Heliyon 10 (2024) e39132

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Strategies to enhance the corporate innovation resilience in digital era: A cross-organizational collaboration perspective

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ARTICLE INFO

Keywords:
Innovation resilience
Cross-organizational collaboration
Market-based cooperation
Science-based cooperation
Digital transformation
Current assets

ABSTRACT

The current economic environment is characterized by increasing uncertainty, while digitalization has led to profound transformations in both the economy and society. There is a pressing need to conduct an in-depth investigation into the specific effects of cross-organizational cooperation on firms' innovation resilience (FIR) in the digital era, as well as the underlying mechanisms driving these effects. This study utilizes panel data encompassing 30 Chinese provinces and municipalities, intending to analyze the impact of market-based and science-based cross-organizational cooperation on FIR and explore the heterogeneity of this impact. Moreover, the study examines the mediating and moderating mechanisms that influence the relationship between cross-organizational cooperation and FIR. The findings indicate that both market-based cooperation, including cooperation with suppliers (CS) and cooperation with customers (CC), and science-based industry-university-research cooperation (IURC) significantly enhance FIR, with science-based IURC demonstrating the most pronounced effect. Additionally, it is revealed that the impact of market-based and science-based cross-organizational cooperation exhibits spatial heterogeneity in promoting FIR. Market-based and science-based cross-organizational cooperation effectively improves enterprise liquidity, enhances operational efficiency, and consequently enhances innovation resilience (IR). Moreover, the positive impact of cross-organizational cooperation on FIR is amplified by increasing the degree of digital transformation and digital technological innovation.

1. Introduction

Over the past decade, the escalation in the frequency of major emergencies and the growing uncertainty in the global economic landscape have profoundly impacted the regional economy and individual businesses. These impacts include economic downturns, declines in productivity, and business failures [1–3]. The market environment has become characterized by VUCA (variable, uncertain, complex, and ambiguous) conditions, making resilience gradually supplant profit as the primary objective pursued by enterprises [4]. Consequently, an increasing number of scholars have begun to focus on firm resilience. Originally rooted in engineering mechanics, resilience refers to a substance's property to return to its original state after changing pressure. Due to its versatile applicability, the concept of resilience has been subsequently employed in disciplines such as psychology, environmental science, medicine, and regional economics [5]. Meyer [6] was the first to introduce resilience into the management field, opening the study of firm resilience.

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https://doi.org/10.1016/j.heliyon.2024.e39132
Received 18 December 2023; Received in revised form 25 September 2024; Accepted 8 October 2024
Available online 9 October 2024

Although a definitive definition of firm resilience remains elusive, Sanchis and Poler [7] posited that it is the proactive ability of firms to react to disruptive events, adapt to shocks, and recover from them. Meanwhile, Gilly et al. [8] defined resilience as the ability to withstand shocks or limit their impacts, ultimately adapting to these shocks and evolving rapidly. In summary, while these definitions differ in expression, they all fundamentally encompass organizations' ability to withstand and recover from shocks. Prior research has demonstrated that more resilient firms, equipped with ample resource reserves and superior adaptability, are often capable of enduring risks and even thriving amidst adversity [4]. Conversely, less resilient firms are prone to vulnerability when confronted with external shocks.

Notably, in the face of crises, it becomes difficult for firms to quickly acquire new resources and capabilities to effectively deal with them. Innovation, which not only involves the creation of new products and services but also the accumulation and iteration of knowledge and technology, can provide firms with a competitive advantage. Consequently, researchers have sought to incorporate innovation into the study of resilience. Oeij et al. [9] were the first to discuss the management of innovation in conjunction with resilience. They proposed the concept of "innovation resilience," which pertains to the ability of organizations to withstand and rectify ineffective innovation processes or external shocks, thereby reestablishing their trajectory. Taking this idea further, Lv et al. [10] perceived innovation resilience (IR) as an organization's capacity to navigate the uncertainties associated with its innovation activities, achieved through enhancing stability and adaptability. Wziątek-Kubiak and Pęczkowski [11] emphasized that resilience in innovation for firms is a dynamic and ongoing process, and they regard IR as the capability of firms to persistently innovate and accumulate knowledge in turbulent environments, while simultaneously developing new functionalities throughout the process. Drawing on various existing perspectives on IR, including its characteristics, outcomes, capabilities, and processes, Liang and Liu [12] defined corporate IR as the ability of an enterprise to mitigate or reduce the negative impacts of external shocks and maintain a stable and sustainable development of its innovation system. In complex and volatile environments, the ability to respond to change and continuously develop new knowledge is crucial for firm success. Moreover, more innovative firms are better positioned to enhance their survival prospects by effectively translating crisis experiences into actionable innovations. Prior research has primarily centered on evaluating organizational resilience, supply chain resilience, and economic resilience [13,14]. However, there has been relatively limited attention given to exploring corporate IR from a scholarly perspective. Furthermore, scant literature has delved into the examination of factors and mechanisms that facilitate firm innovation resilience (FIR). Consequently, this study seeks to investigate the direct impact of cross-organizational collaboration on FIR, taking into account the potential moderating role of digital transformation.

Adapting to external shocks typically necessitates collaboration to drive innovation in products, technologies, or services, thereby enhancing a company's survival prospects in the face of disruptive events [15]. Priego-Roche et al. [16] explored partnerships starting from organizational boundaries, including intra-organizational, inter-organizational, and extra-organizational relationships. Intra-organizational relationships refer to interactions among departments within a company, while inter-organizational relationships encompass collaborations with other companies within a group (e.g. joint operation or partnership). Extra-organizational relationships pertain to interactions with external entities or companies, such as universities, suppliers, and customers. Intra-organizational collaboration is a dynamic process, with varying degrees of internal collaboration impacting collaboration outcomes. Due to shared company or group affiliation, internal and inter-organizational partners can establish strong mutual understanding and trust. However, when unforeseen events occur, resource constraints internally challenge a company's resilience, prompting the need to transcend organizational boundaries and establish relationships with external partners. Engaging in cross-organizational collaboration with external partners enables companies to access additional innovation resources, and integrate diverse knowledge and skills from all stakeholders, thereby enhancing innovation capabilities and resilience, particularly beneficial for small and medium-sized enterprises [17]. According to the China Enterprise Innovation Survey Yearbook (2021), 34.7 % of enterprises opt for innovation collaboration with partners. The top three choices for partners are customers, suppliers, and universities, representing 45.8 %, 40.8 %, and 28.8 % of enterprises engaging in innovation collaboration, respectively. Previous literature also indicates that transcending organizational boundaries for cross-organizational collaboration and open innovation fosters innovation processes and novelty, enhancing the financial performance of research and development projects [18].

Numerous previous studies have focused on the relationship between cross-organizational cooperation and innovation or resilience, with an emphasis on collaboration with suppliers or customers (CS or CC) as well as Industry-university-research cooperation (IURC) [19,20]. Therefore, this study incorporates the collaboration practices identified by Ref. [21] by selecting market-based collaboration and science-based collaboration. Market-based collaboration involves cooperation with suppliers and customers (CS and CC) to involve them in the process of enhancing IR. On the other hand, science-based collaborations entail partnerships with universities and research institutions. Additionally, differences in value orientation and goal orientation exist among different cooperation subjects, with enterprises being market-oriented and focusing on technology commercialization, while universities and research institutes are science-oriented and emphasize innovation in basic and applied research. Moreover, there are heterogeneous and complementary resource differences between different cooperation subjects. These differences result in varied effects for firms choosing different cooperation subjects to participate in enhancing IR. Previous studies do not unanimously agree on which type of cooperation is more effective. While some studies suggest that UIRC plays a more positive role in enhancing innovation than market-based collaborations [22], others have found contrasting results, suggesting that CS and CC are more effective than IURC [18,23]. These discrepant findings prompt further investigation. Indeed, our study aims not only to analyze the impact of cross-organizational collaboration on enhancing FIR but also to explore further which type of collaboration is most effective. In addition, enhancing liquidity and increasing revenue are crucial indicators of the effectiveness and benefits of cross-organizational cooperation for firms. Through robust cross-organizational cooperation, companies can enhance their financial performance and optimize their capital flow, thereby safeguarding their research and development (R&D) investments and mitigating risks [24]. Therefore, to comprehensively comprehend the underlying mechanisms by which cross-organizational cooperation influences FIR, it is imperative to investigate whether current assets and primary business income serve as mediators in the relationship between cross-organizational cooperation and FIR.

Finally, with the advent of the digital age, there have been significant advancements in digital and communication technologies worldwide, leading to profound changes in the economy and society [25]. Businesses are increasingly recognizing the importance of digitalization and embracing digital transformation. The manufacturing industry, in particular, has undergone a fundamental transformation in its production methods as a result of digitalization [26]. The use of digital technologies such as big data and the industrial Internet has enhanced production and management efficiency and convenience, becoming a key factor for enterprises to gain a competitive advantage. Digital transformation is commonly discussed in the literature in terms of firms' production capabilities, operating models, organizational structures, and business development strategies [27,28]. While some research touches on partnerships [29], few studies have specifically focused on the role of digital transformation in the impact of cross-organizational cooperation on FIR. Digital transformation encompasses the integration of information, computing, communication, and connectivity technologies. It involves converting business-generated information into a digital format that can be easily collected, processed, disseminated, accessed, and exchanged within and outside the organization, ultimately leading to actionable knowledge. Through digital technological innovation, digital transformation enables a new pattern of networking, three-dimensionality, and informatization in the innovation body of the value chain. This, in turn, facilitates cooperation and innovation between enterprises and stakeholders such as suppliers, customers, and universities [26]. Recent research highlights the importance of digital transformation. For example, various studies argued that digital transformation enhances the transparency, visibility, and responsiveness of supply chains, thereby contributing to supply chain resilience [30,31]. Han & Trimi [32] also suggested that digital transformation improves small and medium-sized enterprises' collaboration with other organizations, enhancing their agility and adaptability to cope with complex and evolving market environments. Thus, in addition to examining the direct relationship between cross-organizational collaboration and FIR, we also explore the moderating influence of digital transformation and digital technology innovation.

