	Reduced data hoarding; data scalability and availability; improved data visibility
SII → ETA	Improved employee-machine integration; improved data accessibility of operators; better understanding and capturing of human elements in unstructured/structured data contexts
SII → INA	Integration of intelligent process components; better integration of AI and robotic process automation modules
SII → RIN	Better integration of energy generation technologies; integration of adaptive energy storage technologies; integration of hybrid energy generation and delivery technologies
SII → RTC	Improved data packet priority prioritization; Improved communication paths, availability, and fault tolerance
SII → SCA	Information accessibility across the value network; improved connectivity with cloud infrastructure; improved synchronization and connectivity of data collection, transformation, aggregation, and analytics layer
SII → SCM	Improved supply chain module monitoring; improved customer and supplier module integrability; elimination of data silos, and improved data integrity
SII → SOP	Improved accessibility and aggregation of supply chain-wide contextual data
SII → VUI	Integrability and connectivity of smart products, machinery, production facilities, warehousing infrastructure, smart customers, and distribution modules
SII → SUD	Integration of human-centered technologies; deployment of distributed energy resources; better integration of customer preferences; IT/OT operational efficiency
Real-time communication (RTC)	
RTC → BPM	Real-time monitoring of application and technical related business functions; real-time monitoring of technical infrastructure and data transfer
RTC → CIP	Real-time monitoring and analysis of product life cycle performance; real-time collaborative product visualization and design; facilitating reuse and recycling via real-time product structure record management
RTC → DST	Real-time visibility of organizational assets; instant access to modular data points; accessibility of hard-to-get data across the value network; business agility; improved business disruption sensing
RTC → ETA	Improved human-information processing capabilities; improved man-machine interconnection and integration; real-time monitoring and recognition of working environment conditions
RTC → INA	More efficient accessing and analysis of structured and unstructured data; better leveraging of AI insights for handling complex tasks; closed-loop real-time data exchange between automation subsystem
RTC → RIN	Real-time grid integration of renewable energy sources; visibility into renewable energy generation infrastructure; real-time energy pricing management; real-time energy source availability assessment
RTC → SCA	Data-driven early trend and disruption forecasting; data accessibility across supply chain modules; streamlined end-to-end process risk assessment; eliminating information and functional silos across the supply network
RTC → SOP	Transitioning toward service-oriented business models such as product-as-a-service or cloud manufacturing; introduction of smart products to the business model
RTC → SUD	Real-time risk and failure monitoring; real-time environmental performance assessment; improved customer experience
Value network integration (VUI)	
VUI → BPM	Value network-wide detection and management of process disruptions; improved quality and performance of business process execution across the supply network
VUI → CIP	Interorganizational communication of knowledge concerning the design, features, performance, and end-of-life plans of smart sustainable products; integration of smart sustainable product innovation into business models
VUI → DST	Improved information access; streamlined information flow across supply partners and customers; trust-driven information sharing; higher data reliability
VUI → INA	Supply chain-wide intelligence and automation investment alignment; collaborative automation and digitalization strategic planning; shared resources for intelligent automation
VUI → ORE	Clear communication among various supply chain functions; streamlined supply chain planning; supply chain waste reduction (e.g., via warehousing efficiency, reduction of time to market, or higher operational reliability)
VUI → OSI	External collaboration for improving ideation and problem-solving capabilities; improved customer exploration, collaborative ideation, and developing actionable plans for addressing customer needs
VUI → RIN	Flexible response to energy supply-demand balance variability and uncertainty; security of renewable energy supply; collaborative renewables procurement strategies; collaborative renewable investment risk management
VUI → RTC	Interoperability of independent logistics and supply chain modules/subsystems; standardization of communication protocols
VUI → SOP	Customer-oriented collaborative product design; cost-efficiencies through supply chain optimization; improved customer management and access to customer and product behavior data
VUI → SUD	Resource consumption efficiency; supply chain resilience; sustainability talent management; material flow efficiency; waste and pollution reduction; circular production and supply chain
Data sharing and transparency (DST)	
DST → BPM	Transparency of end-to-end processes based on predefined key performance indices; visibility into business operations, and early detection of process disruptions
DST → CIP	Improved information sharing and collaboration among circular product development teams; facilitating circular consumption models such as collaborative

Table A2 (*continued*)

