



OPEN Explorative industrial internet promotes open green innovation in manufacturing enterprises

Rui Hu¹, Ma Guoyong¹✉, Adnan Abbas² & Muhammad Umair Wattoo¹

This study investigates the effect of the explorative industrial Internet on open green innovation in manufacturing enterprises. This study draws on a robust theoretical foundation to develop and examine the hypothesized relationships among the key framework variables. A total of 406 manufacturing enterprises participated in the study through a structured questionnaire survey. SEM was used to analyze the collected data and test the relationships described in this study. The results show that manufacturing enterprises benefit from the direct and significant relationship between explorative industrial Internet and open green innovation. The relationship between the explorative industrial Internet and open green innovation in manufacturing is boosted by value co-creation, which advanced manufacturing technology facilitates as a crucial mediator. Firm resources are necessary when companies use the explorative industrial Internet to enhance innovation results. This research provides vital insights for scholars and business professionals on how digital transformation enables manufacturing enterprises to develop sustainable innovation. This study provides essential operational guidance to organizations seeking to integrate industrial Internet technologies to enable open green innovation and competitive market advantage. This study advances academic knowledge of digital transformation and sustainable innovation by analyzing the relationships between explorative industrial Internet open green innovation and advanced manufacturing technology. This study explains why manufacturers use digital technologies to improve their sustainability and economic performance.

Keywords Explorative industrial internet, Firm resources, Value co-creation, Open green innovation

A new wave of scientific, technological, and industrial breakthroughs is currently unfolding. This ongoing evolution is marked by groundbreaking innovations that are transforming industries and opening new growth opportunities for companies. The core characteristics of which—digitalization, networking, and intelligence—are being examined in depth on a global scale. This transformation fosters increased efficiency, sustainability, and the development of novel business models across various sectors. These shifts are not only redefining economic landscapes but also enhancing global competitiveness and fostering a more interconnected and automated world^{1,2}. This change is mainly aimed at the in-depth promotion and application of new technologies, which will have a profound influence on the global economy and industrial landscape³. This revolutionary change, characterized by digitalization, networking, and intelligence, is gradually transforming the global economic landscape. As a network and manufacturing power, China urgently needs to seize new opportunities in industrialization and intelligent integration and transform into a network- and manufacturing-driven power driven by innovation⁴.

Various unpredictable factors have emerged to shape global markets in recent years, owing to the complex international environment and market uncertainties. These elements include socioeconomic shifts, international political dynamics, and technological progress⁵. Modern businesses face extraordinary challenges because next-generation digital technologies, including big data, cloud computing, and artificial intelligence, have progressed rapidly. The digital revolution has spread worldwide because the digital economy has established a transformative model⁶. Against this backdrop, countries worldwide are embracing these changes. The digital economy has emerged as an industry that integrates data utilization in manufacturing processes and digital technology through internet platforms⁷. From an economic perspective, the industrial Internet is characterized by the integration of the Internet of Things and data analytics into industrial processes⁸. By monitoring operations in real time and making optimal adjustments, operational efficiency and sustainability can be significantly improved. Industrial Internet technology focuses on augmenting existing capabilities by improving process efficiency and resource management⁹.

¹College of Economics and Management, Northeast Forestry University, Harbin, China. ²School of Accounting, Harbin Finance University, Harbin, China. ✉email: maguoyong@nefu.edu.cn

Many recent studies have confirmed that these technologies can drive operational excellence and foster sustainable innovation^{10,11}. Traditional industrial operations face significant challenges because supply and demand structures are misaligned, external events disrupt operations, and excessive industrial capacity requires effective management. Through innovation and efficiency, the technology-based industrial Internet offers three benefits that help conventional companies optimize operational and resource management. Numerous studies have shown that the explorative industrial Internet enables organizations to foster cultural environments that promote creative approaches to radical innovation and business model transformations¹². The practical use of the Industrial Internet through explorative methods delivers substantial improvements in manufacturing sustainability. Companies develop new products and production methods that reduce environmental impacts. The development of environmentally friendly products and processes using this method reduces companies' environmental impact. This explorative strategic orientation not only enhances the company's adaptability in a rapidly changing market but also positions it as a leader in green innovation and sustainability.

The relationship between digital economic elements and environmentally friendly open innovation models has already been analyzed¹³. (1) The growing interest among businesses in developing environmentally friendly innovations for sustainability has not been thoroughly analyzed alongside the effect of emerging digital technologies, such as the industrial Internet, on encouraging open green innovation. This raises the question of whether the industrial Internet is sufficient to enable open green innovation ventures. Complex and changing external dilemmas and internal contradictions complicate the impact of the digital transformation of traditional industries on open green innovation. The industrial Internet is driven by innovation; however, in its early stages, significant funding is required to develop digital facilities and platforms, thereby delaying its impact on open green innovation. The application scenarios of industrial Internet platforms are complex, with high standards for industrial infrastructure, and their deployment process is relatively cumbersome. In addition, its operational model involves multiple participants; therefore, the platform's construction and operation require substantial human, material, and financial resources. The platform operates in an industry with a long return-on-investment cycle; therefore, its direct economic benefits are not significant.

(2) Researchers have focused on discovering productive ways to boost the impact of the explorative industrial Internet on OGI and have analyzed the fundamental connections between these two components. The theoretical model of the impact mechanism of the industrial Internet on the OGI was clarified. The development of the industrial Internet presents significant stage characteristics and regional differences in China. In this study, we investigated the complex causal relationship between the Industrial Internet and OGI and further analyzed the heterogeneous effects of this relationship in different regions. This study reveals how the industrial Internet affects the OGI of traditional industries by driving open innovation and developing quality economic growth through modernized traditional industry models.