Overall, this study of FIR hopes to achieve several objectives. Firstly, as there has been limited focus on firm innovation resilience it is worthwhile to explore whether market-based cross-organizational cooperation or science-based IURC has a stronger or weaker impact on FIR. Therefore, this study, based on the construction of an innovation resilience composite index using the entropy weight TOPSIS method, aims to explore the impact relationship of cross-organizational cooperation on FIR from two different driving modes of cooperation. Secondly, in the digital era, digital transformation brings great changes at the business level. It is important to conduct further analysis on how this digital transformation impacts FIR. Therefore, we reveal the mechanisms of moderating and mediating effects under this influence relationship based on benchmark regression analysis, thus deepening the understanding of the impact of cross-organizational cooperation on FIR in the digital era.

The rest of the paper is presented below. Section 2 presents the literature review related to the study and formulates the hypotheses. Section 3 presents the research methodology and data. Section 4 shows the empirical results. Then, the mechanism analysis is carried out in Section 5. Finally, the paper discusses and concludes the study and presents recommendations in the last Section.

2. Literature review and hypotheses

2.1. The relationship between cross-organizational collaboration and FIR

The ability to adapt to uncertain shocks and continually acquire new knowledge is crucial for the success of enterprises in the "VUCA" era. Some scholars view firm resilience as the capacity of a firm to withstand and grow from adversity through preparation, adaptation, and learning [33,34]. From a duality perspective, Lv et al. [10] contend that stability and adaptation are crucial components of IR. Furthermore, Liang and Liu [12] defined the specific attributes of FIR, namely flexibility, continuity, and creativity. Flexibility refers to a firm's ability to swiftly and adaptively adjust its innovation strategy to anticipate and respond to shocks, effectively buffering and mitigating the impact of uncertainty [12]. This concept combines the aspects of "robustness" and "agility" within enterprise resilience, emphasizing their mutually reinforcing nature within time and space. Flexible firms can effectively mitigate the impact of external shocks. Continuity denotes the ability to maintain a consistent flow of innovative inputs and outputs. By establishing strong and reliable networks with external stakeholders such as universities, suppliers, and customers, firms can acquire valuable resources and technologies during times of shock, thereby stabilizing their innovation outcomes. Creativity represents the ability to not only recover innovative performance after a shock but to consciously evolve [12]. Strong IR enables firms to transform crisis-induced knowledge into a competitive advantage, propelling them forward.

From a resource perspective, grounded in resource-based theory, resource constraints are considered critical in limiting firms' recovery and rebounding from shocks. Due to the complexity and uncertainty of innovation, most firms are unable to generate all the necessary resources internally, leading them to engage in cross-organizational cooperation to exchange resources and optimize resource allocation. For instance, in the traditional manufacturing industry, companies often select logistics partners with high timeliness, carrying capacity, and informatization levels [35]. Additionally, resources are heterogeneous and challenging to imitate outside the original organization, incurring costs and time. Hence, firms can collaborate with other organizations possessing unique resources to gain competitive advantages within their respective markets. Furthermore, knowledge stands as the most important strategic resource for an organization and a core element of innovation [36]. Hosseini et al. [37] employed a structural equation modeling approach to investigate the impact of resilience on the performance of information technology-based knowledge-intensive enterprises, with a focus on resilient structural trust capabilities, organizational dynamic capabilities, and process continuity perspectives. The study also considered the mediating role of entrepreneurial thinking. Findings revealed that, under the mediating influence of entrepreneurial thinking, knowledge-based enterprises with robust resilience exhibited significantly enhanced performance.

Firms engage in cooperation, building trust, and exchanging information, with the primary goal of acquiring valuable knowledge and information. The organization's ability to understand and integrate external knowledge and technology is referred to as absorptive capacity [38]. Absorptive capacity relies not only on in-house R&D capabilities but also on knowledge sharing. Cross-organizational cooperation establishes a knowledge-sharing environment between enterprises and external organizations. Through technology crossover, personnel exchange, and knowledge internalization, collaborating parties effectively transfer knowledge of technological innovation to each participating enterprise, thereby strengthening and updating the core technological capabilities of the firms. Thus, Hypothesis 1 is proposed as follows.

H1. Cross-organizational collaboration has a positive effect on FIR.

2.1.1. The relationship between market-based cross-organizational collaboration and FIR

In market-based collaboration, market demand serves as a crucial catalyst for firms' collaborative innovation efforts. Given the constantly evolving nature of markets and customer needs, firms aiming to maintain a long-term competitive advantage must enhance their ability to sense external changes and respond to evolving customer demands. CS and CC assume a fundamental role in promoting firm innovation and resilience. To begin with, being upstream in the supply chain, suppliers can have a big impact on corporate innovation. CS enables firms to gain a deeper understanding of the products, equipment, and technologies they provide, thereby maximizing value, reducing costs, and mitigating risks [39]. By establishing clearer communication channels with suppliers, firms can articulate their requirements more effectively, while receiving novel and enhanced products and technologies from upstream sources, ultimately driving innovation. Furthermore, suppliers can aid in reducing development cycles by supplying compatible components and ensuring the quality of new products during the production process. Secondly, customers, being positioned downstream and closer to the market, possess valuable market feedback regarding products. Consequently, CC aids firms in developing a deeper understanding of market needs, facilitating the transformation of innovative ideas into viable products [40]. Moreover, cooperative relationships with customers result in reduced sales and advertising costs, enabling firms to allocate more resources toward the development of differentiated products that better align with market demands. Crucially, suppliers, customers, and firms emerge as key stakeholders. Successful innovation outcomes generate mutual benefits for all parties involved, as suppliers observe increased sales and customers gain access to more satisfactory products. This creates strong incentives for collaborative cooperation, leading to the formation of a robust innovation network.

Resource-based theory further underscores the importance of inter-firm cooperation. Firstly, the heterogeneity and limited mobility of a firm's resources contribute to its unique value proposition. No individual firm possesses all the necessary resources required for the entire value chain, necessitating cooperation between firms and their upstream suppliers and downstream customers. This collaborative approach leads to the mutual complementation of resources, ultimately fostering sustained competitive advantages. Secondly, suppliers and customers can serve as vital sources of key resources. Collaborative relationships with suppliers and customers benefit firms through cost reduction in transactions, integration and optimization of resource allocation, enhanced operational efficiency, and improved inventory management [41,42]. Indeed, when confronted with external shocks, firms sometimes exhibit caution and reduce essential R&D expenditures, potentially disrupting innovation efforts. CS and CC can help mitigate uncertainty in the operating environment, spread risks, and enhance flexibility to effectively respond to shocks and risks. Based on the aforementioned arguments, we propose the following hypothesis.

H1a. Market-based cross-organizational collaboration has a positive effect on FIR.

2.1.2. The relationship between science-based cross-organizational collaboration and FIR

Science-based cooperation refers to the collaboration between enterprises and institutions such as universities and research institutes, which can provide fundamental and applied research, scientific knowledge, and human resources training [21]. Its essence lies in the integration of knowledge and technology from multiple actors. Universities and research institutes serve as a continuous source of scientific knowledge creation and innovation, and therefore IURC is believed to help enterprises access cutting-edge science and advanced technology, leading to mutual benefits through joint science-based research and development. Firstly, several studies have demonstrated that technological innovation heavily relies on the knowledge provided by science-based partners [43,44]. By participating in IURC partnerships, enterprises can gain access to complementary research outcomes and exchange knowledge with experts from universities and research institutions, thereby fostering innovation in their products or processes. Secondly, IURC enables the sharing of research and development costs, mitigating the risks associated with intensive R&D. Specifically, universities, and research institutes possess costly laboratories, high-quality experts, and professors. Through collaboration, firms can share these resources and knowledge, thereby reducing the cost of innovation. Muhammad et al. [45]posited that large firms had a greater capacity to facilitate research and development investments and to bear the risks associated with innovation. Arslan et al. [18]posited that cross-organizational public-private and private-private collaborations could reduce the research and development costs for biopharmaceutical companies and advance drug development initiatives. Moreover, the academic quality of partner universities has a considerable impact on firm-level innovation [46]. Thirdly, in addition to conducting scientific research, universities and research institutes play a crucial role in talent training. Through IURC, enterprises have the opportunity to access staff training and talent reserves, which significantly enhances the level of enterprise research. Finally, from the perspective of innovation creativity, and resilience, opportunities can be found within risks [12]. The robust R&D capabilities of universities and research institutes assist firms in appropriately allocating resources in unstable market environments and breaking their dependence on traditional technologies. This effectively mitigates the negative impact of external shocks on innovation. For instance, the collaboration between AstraZeneca and the University of Oxford in developing the COVID-19 vaccine has not only contributed to society but also generated significant profits for the company.

H1b. Science-based cross-organizational collaboration has a positive impact on FIR.

2.2. The mediating role of current assets and main operating income

The previous section highlighted the potential for firms to enhance their resilience to innovation through cross-organizational cooperation, particularly in the form of market-based CS, CC, and science-based IURC. Building upon this discussion, we propose in this section that current assets and main operating income play a mediating role in this relationship. Liquidity represents a firm's ability to repay short-term debt obligations at minimal cost upon maturity while operating income serves as a critical source of profitability. These financial indicators reflect the level of business performance and the firm's ability to effectively address short-term contingencies [47]. Previous studies have predominantly considered current assets and main operating income as independent variables and examined their impact on innovation and resilience [48–50]. For instance, Cardillo et al. [49] found that firms with sustainability characteristics, along with higher cash holdings and liquid assets, are better equipped to handle crises before the occurrence of external shocks. Similarly, Kaya [50] employed financial indicators such as turnover, current assets, and liabilities to assess the health of firms, discovering that external shocks escalate the risk of insolvency among European SMEs, with innovation serving as a mitigating factor.