Contextual relationship	Enabling role
	consumption
DST → ETA	Information-driven employee empowerment; improved decision-making capabilities of employees
DST → OSI	Streamlined idea and intellectual property sharing for collaborative innovation; development of open idea ecosystems
DST → RIN	Better communication of benefits and impacts of renewable integration to stakeholders; visibility into impacts, costs, and difficulties associated with various reviewable integration strategies; streamlined partnership for reviewable innovation and growth
DST → SCA	Supply chain openness to change; proactive supply chain threat/disruption discovery and analysis; streamlined stakeholder interactions and integration for better adapting to dynamic environmental (especially new market) conditions
DST → STH	Communication of prevailing sustainability challenges; understanding of the need for transitioning from neoliberal capitalism and profit-centricity toward more shareholder primacy and circular economic models
DST → UPR	Better highlighting of the value of upskilling and reskilling; breaking resistance toward learning among the workforce; communicating the objectives and benefits of training programs; better alignment of the human resource team with training requirements
DST → VUI	Building trust in supply chain relationships; accessibility of factual information concerning various internal and external supply chain operations; elimination of information and functional silos; shared development of integration goals and performance metrics
DST → SUD	Customer reassurance and satisfaction; improved stakeholder partnership; productivity-driven competitive advantage; ethical value creation and fighting child/forced labor; sustainability performance monitoring; sustainability skill gap identification
Intelligent automation (INA)	
INA → BPM	Improved integration with process architecture part under the enterprise systems; better integration with process engines for process monitoring; improved cognitive capabilities of employees
INA → DST	Automated data collection, processing, and exchange; reduced data errors; improved data security; data clarity and accuracy; improved energy demand-side management
INA → ETA	Automation of repetitive and labor-intensive tasks; improved employee experience, engagement, and empowerment; increasing employee performance while minimizing human errors
INA → ORE	Higher process efficiency; optimization of back-office operations; operational risk and failure reduction; customer service productivity; reduction of end-to-end business process times
INA → RIN	Automation of renewable equipment production; improved consumption and demand forecasting via integrated application of self-learning models, historical/real-time sensor-driven data, and cloud information; improved grid management
INA → SCA	Improved supply chain resource orchestration; reconfigurability of supply chin modules and system components; automation, decentralization, and integration of decision processes
INA → SCM	Decentralized decision-making capability of supply chain modules; autonomous data transfer among disparate supply chain systems; improved responsiveness of supply chain modules
INA → UPR	Identification of training priorities; autonomous and data-driven identification and forecasting of skill gaps; data-driven development of career development paths; autonomous skill assessment
INA → SUD	Improving operational efficiency; economic transparency; facilitating energy transition; waste and emission reduction; more resilient industrial operations; resource productivity
Open sustainable innovation (OSI)	
OSI → CIP	Communicating sustainability objectives and knowledge across the value network; commercial development and implementation of cleaner and energy-aware operations technology, non-polluting raw material, remanufactured components, and recycled material
OSI → ETA	Development and implementation of employee (operator) assist technologies; prioritizing human-centric approaches to business, operations, and technology management
OSI → RIN	Open collaboration for promoting renewables innovation; innovation for structural development for renewables localization and integration; collective investment in renewables research and development; leveraging external knowledge by stakeholders to increase renewables innovation performance
OSI → SCA	Supply chain-wide audit of sustainability initiatives; demand-driven and collaborative eco-friendly product and process innovation
OSI → SOP	Customer-centric innovation; open collaboration for customer-oriented product and process innovation; re-vectoring business model for implementing servitization strategies
OSI → UPR	Strategies for developing necessary skillsets for long-term employability; development of employee-friendly training technologies and platforms
OSI → SUD	Improved customer satisfaction, experience, and rights; employment growth; equal employment opportunity; sustainable partnership; sustainable innovation growth
Upskilling and reskilling (UPR)	
UPR → ETA	Improving employees' capability to integrate and interact with emerging disruptive technologies; enhancing employees' technological self-efficacy and self-realization
UPR → SUD	Improved workforce digital literacy; reduction of job complexity; improved job security; reducing skill discrepancies; income equality; new employment opportunities; minimizing job displacement
Employee technical assistance (ETA)	
ETA→ BPM	Better access to employee performance data for business process optimization; improved employee tracking for preventing errors and risks
ETA→ ORE	Higher employee productivity; workforce time efficiency; reduction of human errors; efficient decision making
ETA→ STH	Improved sustainability decision processes; providing employees with valuable sustainability knowledge; enhancing the sustainability-oriented absorptive capacity of individuals
ETA→ SUD	Improving working environment; workplace dignity; improved job satisfaction; reduced work accidents; employee productivity
Supply chain modularity (SCM)	
SCM → BPM	Decentralized monitoring procedures across technical components; faster problem identification and proactiveness in addressing risks and problems; flexibility in addressing process disruptions
SCM → ORE	Faster infrastructural and product adaptation to market turbulence; operational agility and scalability; reduction of supply chain complexity
SCM → SCA	Higher responsiveness of logistics processes and operations; supply chain flexibility and agility; adaptable supply chain capabilities
SCM → SOP	Production infrastructure flexibility and reconfigurability for rapid integration of new product designs; adaptability of sourcing and delivery channels to the shifting consumer preferences and demands
SCM → SUD	Supply chain resilience; supply chain productivity and profitability
Sustainable thinking (STH)	
STH → CIP	Capacity to involve critical stakeholders in sustainable product innovation; identifying the product sustainability priorities and developing necessary initiatives; collaborative sustainability benchmarking of smart products