Based on the prior research, this paper proposes the existence of a significant pathway from cross-organizational cooperation to current assets and main operating income, ultimately leading to FIR. Specifically, first, intense competition and conflicts of interest within a competitive marketplace often undermine the liquidity of funds and diminish profits. For instance, dominant upstream firms may require buyers to make advance payments, thereby facilitating faster cash inflows and maintaining a healthier balance sheet for themselves [51]. On the other hand, customers with a wide range of supplier options and strong bargaining power tend to decrease suppliers' profit margins. Similarly [52], found that the stronger the market power of the customer, the lower the operational efficiency and profit margin of the supplier, ultimately negatively impacting the supplier's innovation level. Hence, robust and satisfactory cross-organizational cooperation is imperative for all parties involved. Secondly, effective cross-organizational cooperation can enhance the efficiency and quality of products within the supply chain, thereby improving firms' financial performance. In other words, CS ensures the stability of the enterprise's supply chain, avoiding production and innovation disruptions caused by material shortages. CC generates consistent orders and sales revenues, augmenting cash flow and allowing firms to invest more in strengthening IR. Thirdly, innovation plays a crucial role in expanding markets, reducing costs, and improving performance for businesses. Market-oriented cross-organizational cooperation allows for continuous monitoring of market needs and rapid development of new processes and products. Similarly, science-based IURC can greatly enhance firms' research and development capabilities and promote product and process innovation. Product innovations that meet consumer needs increase firms' revenue, bolstering profits and further stimulating investment in innovation. Consequently, we posit Hypothesis 2.

H2. Cross-organizational cooperation enhances FIR by increasing current assets and main operating income.

2.3. The moderating role of digital transformation and digital technology innovation

In this section, we propose that digital transformation and digital technology innovation can serve as a moderating variable in the relationship between cross-organizational collaboration and FIR. Theoretical perspectives regard digital technology as an advanced communication technology that enables the collection, storage, analysis, and sharing of information [53]. Examples of these digital technologies include the Internet of Things (IoT), big data analysis, cloud computing, and artificial intelligence. Digital transformation refers to the widespread application of digital technologies in economic production and social practices [54]. Digital technologies are editable, scalable, and open, which can improve the efficiency of information acquisition, processing, and transmission, and thus affect the level of inter-organizational collaboration in firms' innovation networks. The moderating effect of digital transformation and digital technology innovation can be understood from the following perspectives:

Firstly, digital transformation facilitates the reduction of information asymmetry and assists enterprises in identifying suitable partners. By expanding the scope of information collection, analysis, and utilization, digital transformation enables enterprises to gather transactional information through innovations like big data, cloud computing, and blockchain [55]. This expanded access to information allows enterprises to identify potential partners who share similar innovation needs and evaluate their credibility and innovation quality in greater detail. Additionally, the abundance and accessibility of information resulting from digital transformation promote transparency in transactional activities, reducing monitoring costs and the likelihood of opportunistic behavior and default among partners.

Secondly, from the perspective of resource flows, digital transformation diminishes obstacles to cross-organizational resource integration, thereby facilitating inter-organizational cooperation and innovation. The integration of digital technology with monetary capital, human talent, and knowledge accelerates the speed of resource flow within and between firms [56]. This enhances the efficiency of cross-organizational resource integration. Moreover, firms with a high level of digital transformation are more likely to engage in frequent interactions and knowledge-sharing, thus facilitating access to diverse knowledge resources that are crucial for IR. Additionally, firms' digital technological innovations effectively broaden and deepen their access to external knowledge, mitigating limitations associated with homogeneous knowledge accumulation.

Thirdly, scholars have found that timely communication among partners is a critical capability for enhancing trust and reducing conflicts among partners [57]. Moreover, firms need to allocate tasks and synchronize activities among partners through effective communication and coordination [57]. Market-driven cross-organizational cooperation and coordination require digital transformation to ensure collaboration and transparency of data. Specifically, in contexts of volatile and unpredictable demand, leveraging digital technology innovations becomes particularly important in enabling the real-time sharing of planning, execution, and management information across organizations, ensuring a seamless flow of demand information across the supply chain. Additionally, digital technologies have significantly reduced the spatial barriers imposed by geographical distance, facilitating the exchange of knowledge and information across organizations [58]. This reduction in the cost of information exchange enhances the efficiency of information transfer. Innovative organizations can achieve effective intra- and interregional interactions through digital transformation. In the context of science-based collaborations, it has been observed that the cost of knowledge transfer increases with the geographical distance between firms and universities [59]. However, the development of innovative digital technologies has facilitated IURC, breaking through spatial constraints and significantly enhancing the flow of advanced scientific knowledge to firms.

Fourthly, concerning the ability to respond to emergencies, digital transformation has strengthened firms' crisis response capabilities. The utilization of digital technology enables firms to extensively analyze and mine large amounts of data, thereby enhancing their early warning and response capabilities to crises. Market-oriented collaborations, in particular, benefit from digital transformation through the customization and tracking of products in the supply chain, which improves resilience to crises by enabling control over production batches and reducing inventory levels [60]. Furthermore, while external shocks may disrupt existing communication channels, digital transformation improves interaction patterns within and between firms and other partners, effectively integrating them as a cohesive unit, thus enhancing firms' innovative resilience.

In summary, we posit that digital transformation and digital technology innovation play a moderating role in the relationship between cross-organizational cooperation and FIR. Firstly, digital transformation alleviates information asymmetry and facilitates the identification of quality partners. Secondly, digital technological innovation facilitates the free flow of information and resources across organizations and geographical boundaries, thereby enhancing the efficiency of information transfer, resource integration, and firms' ability to absorb knowledge. Additionally, digital transformation strengthens firms' crisis response capabilities. Therefore, we propose the following hypothesis.

H3. Digital transformation and digital technology innovation strengthen the relationship between cross-organizational collaboration and FIR.

Based on the aforementioned hypotheses, this study proposes the theoretical model illustrated in Fig. 1.

3. Research method

3.1. Measures

3.1.1. Dependent variable

IR, as the dependent variable, is defined as the capacity of innovation to withstand external shocks, maintain system stability, adapt to recover, and potentially evolve to a higher state of functionality [12]. The ability to adapt and recover from shocks is recognized as a fundamental indicator of resilience. Previous research suggests that constraints related to resource factors can significantly influence the resilience of firms following a crisis [61], while resilient firms demonstrate improved optimization of resource allocation [62]. Innovation resources primarily encompass financial and human capital. Innovation initiatives often entail substantial financial investment and high costs. Failure to secure adequate funding, both internally and externally, can severely curtail innovation endeavors, particularly amidst volatile conditions [11]. Access to robust financing channels from banks and venture capital firms can significantly enhance the probability of innovation continuity and mitigate the risk of bankruptcy, amid risk and internal financial pressures [11,12,50]. Regarding the influence of human capital on innovation, attracting and managing innovative talent yields heightened innovation

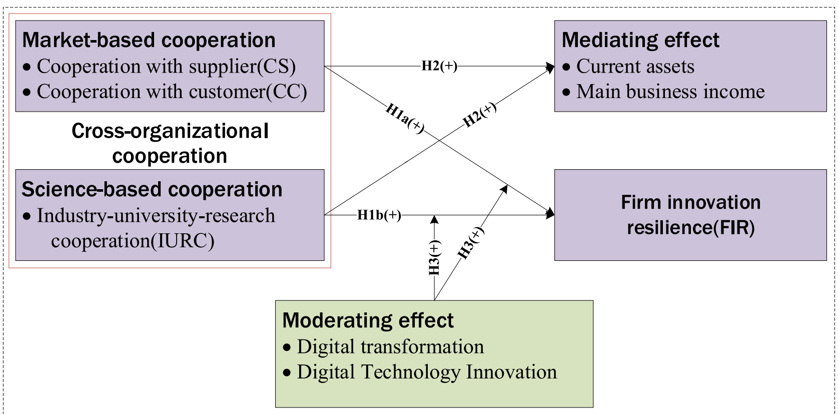

Fig. 1. Theoretical model.

efficiency for enterprises [24]. Additionally, entrepreneurial spirit serves as a beneficial remedial measure in addressing innovation crises [15]. Apart from innovation resources, autonomous research and technological innovation can significantly enhance enterprises' resilience, particularly evident in the manufacturing sector [10,11,24]. Through autonomous research and technological innovation, enterprises can possess complex technologies, trade secrets, and core technologies that are difficult to replicate, thereby establishing technological barriers. This "technological moat" aids enterprises in maintaining a leading market position and prevents competitors from imitating or surpassing them. It is noteworthy that highly uncertain market environments can hurt IR. For instance, market uncertainty can affect the resilience of manufacturing enterprises and regional economies [11,14]. However, enterprises' self-awareness and adaptability to environmental dynamics can mitigate the negative effects of uncertainty [33]. Finally, in response to the impact of unforeseen events, organizational restructuring or marketing innovation can assist enterprises in adapting flexibly to changes in market demands and competitive pressures, thus sustaining the sustainability of innovation [11,33].

Building upon previous research and integrating insights from the National Enterprise Innovation Survey Yearbook, this paper proposes a comprehensive framework for evaluating IR across five dimensions, considering data availability. Secondary indicators

Table 1
The innovation resilience indicators.

Level indicators	Secondary indicators	Measure	Weights	Direction	References
(1) Factor shortage tolerance	Is the lack of internal capital an obstacle to firm's innovation under the impacts of unexpected events or a sudden shock?	The proportion of firms which hold that the shortage of internal capital is not a major obstacle to innovation	0.03	Positive	[11,50]
	Is the lack of venture funding an obstacle to firm's innovation?	The proportion of firms which hold that the shortage of venture funding is not a major obstacle to innovation	0.08	Positive	[12,49]
	Is the lack of bank lending an obstacle to firm's innovation?	The proportion of firms which hold that the shortage of bank loans is not a major obstacle to innovation	0.09	Positive	[14,51]
	Is the high cost an obstacle to firm's innovation?	The proportion of firms that hold that high costs are not a major obstacle to innovation	0.02	Positive	[48,63]
	Is a lack of talent or brain drain a barrier to firm's innovation?	The proportion of firms that hold that the shortage of talent or brain drain is not a major obstacle to innovation	0.02	Positive	[24,53]
	Is the lack of entrepreneurship a barrier to firm's innovation?	The proportion of firms that hold that entrepreneurship has no high impact on innovation	0.03	Positive	[10,15]
(2) Independent R&D security	Does the firm have independent research and development capabilities?	The proportion of enterprises independently developing new products	0.01	Positive	[11]
	Does the company not need to rely on external firms for developing new products?	The proportion of companies that collaborate with the internal firms in the group to develop new products	0.06	Positive	[9,22]
(3) Core technology self-sufficiency	Does the enterprise establish national or industry technical standards?	The proportion of enterprises formulating national or industry technical standards	0.02	Positive	[32]
	Do enterprises have complex technologies that are difficult to replicate?	The proportion of enterprises holding complex technologies that are difficult to replicate	0.03	Positive	[31]
	Does the enterprise possess the technical secrets and provide internal protection for them?	The proportion of enterprises that possess technical secrets and provide internal protection for them	0.03	Positive	[17]
	Does the enterprise have the core technologies with a time first-mover advantage?	The proportion of enterprises that hold the core technologies with time first mover advantage	0.02	Positive	[10,24,26]
	Does enterprise have the brand ownership of the main products?	The proportion of enterprises that have brand ownership of their main products	0.12	Positive	[3,64]
(4) Market uncertainty tolerance	Is the lack of market information an obstacle to firm's innovation?	The proportion of firms which hold that shortage of market information is not a major obstacle to innovation	0.05	Positive	[14,30]
	Do other enterprises occupy the market an obstacle to firm's innovation?	The proportion of firms that hold that market occupied by others is not a major obstacle to innovation	0.02	Positive	[26,33]
	Is the uncertainty in market demand caused by major emergencies or a sudden shock an obstacle to firm's innovation?	The proportion of firms which hold that the uncertainty of market demand is not a major obstacle to innovation	0.02	Positive	[50,61]
	Do companies have the ability to explore international markets when the local market is affected by unexpected events?	The proportion of enterprises that develop new products in the international market	0.05	Positive	[33,63]
(5) Flexible capability	Faced with the impacts of unexpected events, enterprises can undergo organizational change or marketing innovation	Ln (the number of firms that achieved organizational or marketing innovation)	0.21	Positive	[15]
		The proportion of enterprises that achieve organizational innovation	0.03	Positive	[33,61]
		The proportion of enterprises that achieve marketing innovation	0.05	Positive	[11]

have been devised accordingly. The five dimensions encompass tolerance for factor shortages, independent R&D security, core technology self-sufficiency, market constraint tolerance, and flexible capability. Among them, Tolerance for factor shortages comprises six sub-indicators, including internal fund scarcity not being a primary innovation barrier, insufficient venture capital not being a primary innovation barrier, etc. Independent R&D security encompasses independent R&D and collaborative R&D within corporate groups. Core technology self-sufficiency involves holding national or industry technical standards, holding secret technology, etc. Market constraint tolerance includes insufficient market information not being a primary innovation barrier, occupied markets not being a primary innovation barrier, etc. The flexible capability includes the number of firms that achieved organizational or marketing innovation, achieved organizational innovation, and achieved marketing innovation. Specific details are outlined in Table 1.

This study leverages the research methodologies of Wang et al. [65], Shih & Olson [66], employing the entropy weight TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) model for measuring IR. The TOPSIS model is a sorting method that involves several steps. Firstly, the indicators are objectively assigned weights based on standardized processing to calculate the entropy utility value of the indicator information. Subsequently, the development index is determined by assessing the distances between the evaluation unit and the optimal solution as well as the worst solution. The specific application steps of the model are as follows.

To standardize the original data of various indicators and adopt extreme value standardization:

$$x'_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})} \bullet \rho + (1-\rho) \tag{1}$$

$$x'_{ij} = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})} \bullet \rho + (1-\rho) \tag{2}$$

In Equations (1) and (2), x'_{ij} is the standardized value of each index; x_{ij} is the evaluation index of item j of i province; $min(x_{ij})$ is the minimum value of the index; and $max(x_{ij})$ is the maximum value of the index; setting $0 < \rho < 1$; referring to Liu et al. [67], we take $\rho = 0.995$ in this paper to circumvent the possible inability to compute the natural logarithm.

To calculate the value of entropy U_j, use the formula shown in Equation (3).

$$U_j = -\frac{1}{\ln n}\sum\nolimits_{i=1}^{n}\left[\left(x'_{ij} / \sum\nolimits_{i=1}^{n} x'_{ij}\right)\ln\left(x'_{ij} / \sum\nolimits_{i=1}^{n} x'_{ij}\right)\right] \tag{3}$$

To calculate the index weight ω_j, refer to the formula presented in Equation (4).

$$\omega_j = \frac{1-U_j}{\sum\nolimits_{j=1}^{m}(1-U_j)}\left(0 < W_j < 1\ ,\ \sum\nolimits_{j=1}^{m} W_j = 1\right) \tag{4}$$

To establish a standardized decision matrix M, use the formula shown in Equation (5).

$$M = x'_{ij} \times \omega_j = \begin{bmatrix} x'_{11}\omega_1 & \cdots & x'_{1j}\omega_m \\ \vdots & \ddots & \vdots \\ x'_{i1}\omega_1 & \cdots & x'_{ij}\omega_m \end{bmatrix} \tag{5}$$

To determine the positive and negative ideal solutions:

$$\begin{aligned} S^+ &= [\max M_{i1}\ ,\ \max M_{i2}\ ,\ \cdots\ ,\ \max M_{im}] \\ S^- &= [\min M_{i1}\ ,\ \min M_{i2}\ ,\ \cdots\ ,\ \min M_{im}] \end{aligned} \tag{6}$$

In Equation (6), S^+ and S^- represent the positive and negative ideal solutions, respectively.

To calculate the distance between the positive and negative ideal solutions for each province:

$$\begin{aligned} G_i^+ &= \sqrt{\sum\nolimits_{j=1}^{m}(M_{ij} - S^+)^2} \\ G_i^- &= \sqrt{\sum\nolimits_{j=1}^{m}(M_{ij} - S^-)^2} \end{aligned} \tag{7}$$

In Equation (7), G_i^+ and G_i^- are the distances of the positive and negative ideal solutions, respectively.

To calculate the score of comprehensive evaluation, apply the formula provided in Equation (8).

$$D_i = \frac{G_i^-}{G_i^+ + G_i^-} \tag{8}$$

Where $0 < D_i < 1$; the larger value of D_i indicates the stronger FIR; the smaller value of D_i, the weaker FIR.

3.1.2. Independent variable

The behavior of cross-organizational cooperation is often defined through collaborative business processes which indicates the interactions between organizations to achieve common business goals, also called choreographies [68]. The subjects of cross-organizational cooperation are usually enterprises, suppliers, customers, universities, research institutions [69,70], *etc*. In this article, cross-organizational cooperation is divided into two forms, one is market-based and the other is science-based. The former expressing a collaborative behavior in response to market demand is defined as the number of companies that engage in innovative collaboration with suppliers or customers. The latter denoting a cooperative behavior in response to scientific needs is defined as the number of enterprises that carry out IURC with universities or research institutions. The quantity of collaborative engagements by enterprises implicitly signifies their involvement in the innovation process with suppliers, customers, or universities, reflecting the intensity of their collaborative relationships with these partners. Following established literature [71,72], we adopt the approach of using the number of enterprises engaged in different types of collaboration to gauge inter-organizational collaboration. To capture the extent of enterprises' engagement in diverse forms of cross-organizational cooperation, we rely on the National Enterprise Innovation Survey Yearbook. This yearbook discloses the total number of enterprises involved in innovation collaboration, along with the proportion of collaboration with different partners (suppliers, customers, universities, research institutes, etc.). Finally, considering the hypothesized non-linear relationship, we take the natural logarithm of this count. Specific details are outlined in Table 2.

3.1.3. Mediator variables

An important objective for businesses pursuing cross-organizational cooperation is to enhance operational efficiency and attain the resulting benefits. Collaborative partnerships facilitate the improvement of logistics efficiency and asset liquidity while mitigating potential risks. Additionally, such partnerships enable companies to share research and development expenses, augment sales of innovative products, and generate increased profits [24,73]. These outcomes are reflected in the financial indicators within the financial statements. Therefore, this study incorporates current assets and main business income as mediating variables. Current assets, as presented in the balance sheet, comprise short-term assets involved in the company's operational activities, including cash, accounts receivable, and inventory, which can be swiftly converted into cash and are pertinent to the company's liquidity and risk management. Income from the main business, as manifested in the income statement, pertains to the revenue derived from the company's fundamental business operations, thereby indicating the company's market competitiveness and profitability.