(continued on next page)

Table A2 (*continued*)

Contextual relationship	Enabling role
STH → OSI	Cleaner objectives for innovation externalization; positive attitude toward collaborative innovation; improved commitment and participation; supportive public-private partnerships
STH → RIN	Sectorial, regional, and international innovation system approaches to supporting renewables; developing a comprehensive policy mix for supporting energy system transformation toward renewables; prioritizing reviewable integration by individual consumers, business units, and supply networks
STH → SOP	Inclusive change management for processes, technologies, and people; developing actionable objectives for the development of connected and customer-oriented products and processes; collaborative market sensing for smart, sustainable, and customizable products and services
STH → UPR	Equitable reskilling and upskilling opportunities; supportive policies for promoting skilling and upskilling training opportunities; introducing reskilling and upskilling as social-economic responsibility
STH → SUD	Equipping social actors with knowledge, competencies, skills, values, and behavior for contributing to the sustainable and circular economy; alleviating overconsumption; Social actors' engagement in monitoring the progress of sustainable development goals
Business process monitoring (BPM)	
BPM → CIP	Improved end-of-life product recovery; higher reliability and quality of smart sustainable products; improved prototyping and mass production of smart sustainable products; performance monitoring of smart sustainable products
BPM → ORE	Identifying and addressing root causes of performance issues; lower equipment and machinery downtime; avoiding legal liabilities; reduced material and energy variability; higher product quality
BPM → SCA	Efficiency of reactive and proactive decision-making processes; proactive and data-driven demand responsiveness; better forecasting of supply chain disruption scope and scale of impact; better monitoring and control of supply chain risk and failure factors
BPM → SUD	Improved resilience against business disruptions; end-to-end environmental transparency of business operations; risk and waste-averse business processes; safer and smarter working environment
Service-orientation and personalization (SOP)	
SOP → CIP	Acceptance of new smart sustainable products by customers; improved data acquisition, mapping, and profiling of smart products for sustainability performance improvement
SOP → ORE	Demand reliability; on-demand scalability; efficiency of customer service; marketing efficiency; cash flow reliability
SOP → SUD	Improved energy and material consumption; business resilience; customer satisfaction; new employment opportunities; improved customer experience; promoting circular economy
Renewable integration (RIN)	
RIN → CIP	Less carbon-intensive products; ease of end-of-life recovery, recycling, remanufacturing, or repurposing
RIN → SUD	Preventing environmental degradation; pollution and emission reduction; regional economic development; localized value generation; inclusive and equitable energy accessibility
Circular intelligent products (CIP)	
CIP → ORE	Extended product life cycle; improved product recyclability or reusability; product development or updating efficiency; streamlined product maintenance and after-sale services
CIP → RIN	Integrability with modular renewable energy systems; synchronization of energy consumption needs with renewable energy grids
CIP → SCA	Data-driven forecasting of consumers' future demand and preferences; more adaptable business models; better sensing of imminent market disruptions or opportunities
CIP → SUD	Energy consumption efficiency; prolonged product life-cycle; promoting consumer digital literacy; emission reduction; waste reduction; improved end-of-life recovery
Operational and resource efficiency (ORE)	
ORE→ SCA	Operational cost efficiency; operational agility in implementing the necessary change processes and action plans; product mix adaptability and expandability
ORE→ SUD	Improved resource and energy footprints of industrial operations; economic, supply chain, and business-level resilience; reduction of industrial and post-consumer waste; reduced rebound effect; facilitating circular economy
Supply chain adaptability (SCA)	
SCA → SUD	Economic resilience; supply chain productivity; job security and stability; improved product accessibility; sustainable supply chain processes

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Areas of research interest

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Scientific papers

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