3.1.4. Moderator variables

To gain a deeper understanding of the innovation resilience of enterprises in the digital age, we consider the digital transformation and digital technology innovation of firms as moderating variables in this study. Measuring enterprise digital transformation accurately presents challenges as it is a long-term, multidimensional process. Scholars increasingly recognize the critical role of digital technology as a driver of enterprise digital transformation. As digital technology primarily manifests through software [74], this study focuses on measuring the level of enterprise digital transformation from a software perspective [75]. employed the ratio of intangible assets related to digital transformation to total intangible assets as a measure of the degree of digital transformation. However, this measure may be influenced by ostentatious investments made by enterprises [76], and errors may arise due to differences in enterprise size. Therefore, this paper enhances the measurement method proposed by Zhang et al. [75] by substituting total corporate assets for total intangible assets. Specifically, the definition of digital technology intangible assets involves filtering specific items of enterprise intangible assets using keywords such as "software," "network," "client," "system," "platform," "information," and "e-commerce." Subsequently, the ratio of the sum of digital technology intangible assets to the total assets for the year is utilized to gauge the extent of digital transformation within the enterprise. A higher value indicates a greater degree of digital transformation. As one of the widely recognized measures of technological innovation, patents are highly consistent with technological development trends, and can directly reflect the technological foresight capabilities. Referring to the previous research, this article measures digital technology innovation by the total number of invention patents and utility patents in the field of digital economy.

Table 2
Definitions and descriptive statistics of the variables.

Variables	Definitions	Mean	Std. Dev.	Min	Max
Dependent variable					
Innovation resilience (IR)	The index of firm's innovation resilience	0.241	0.091	0.134	0.552
Independent variables					
Cooperation with supplier (CS)	Ln (number of enterprises cooperating with suppliers in innovation activities)	6.456	1.352	3.466	9.296
Cooperation with customer (CC)	Ln (number of enterprises cooperating with customers in innovation activities)	6.465	1.488	2.994	9.359
Industry-university-research cooperation (IURC)	Ln (number of enterprises participating in industry-university-research cooperation)	6.618	1.183	4.007	9.029
Control variables					
Urbanization	The proportion of urban population to the total population	0.623	0.106	0.446	0.893
Economy	Per capita GDP after price adjustment based on the year 2000	11.546	0.854	9.350	12.618
Technical market development	Technology market turnover/GDP	0.009	0.021	0.000	0.144
R&D intensity	Internal expenditure of R&D/GDP	0.014	0.010	0.002	0.060
Technical capabilities	Natural logarithm of the number of invention patent applications	8.521	1.469	4.997	11.858
Taxation	Tax revenue/GDP	0.076	0.029	0.038	0.177
Labor force	Natural logarithm of the number of employed people	7.583	0.794	5.707	8.744

3.1.5. Control variables

Innovation is a complex process, with a multitude of factors influencing IR [10–12,14,24]. To control the factors that may confound the relationship between cross-organizational cooperation and FIR and to reduce noise, thereby focusing more attention on explaining the main results, this study incorporates regional-level control variables based on previous research [65,77,78]. Specifically, urbanization is represented by the proportion of the urban population to the total population. The process of urbanization is typically accompanied by industrial upgrading and population concentration, thus regions with higher levels of urbanization may have more resources and opportunities to support innovation activities. Economic indicators are measured by the Per capita GDP after price adjustment based on the year 2000. Economic level reflects the overall prosperity and market capacity of a region, where a higher economic level signifies more funds and resources available for innovation activities, and is therefore often associated with stronger IR. Technological market development is defined as the ratio of technological market turnover to GDP, which can measure the marketization level and efficiency of technological innovation achievements in a region. Technological market development directly impacts the ease of enterprises acquiring external technology and knowledge, thereby affecting their innovation capability and resilience. R&D intensity is expressed as the ratio of internal R&D expenditure to GDP. Higher R&D intensity typically indicates greater innovation input and capability. Technological capability is measured by the natural logarithm of the number of patent applications, reflecting the technological innovation output and potential technological accumulation of a region or enterprise. Enterprises with stronger technological capabilities generally exhibit higher levels of innovation and greater IR. Taxation is represented by the ratio of tax revenue to GDP. Changes in tax burden can influence enterprises' enthusiasm for innovation. Reasonable taxation can motivate enterprises to increase innovation input, while high taxes may reduce enterprises' disposable funds, diminishing their investment in research and development. The labor force is measured by the natural logarithm of the number of employed individuals. A larger labor force base implies a wider range of professional skills and knowledge diversity, which can help enterprises enhance innovation capabilities. The definitions and computing methods of variables are shown in Table 2. It is worth mentioning that the standard deviation of the data used in this article is less than 1.5, indicating that the data dispersion is not high, and the internal development differences among various indicators are not obvious. This conclusion provides a good foundation for us to exclude the unconventional influence of outliers.

3.2. Sampling and data collection

The data in this paper are mainly from the National Enterprise Innovation Survey Yearbook, the China Research Data Service (CNRDS), and the China Stock Market & Accounting Research (CSMAR) database. To be specific, first, the survey scope of the National Enterprise Innovation Survey Yearbook spans various national economic industries, including manufacturing, information transmission, software and information technology services, wholesale and retail trade, transportation, construction, leasing, and business services. The survey targets industrial enterprises above a certain size, entities exceeding stipulated thresholds in the wholesale and retail trade, as well as businesses in the information transmission, software, and information technology services industry. Encompassing dimensions such as product innovation, process innovation, organizational innovation, and marketing innovation, this yearbook offers high-quality survey data that comprehensively reflects the state of FIR in China, serving as a valuable resource for research on IR. Second, the CNRDS is a high-quality, open, and platform-based comprehensive data platform for Chinese economic, financial, and business research. It is based on China issues, closely follows academic hot spots and academic frontiers, and can provide characteristic research data that is not available in the market or is difficult to obtain. As a result, it is a high-quality data source for studying digital transformation. Furthermore, we have specifically selected CSMAR as an additional data source to complement our research.

In our empirical analysis, we utilize panel data encompassing the years 2016–2020, focusing on 30 Chinese provinces and direct-controlled municipalities. It is important to note that due to the unavailability of data about certain indicators in Tibet, Hong Kong, Macao, and Taiwan provinces, this research sample does not encompass the aforementioned regions of China at present.

Table 3
Results of multicollinearity analysis.

	(1)	(2)	(3)
CS	6.90		
CC		7.01	
IURC			8.83
Urbanization	8.18	8.16	8.16
Economy	6.21	6.00	6.05
Technical market development	8.68	8.88	9.41
R&D intensity	16.90	17.43	18.31
Technical capabilities	10.03	9.95	9.88
Taxation	1.21	1.21	1.21
Labor force	8.20	8.39	10.14
Mean VIF	8.29	8.38	9.00

4. Empirical findings

4.1. Multicollinearity test

In empirical analysis, the presence of multicollinearity among explanatory and control variables can undermine the effectiveness of regression models, impairing their ability to accurately reflect relationships between the variables of interest. This study's focus is on three core independent variables: collaboration with suppliers (CS), collaboration with customers (CC), and industry-university-research cooperation (IURC), and their impact on innovation resilience. Furthermore, it's important to note that the paper did not include all three main variables simultaneously in one model; instead, we assessed each collaboration type separately—either independently or together with control variables—to isolate their specific effects. This method mitigates concerns about potential multicollinearity that could otherwise obscure each core variable's unique contribution. To further address this concern, a multicollinearity test was conducted prior to empirical analysis. The results in Table 3 indicate that the variance inflation factors (VIF) for CS, CC, and IURC are 6.90, 7.01, and 8.83, respectively, while the mean VIF across all models is below 10. Additionally, we calculate the correlation coefficients among variables such as CS, CC, IURC, and control variables, finding that most of these correlations fall below 0.5. These findings suggest that the models employed in this study do not suffer from severe multicollinearity or high correlation issues, thus allowing for an effective reflection of the relationships between cross-organizational collaboration and FIR.

4.2. Baseline regression

Table 4 presents the results of the baseline regression between cross-organizational cooperation and FIR. Specifically, columns (1), (2), and (3) display the regression outcomes of CS, CC, and IURC on FIR, respectively, controlling for the fixed effects of province and year, without incorporating relevant control variables. Subsequently, columns (4), (5), and (6) incorporate a series of control variables. The inclusion of control variables is accompanied by an enhancement in the model's goodness-of-fit, indicating an improved explanatory power of the variables for FIR. The findings in columns (4) and (5) reveal that the regression coefficients for CS and CC are 0.063 and 0.069, respectively, both significant at the 5 % confidence level. This suggests that market-based cross-organizational cooperation exerts a significant positive influence on FIR, thus providing initial support for H1a. In column (6), the result indicates that the regression coefficient of IURC is 0.078 and significant at the 10 % confidence level. Consequently, for each 1 % increase in IURC, FIR is projected to increase by 7.8 %, thereby preliminarily supporting H1b. Taken together, the regression results presented in Table 4 demonstrate the significant impact of cross-organizational collaboration on enhancing FIR, thus providing empirical support for H1. This may be attributed to facilitating resource sharing and cost reduction in innovation endeavors through cross-organizational cooperation, thereby bolstering the capacity to manage risks [42,73].

Comparing the regression results from columns (4) to (6), it becomes apparent that the regression coefficient for IURC is the highest

Table 4
Baseline regression results on cross-organizational cooperation and firms' innovation resilience.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Resilience	Resilience	Resilience	Resilience	Resilience	Resilience
Cooperation with supplier (CS)	0.059* (1.988)			0.063** (2.333)		
Cooperation with customer (CC)		0.069** (2.148)			0.069** (2.457)	
Industry-university-research cooperation (IURC)			0.071* (1.654)			0.078* (1.897)
Urbanization				1.112*** (3.027)	1.099*** (2.983)	0.930** (2.589)
Economy				−0.018 (-0.663)	−0.016 (-0.583)	−0.013 (-0.493)
Technical market development				0.482 (1.291)	0.434 (1.227)	0.321 (0.789)
R&D intensity				6.870** (2.640)	6.488** (2.626)	6.780** (2.435)
Technical capabilities				−0.032** (−2.660)	−0.032** (−2.680)	−0.036** *(-2.975)
Taxation				0.424 (1.320)	0.385 (1.250)	0.506 (1.556)
Labor force				0.079 (1.202)	0.080 (1.323)	0.055 (0.920)
Constant	−0.136 (-0.710)	−0.200 (-0.967)	−0.224 (-0.792)	−1.358 (-1.324)	−1.170 (-1.645)	−0.952 (-1.427)
Observations	150	150	150	150	150	150
R-squared	0.119	0.144	0.087	0.288	0.301	0.263
Province fixed effect	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES

Note: The *z* statistics are reported in parentheses. ***, **, and * indicate that regression coefficients are statistically significant at the 1 %, 5 %, and 10 % levels, respectively.

among the three types of cross-organizational collaboration and passes the significance level test. This finding suggests that, while all three types of collaboration have a positive impact on FIR, the science-based IURC exhibits a more significant enhancement effect compared to the market-based CS and CC. This difference in effect may be attributed to the fact that IURC helps ensure that the funding chain for R&D remains intact [44]. As universities and research organizations primarily receive their funding from the government, they generally have more generous financial resources than firms, particularly during external shocks or economic downturns. Consequently, IURC is believed to be more effective in enhancing FIR.

The case of Procter & Gamble (P&G) illustrates the positive impact of collaborating with external organizations on corporate IR. Established in 1837, P&G is one of the world's largest consumer goods companies. Throughout its development, cross-organizational collaboration has played a crucial role in fostering innovation. In CS, P&G selectively integrates its own value chain innovation activities with those of its suppliers. For instance, in response to its sustainability initiatives, P&G collaborated with Dow Chemical to jointly develop a new recycling technology. Leveraging their respective technological strengths, they developed a new dissolving process to transform non-recyclable plastic packaging into "near-virgin quality" recycled polyethylene, thereby reducing greenhouse gas emissions. The collaboration with Dow Chemical enables P&G to scale industry solutions, creating a circular future where materials are recycled and remanufactured rather than becoming waste. In CC, P&G's partnership with Walmart extends beyond logistics to encompass information management systems, retailer connectivity platforms, and customer relationship management training. This close and longstanding collaboration has established the "P&G-Walmart" model, now a paradigm of cooperation between companies and retailers. Furthermore, P&G places significant emphasis on IURC, establishing collaborations with research institutions and universities in various countries, including Durham University in the UK, Tianjin University in China, and the Fraunhofer Society in Germany. Collaborations with universities inject vitality into P&G's research and development innovation. For example, P&G established an Innovation Center at the University of Leeds, recruiting PhD students from diverse academic backgrounds under six-month, 20-h-per-week project contracts tailored to specific project needs, but not necessarily full-time research with P&G.

4.3. Heterogeneity analysis

4.3.1. Heterogeneity analysis of eastern and western regions

Due to disparities in economic development, cross-organizational cooperation, innovation capabilities, and digital transformation levels across regions, the driving effect of cross-organizational cooperation on FIR may exhibit spatial heterogeneity. To address this issue, we classify the sample into two subgroups: the eastern region and the western region. We then conduct regression analyses to explore the aforementioned driving effect. The results in Table 5 indicate that in the eastern region, both CS and CC significantly facilitate FIR (with regression coefficients of 0.123 and 0.114, respectively) at the 5 % confidence level. However, the effect of IURC on FIR is positive but statistically insignificant. In contrast, firms in the Western region do not significantly benefit from cross-organizational cooperation. Specifically, the regression coefficients of the three cross-organizational cooperation on FIR in the table do not pass the significance test. Thus, cross-organizational cooperation has a stronger facilitating effect on FIR in the eastern region than in the western region, with market-based cross-organizational cooperation being particularly effective in the former. Conversely, the development of cross-organizational cooperation has no significant impact on the improvement of FIR in the western region.

There are several possible reasons for this spatial heterogeneity. Firstly, compared to the western region, the eastern region exhibits a higher level of economic development, characterized by superior infrastructure, more active markets, greater concentration of resources, and a larger number of firms. These advantages enable easier networking, knowledge sharing, and experience exchange among firms. Furthermore, the agglomeration effect promotes the convergence and exchange of innovation resources, thereby enhancing the positive impact of cross-organizational cooperation on IR. Secondly, the eastern region possesses a more developed and diversified industrial structure. This provides firms with increased opportunities to form close cooperative relationships within the supply and value chains. Market-based CS and CC can lead to technological innovation, market feedback, and resource sharing, thereby bolstering FIR. However, it should be noted that this might lead to a certain degree of path dependence, where science-based

Table 5
Heterogeneity estimation results for eastern and western regions.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Eastern	Eastern	Eastern	Western	Western	Western
Cooperation with supplier (CS)	0.123** (2.452)			0.037 (1.492)		
Cooperation with customer (CC)		0.114** (2.114)			0.045 (1.662)	
Industry-university-research cooperation (IURC)			0.142 (1.703)			0.055 (1.401)
Controls	YES	YES	YES	YES	YES	YES
Constant	−0.933 (−0.863)	−0.931 (−0.812)	−0.721 (−0.534)	−0.816 (−1.062)	−0.816 (−1.130)	−0.913 (−1.212)
Observations	65	65	65	85	85	85
R-squared	0.597	0.579	0.532	0.206	0.217	0.206
Province fixed effect	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES

Note: The *z* statistics are reported in parentheses. ***, **, and * indicate that regression coefficients are statistically significant at the 1 %, 5 %, and 10 % levels, respectively.

IURC is relatively undervalued in the eastern region and thus less effective in promoting FIR. Additionally, the eastern region has exhibited an earlier and more advanced stage of digital transformation compared to the western region. This facilitates cross-organizational cooperation and further unleashes the benefits of such cooperation on FIR.

4.3.2. Heterogeneity analysis of the Yangtze and Yellow River Basins

The Yangtze River and Yellow River are the two longest rivers in China, and the provinces located within their basins play a crucial role in shaping the regional economy and fostering innovation. The Yangtze River basin, represented by Shanghai, Jiangsu, and Zhejiang, boasts a well-developed manufacturing sector, high-tech industries, and advanced services. In contrast, the Yellow River Basin, centered around Henan, Shandong, and Shaanxi, is rich in mineral resources and is emerging as a hub for high-end manufacturing. Therefore, the influence of different river basins on cross-organizational cooperation and FIR cannot be overlooked. To investigate this, we partitioned the sample into two subgroups: the Yangtze River Basin and the Yellow River Basin. Columns (1)–(3) and (4)–(6) of Table 6 present the regression results for these two subgroups, respectively. The results indicate that within the subgroup of the Yangtze River Basin, only the regression coefficient for enterprise-customer cooperation is significantly positive at the 5 % confidence level. The regression coefficients for enterprise-supplier cooperation and IURC are 0.045 and 0.094 respectively, but they do not demonstrate statistical significance. In the Yellow River Basin subgroup, the regression results of CS, CC, and IURC do not pass the significance test. These results suggest that promoting market-based cross-organizational cooperation can effectively enhance FIR in the Yangtze River Basin. However, in the Yellow River Basin, the impact of cross-organizational cooperation on FIR is not statistically significant.

4.4. Robustness test

To enhance the robustness of our findings, we conducted robustness tests by substituting the dependent variables. The inclusion of the proportion of firms achieving technological innovation and the proportion of firms increasing innovation investment to improve competitiveness as dependent variables provides a more intuitive reflection of FIR in terms of technology and finance. Regression results are presented in Table 7. The coefficients of CS, CC, and IURC remain significantly positive after the substitution of dependent variables, consistent with the outcomes presented in Table 4. These results indicate the robustness of the benchmark estimation findings in this study.

5. Mechanism analysis

5.1. The mediating effect of current assets and main operating income

The previous empirical results show that cross-organizational cooperation significantly contributes to FIR, and the finding is robust. Next, we further explore the mechanism of cross-organizational cooperation on FIR. Cross-organizational cooperation expands firms' assets by exchanging resources and reducing transaction costs [63], thereby providing financing for ongoing business and innovation activities. Consequently, cross-organizational cooperation has the potential to enhance FIR by increasing both current assets and main business income. To examine the mediating effect of current assets and main business income on the relationship between cross-organizational cooperation and IR, we include these variables in our benchmark regression model. The regression results are presented in Table 8. In Columns (1) to (3), we assess the mediating role of current assets. The results indicate that the regression coefficients for CS, CC, and IURC are all statistically significant at the 1 % confidence level and exhibit positive signs. This suggests that cross-organizational collaboration plays a crucial role in enhancing FIR by increasing its liquid assets, thereby tentatively confirming H2. Specifically, market-based CS and CC are associated with higher inventory turnover, shorter lead times, lower costs, and increased

Table 6
Heterogeneity estimation results for the Yangtze River Basin and the Yellow River Basin.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Yangtze river basin	Yangtze river basin	Yangtze river basin	Yellow River basin	Yellow River basin	Yellow River basin
Cooperation with supplier (CS)	0.045 (1.469)			0.055 (1.825)		
Cooperation with customer (CC)		0.059** (2.851)			0.030 (1.113)	
Industry-university-research cooperation (IURC)			0.094 (1.427)			0.017 (0.405)
Controls	YES	YES	YES	YES	YES	YES
Constant	1.190 (0.872)	0.792 (0.625)	1.328 (1.080)	−1.044 (−0.745)	−0.964 (−0.599)	−1.066 (−0.608)
Observations	55	55	55	45	45	45
R-squared	0.502	0.528	0.518	0.299	0.273	0.262
Province fixed effect	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES

Note: The *z* statistics are reported in parentheses. ***, **, and * indicate that regression coefficients are statistically significant at the 1 %, 5 %, and 10 % levels, respectively.

Table 7
Robustness test of cross-organizational cooperation on firms' innovation resilience.

Variables	(1) Realize technological innovation	(2) Realize technological innovation	(3) Realize technological innovation	(4) Increase innovation investment	(5) Increase innovation investment	(6) Increase innovation investment
Cooperation with supplier (CS)	0.108*** (5.615)			0.061*** (2.940)		
Cooperation with customer (CC)		0.094*** (3.850)			0.049*** (2.851)	
Industry-university-research cooperation (IURC)			0.127*** (3.593)			0.061*** (3.925)
Controls	YES	YES	YES	YES	YES	YES
Constant	0.641 (0.755)	0.779 (0.930)	0.954 (1.317)	0.416 (1.034)	0.536 (1.299)	0.653* (1.996)
Observations	150	150	150	150	150	150
R-squared	0.827	0.813	0.808	0.166	0.126	0.114
Province fixed effect	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES

Note: The *z* statistics are reported in parentheses. ***, **, and * indicate that regression coefficients are statistically significant at the 1 %, 5 %, and 10 % levels, respectively.

Table 8
The mediating effect of current assets and main operating income.

Variables	(1) Current asset	(2) Current asset	(3) Current asset	(4) Main operating income	(5) Main operating income	(6) Main operating income
Cooperation with supplier (CS)	0.161*** (2.802)			0.163 (1.450)		
Cooperation with customer (CC)		0.238*** (4.529)			0.258** (2.538)	
Industry-university-research cooperation (IURC)			0.211*** (2.998)			0.563*** (4.000)
Controls	YES	YES	YES	YES	YES	YES
Constant	1.165 (0.533)	0.455 (0.240)	1.512 (0.768)	−4.756 (−1.401)	−5.637* (−1.838)	−6.350** (−2.426)
Observations	150	150	150	150	150	150
R-squared	0.738	0.772	0.731	0.319	0.348	0.409
Province fixed effect	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES

Note: The *z* statistics are reported in parentheses. ***, **, and * indicate that regression coefficients are statistically significant at the 1 %, 5 %, and 10 % levels, respectively.

sales levels. On the other hand, science-based IURC enables firms to leverage shared resources such as expensive laboratories and specialized expertise, thereby reducing the costs and risks associated with R&D and innovation processes. In summary, cross-organizational cooperation effectively bolsters firms' liquid assets, which in turn contributes to the overall enhancement of IR.

The results displayed in column (5) of Table 8 indicate that the regression coefficients for CC show significance at the 5 % confidence level, suggesting that the augmentation of main business revenue acts as a mediator in strengthening FIR through CC. Sharing resources with customers enables firms to gather comprehensive and timely market feedback, as well as expand product sales channels, thereby driving an increase in firms' main business income and supplying financial support for innovation endeavors. Upon examination of the regression model in column (6), the regression coefficient for IURC is calculated as 0.563, and it achieves significance at the 1 % confidence level. This result signifies that the IURC can notably augment main business income, thus bolstering FIR. Thus, H2 is further proved. Through IURC, firms are empowered to introduce fresh technologies and knowledge, continuously update and broaden their technological capabilities, and enhance the likelihood of enhancing main business income by developing new products and services with significant competitive advantages. Consequently, expanding the main business income represents an additional effective avenue through which cross-organizational cooperation can fortify FIR.

5.2. The moderating effect of digital technology innovation and digital transformation

To examine whether the influence of cross-organizational collaboration on FIR is contingent upon the degree of digitization, we assess H3 within the contexts of both digital technology innovation and digital transformation. The regression results are presented in Table 9. Columns (1) to (3) indicate that the regression coefficients of digital technology innovation are significantly positive at the 5 % confidence level, revealing that a higher degree of digital technology innovation is associated with greater support for IR. Furthermore,

Table 9
Moderating effect of digital technology innovation and digital transformation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Digital technology innovation	Digital technology innovation	Digital technology innovation	Digital transformation	Digital transformation	Digital transformation
Cooperation with supplier (CS)	0.036** (2.428)			0.043 (1.550)		
Cooperation with customer (CC)		0.046*** (3.219)			0.050 (1.695)	
Industry-university-research cooperation (IURC)			0.081*** (2.932)			0.084** (2.168)
Digital technology innovation	0.036** (2.312)	0.036** (2.419)	0.039** (2.585)			
*Digital technology innovation *CS*	0.022*** (6.658)					
*Digital technology innovation *CC*		0.018*** (5.832)				
*Digital technology innovation *IURC*			0.026*** (5.274)			
Digital transformation				−1.975 (−0.790)	−1.297 (−0.539)	−1.826 (−0.854)
Digital transformation **CS*				4.397** (2.080)		
Digital transformation **CC*					3.266* (1.743)	
Digital transformation **IURC*						7.553*** (3.249)
Controls	YES	YES	YES	YES	YES	YES
Constant	−1.092* (−1.707)	−1.181* (−1.897)	−1.251** (−2.065)	−0.848 (−1.137)	−0.954 (−1.320)	−0.901 (−1.408)
Observations	150	150	150	150	150	150
R-squared	0.471	0.467	0.468	0.345	0.344	0.383
Province fixed effect	YES	YES	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES	YES	YES

Note: The *z* statistics are reported in parentheses. ***, **, and * indicate that regression coefficients are statistically significant at the 1 %, 5 %, and 10 % levels, respectively.

to investigate the moderating role of digital technological innovation, we introduced interaction terms between digital technological innovation and the three types of cross-organizational cooperation (digital technological innovation*CS, digital technological innovation*CC, and digital technological innovation* IURC) into the baseline model for testing purposes. The results show that the regression coefficients of the interaction terms all pass the significance test at the 1 % confidence level, suggesting that a higher degree of digital technological innovation amplifies the facilitating effect of cross-organizational cooperation on FIR. This finding lends support to the expectation of H3. Notably, digital technological innovation provides a more efficient information-sharing and resource integration platform for cross-organizational cooperation, enhancing firms' collaborative innovation capabilities and therefore strengthening the positive impact of cross-organizational cooperation on IR.

The test results for the moderating effect of digital transformation are presented in columns (4) to (6) of Table 9. These results indicate that the coefficients of the interaction terms between digital transformation and the three types of cross-organizational cooperation also pass the significance test, and the coefficients of Digital Transformation* IURC are significantly positive at the 1 % level. This implies that digital transformation positively moderates the impact of cross-organizational cooperation on enhancing IR; in other words, the impact of cross-organizational cooperation on IR becomes more pronounced with the increased intensity of digital transformation. These findings provide further support for Hypothesis 3. Throughout the process of digital transformation, the obstacles to cross-organizational cooperation across various fields and professions are reduced, allowing the innovation potential of cross-organizational cooperation to be unleashed. Moreover, in the context of digital transformation, IURC is more likely to facilitate the crossover and fusion of technologies across different domains, thereby fostering more innovations that amalgamate cutting-edge scientific advancements with industrial demands. Consequently, the role of cross-organizational cooperation in promoting firm-level IR is further strengthened.

6. Discussion and conclusion

6.1. Discussion

In the current intricate and volatile market landscape, the imperative for enterprises to fortify FIR in response to risks and uphold their competitive edge is undeniable. Amid crises, seeking collaboration with external organizations can help firms alleviate resource constraints and stand as a pivotal vehicle for sustaining innovation and sharing risks. However, prevailing literature predominantly delves into the impact of cross-organizational cooperation on collaborative innovation or supply chain relationships [13,79], leaving an avenue for further exploration of the correlation between the impact of cross-organizational cooperation and FIR, along with the pathways through which this impact is transmitted. Notably, the pervasive influence of digital transformation and technological advancements is fundamentally reshaping the contemporary business milieu, presenting an undeniable force [25]. Hence, it holds paramount theoretical and practical significance to scrutinize whether cross-organizational cooperation can augment FIR in the digital era. In line with this, this study probes the influence of market-based and science-based cross-organizational cooperation on FIR using the fixed effects model and subsequently scrutinizes the heterogeneous characteristics and potential mechanisms underlying this impact.

The findings indicate that both market-based and science-based cross-organizational collaborations yield a significant enhancement in FIR, with the latter demonstrating superior effectiveness. This outcome persists even after undergoing robustness tests. While prior literature has produced similar findings [24], it has not differentiated between various types of cross-organizational collaborations. Collaborations with diverse partners possessing disparate value orientations and varied resources are likely to exert distinct impacts on FIR, thus justifying the segmentation and comparison of cross-organizational collaborations. Market-based cooperation with suppliers and customers facilitates rapid responses to market demands, and enables the comprehensive integration and optimization of supply chain resources, thereby fostering FIR [41,73]. Nevertheless, major disruptions impose financial strains on firms, potentially leading to constraints or cessation of R&D funding. Conversely, universities and research institutes receive substantial research funding from the government and are less susceptible to market shocks, serving as stable repositories of scientific knowledge and innovation. Consequently, science-based IURC significantly bolsters FIR.

Moreover, this study identifies spatial heterogeneity in the impact of cross-organizational cooperation on FIR, manifesting a more favorable role in the eastern region and the Yangtze River Basin region. This finding corroborates existing research outcomes [20]. Both the eastern region and the Yangtze River Basin region exhibit heightened levels of economic development, superior digital infrastructure, and industrial structure, as well as a more concentrated and dynamic exchange of innovation resources. These attributes collectively contribute to the positive impact of cross-organizational cooperation within these regions.

Thirdly, the investigation of the transmission mechanism of cross-organizational cooperation affecting FIR unveils that liquid assets and main operating income play a mediating role. Resilient cross-organizational partnerships serve to alleviate firms' liquidity challenges, enhance the efficiency and precision of product production and manufacturing, and enable swift responses to the market demand for innovative products and services, thereby enhancing financial performance. Sound cash flow and operating income serve as a safeguard for firms' R&D expenditures and their ability to address risks [24,49]. This suggests that the contribution of cross-organizational collaboration to FIR can be realized through the improvement of firms' cash flow levels and operating income.

Finally, this study emphasizes the significance of digital transformation and digital technology innovation for firms seeking to enhance FIR through cross-organizational collaboration in the digital era. On one hand, digital transformation and digital technology innovation enhance the efficiency of information access and dissemination, thus mitigating spatial barriers arising from geographical distances. This facilitates timely communication among partners, diminishes information asymmetry, and elevates the level of trust [55,58]. On the other hand, digital transformation reduces impediments to the cross-organizational flow and absorption of innovative resource elements, lowers the cost of collaboration, and fortifies enterprises' capacity to withstand risks [56,60]. In essence, digital transformation and digital technology innovation positively moderate the impact of cross-organizational cooperation on FIR.

6.2. Research significance

This study makes three significant theoretical contributions. firstly, this study integrates the concept of resilience into the process of enterprise innovation and proposes a quantitative assessment framework for IR. IR is a complex multidimensional concept, encompassing abilities such as stability and adaptability in uncertain environments [10]. Previous research has highlighted the importance of factors such as funding, talent, technology, and market conditions for enterprise innovation. Building upon the existing literature review, this study takes into account the multidimensional and complex nature of IR, utilizing the entropy weight-TOPSIS method to propose a comprehensive indicator system. This system includes five primary indicators, such as tolerance for resource scarcity and market uncertainty, as well as 20 subordinate indicators, providing a thorough and relevant reference for future FIR research.

Secondly, this study contributes empirical evidence on how cross-organizational collaboration influences FIR at a finer granularity, enriching existing literature. The study categorizes cross-organizational collaboration into market-based and science-based types and clarifies ambiguous or contrasting results found in previous literature. Our empirical results unequivocally demonstrate that both forms of collaboration enhance FIR, with science-based collaboration showing a more pronounced positive effect. The study also introduces and supports the mediating roles of asset liquidity and operating income in market-based and science-based alliances, revealing the underlying mechanisms through which cross-organizational collaboration influences IR.

Thirdly, we extend existing research to the digital era characterized by accelerated digital transformation and frequent technological advancements, contributing to the literature. Existing studies indicate that current research on digital transformation primarily focuses on industrial enterprises' production and operation methods (e.g. see Ref. [27]), neglecting the link between cross-organizational cooperation and IR. Building on sound theoretical assumptions and rigorous empirical analysis, we identify a positive moderating effect of digital transformation. In other words, enterprises with high degrees of digital transformation and digital innovation tend to leverage collaboration more effectively to enhance IR. Therefore, our research findings offer theoretical insights into the new challenges and opportunities faced by enterprises in enhancing FIR in the digital era.

In addition to the aforementioned theoretical implications, this study holds significant practical relevance for managers, companies, and policymakers. Firstly, the research findings demonstrate that market-based partnerships and science-based collaborations have distinct impacts on FIR, offering a more nuanced perspective for enhancing FIR. Managers should duly appreciate both forms of partnerships and, based on the specific attributes and needs of their companies, seek out suitable partners. For instance, universities and research institutions serve as crucial producers of highly specialized knowledge, contributing to more innovative outcomes for companies; whereas suppliers and customers, with close market connections, help companies swiftly adapt to changes in the market environment. Secondly, this study emphasizes the impact of digital transformation, providing practical insights for managers and policymakers. Digital transformation plays a crucial role in reducing costs, enhancing collaboration efficiency, and mitigating information asymmetry, thus facilitating collaborative innovation. In this context, managers and policymakers are required to implement effective measures to drive digital transformation, thereby supporting the enhancement of FIR.

6.3. Conclusions

This study empirically investigates the impact of cross-organizational cooperation on FIR using panel data spanning from 2016 to 2020. The province and time double fixed effects model is employed to analyze this relationship. Specifically, this study examines whether market-based cross-organizational cooperation and science-based IURC positively contribute to the enhancement of FIR. These distinct forms of cross-organizational cooperation are included in the benchmark regression model. Moreover, this study explores the mediating and moderating variables of cross-organizational cooperation and IR. The study yields the following key findings: (1) Market-based cross-organizational cooperation and science-based IURC significantly and positively influence IR. Notably, IURC demonstrates the most pronounced effect on enhancing FIR. (2) The positive impact of cross-organizational cooperation on FIR is spatially heterogeneous. Specifically, the facilitating effect of cross-organizational cooperation is more significant in the eastern region than in the western region, and more significant in the Yangtze River Basin than in the Yellow River Basin. (3) The study establishes the mediating role of current assets and main business income, indicating that cross-organizational cooperation drives the enhancement of FIR by augmenting the current assets and main business income of firms. (4) The favorable impact of cross-organizational cooperation on FIR escalates with the advancement of digital technology innovation and digital transformation.

6.4. Policy recommendations

Based on the aforementioned conclusions, this paper proposes the following recommendations: Firstly, it is advised to actively pursue communication and CS and CC, with a particular emphasis on fostering IURC. Establishing an open communication mechanism, an effective sharing channel, a diversified dispute resolution mechanism, and a robust regulatory system among partners are crucial steps toward establishing an open and transparent platform for high-quality cross-organizational cooperation. This will enhance the efficiency of resource integration along the value chain, foster trust among partners, encourage knowledge sharing, and facilitate collaborative innovation, ultimately enabling firms to collectively address the challenges posed by uncertain risks. Furthermore, enterprises should proactively enhance their own learning and absorption capacities. In the process of knowledge sharing, enterprises can leverage digitalization to facilitate the identification, digestion, utilization, and even updating of core technologies. This will further strengthen FIR.

Secondly, as spatial heterogeneity hampers the promotional effect of cross-organizational cooperation on IR, it is imperative to strengthen cross-regional cooperation to facilitate the cross-regional interconnection of innovation factors. Developed cities in the eastern region should leverage their developmental advantages to actively propel less developed regions forward by establishing cross-regional innovation networks and conducting cross-regional innovation talent training, thereby further unlocking the potential of cross-organizational cooperation's impact on IR.

Thirdly, great emphasis should be placed on the positive impact of digital technology innovation and digital transformation in fostering IR, with an active push to increase the level of digitization. Enterprises should keep abreast of digital transformation trends and ramp up investments in core digital technologies such as artificial intelligence, cloud computing, and big data. Actively engaging in the construction of digital collaborative innovation platforms will deepen cross-organizational cooperation and innovation within the framework of advancing the digitization process. The level of digitization is contingent not only on enterprises' internal investment in digital technology but also on external digital infrastructure. Therefore, government departments should further bolster the development of digital infrastructure such as cloud computing platforms and broadband infrastructure networks to alleviate the pressure of digital transformation on enterprises. Simultaneously, the government can establish digital service and consulting centers for enterprises to alleviate the challenges encountered during digital transformation.

Fourthly, it is recommended to establish systematic financial incentives and policy support mechanisms to improve the resilience of enterprises through technological innovation. Specifically, to alleviate the financial liquidity pressure faced by enterprises during technological innovation under uncertain market demand, innovation funds can be established, together with the provision of tax incentives and financial subsidies. Additionally, technology cooperation and transfer between enterprises, or between enterprises and research institutes, should be actively encouraged to introduce competitive new products and services.

6.5. Limitations and future directions

While the study makes valuable contributions and provides meaningful conclusions, it is important to acknowledge certain limitations that should be taken into consideration. Firstly, the sample only covers the collaboration on product or process innovation among large industrial enterprises. This approach has its own merits and drawbacks. On the one hand, these enterprises play a significant role in the national economy, and their collaborative innovation activities can reflect common phenomena within a certain range of enterprises. On the other hand, this limits the generalizability and applicability of the research findings. Future studies should aim to broaden the sample range, distinguishing among enterprises of varying scales and types, to comprehensively investigate the impact of cross-organizational cooperation on IR. Secondly, this study constructs a valuable indicator system for IR using the entropyweighting TOPSIS method. However, due to the research focus and space limitations, a case study approach was not employed to further delve into the proposed framework. As previous studies have shown, case study research offers various benefits (e.g. see Ref. [66]). Therefore, future research could consider delving deeper into specific cases to understand how enterprises address innovation challenges in real-world settings, thus enriching the research perspective. Thirdly, our study primarily examines the relationship between cross-organizational cooperation and IR in the digital age from a financial perspective. However, the factors influencing IR are multidimensional and multifaceted, making it difficult to fully capture them through financial data alone. In future work, we advocate for exploring the interaction between cross-organizational cooperation and IR from various dimensions. For instance, investigating the relationship mechanism from the perspectives of knowledge transfer or corporate strategy may provide additional insights to the research.

CRediT authorship contribution statement

Houxue Xia: Methodology, Investigation, Funding acquisition, Conceptualization. **Mingwei Liu:** Writing – original draft. **Pengcheng Wang:** Validation. **Xiukun Tan:** Writing – review & editing, Conceptualization.

Data availability statement

Data included in article/supp. material/referenced in article.

Ethics declarations

Review and/or approval by an ethics committee was not needed for this study because it does not involve human experimentation.

Additional information

No additional information is available for this paper.

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.

Declaration of competing interest

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Acknowledgements

This research was supported by the National Social Science Foundation of China (granted number：21CJY055).

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