(3) The literature contains studies on the environmental effects of the digital economy and open green innovation. However, it lacks an examination of the specific relationship between the industrial Internet and open green innovation. The lack of research on the relationship between the industrial Internet and OGI undermines the effectiveness of targeted policies, management models, and green development practices. This study makes the following significant contributions through its evaluation system for measuring industrial Internet development levels across regions. This study examines the development trends and regional variations of the industrial Internet and open green innovation. The following section reviews the existing literature to develop theoretical bases for hypotheses examining these relationships.

Theoretical foundation and hypothesis development

Platform theory provides a valuable lens for understanding the transformative role of digital platforms in fostering innovation, collaboration, and value creation across sectors. According to the study¹⁴, technological frameworks and platforms bring together various business entities—customers and suppliers—to enable the collaborative exchange of information assets, resulting in valuable joint production. According to platform theory, enterprises must balance utilitarian and explorative activities to achieve long-term success in the industrial Internet. Organizations adjust their current processes through exploitative activities, whereas explorative activities involve developing new knowledge, technological progress, and innovative approaches. Through this theory, organizations receive guidelines for running both small-scale and groundbreaking innovations from their perspective. In the context of the explorative industrial internet, platforms not only connect stakeholders but also enable open innovation by leveraging real-time data analytics, automation, and smart manufacturing technologies. This theory describes effective methods for companies to conduct utilitarian and explorative activities in the context of green innovations.

OGI develops collaborative solutions for sustainability, grounded in platform theory. Under EPRII and platform theory, firms combine resources and information to create efficient innovations that improve environmental sustainability. Business organizations should actively involve external stakeholders in their innovation systems to achieve better results, as this approach helps address complex sustainability issues¹⁵. Platform theory centers on value co-creation, particularly in the context of digital platforms such as the Industrial Internet. The innovation process becomes a collaborative effort through value co-creation, as firms integrate their customers, suppliers, and other stakeholders to develop new products and technologies^{16,17}. The explorative industrial internet provides an optimal framework for fostering co-creation by enabling seamless collaboration among ecosystem entities in the industrial sector, thereby driving green innovation solutions to address environmental challenges¹⁸.

The value of products or services for users increases directly with the number of existing network members. As networks grow and different user groups interact, the usefulness of products or services for various user segments also grows. This, in turn, attracts more users to the platform, expanding the overall user base. The positive feedback loop created by this process boosts the value of the company's offerings, significantly impacting

the development and sustainment of competitive advantage. According to platform theory, researchers gain crucial insights into modern digital economic mechanisms that influence innovation amid competition. Digital platforms enable diverse groups to interact and generate innovations, leading to improved operational efficiency and competitive shifts. Platforms that benefit from network effects constitute a core element of this theory, where the platform's value rises as more users join, creating a positive feedback cycle. These network effects can be direct—adding more users increases value—or indirect—arising from complementary goods and services. Building on this foundation, this study hypothesizes that explorative industrial Internet has a positive impact on advanced manufacturing technologies, open green innovation, and value co-creation. Additionally, the mediating roles of advanced manufacturing technologies and value co-creation, along with the moderating role of firm resources, deepen the understanding of how platforms promote sustainable industrial innovation.

The direct impact of (EPRII) on (OGI), (VCC), and (AMT)

Worldwide, the industrial Internet has emerged as a shared strategic priority for nations looking toward the future. The power of the Fourth Industrial Revolution is on the rise¹⁹ new era. Developed countries have made significant advances in establishing their presence in the industrial Internet sector, and China is following suit and standing on the same starting line. The industrial Internet is essential for transforming and upgrading traditional manufacturing in China to achieve intelligent manufacturing. It integrates advanced technologies to improve efficiency, enhance productivity, and foster innovation, helping manufacturers become more competitive and sustainable²⁰. At the same time, it plays a crucial role in the growth of the digital economy. China has set a clear goal for the top-level design of the Industrial Internet. This plan emphasizes several key areas: accelerating the development of new infrastructure, expanding the scope of integrated and innovative applications, strengthening security measures, optimizing the industrial ecosystem, and providing appropriate policy support. These initiatives are intended to position China as a leader in the global industrial Internet landscape, fostering innovation and ensuring a robust infrastructure to support future growth²¹. At present, the manufacturing industry faces challenges including shortages of system framework resources and environmental capacity, rising labor costs, and an urgent need for technological innovation. Efficient, low-cost, and environmentally friendly production management has become the only means of developing the manufacturing industry²². The global manufacturing industry's competitive landscape is being reshaped by information technology. To capitalize on the opportunities presented by the industrial Internet and facilitate China's transformation, the manufacturing sector will be instrumental in fostering the growth of a new economy.

The industrial Internet combines IoT, big data, IT, and security to enable strategic integration. Next-generation technologies use these to connect with advanced industries and modernize sectors²⁰. This integration enhances industrial processes, improves data-driven decision-making, and strengthens cybersecurity, fostering innovation and growth across various sectors²³. China has a vast manufacturing base and is currently in a critical period of transformation from scale expansion to quality improvement²⁴. Manufacturing industries are developing industrial Internet subsystems based on these traits. China's 14th Five-Year Plan serves as a strategic blueprint for steering its economy and society toward high-quality, innovative growth, aiming to achieve social prosperity and advance socialist modernization in the new era²⁵. China is currently advancing its economic expansion through high-quality development, driven by innovation and structural changes. Chinese economic development is now shifting toward higher-quality growth that integrates sustainable practices with efficient operations to enhance productivity and market competitiveness.

Industrial Internet infrastructure development with innovation means full adherence to international economic standards and sustainable growth. The current wave of technological advancement, with its emphasis on big data, the Internet of Things, and artificial intelligence, provides China with the strategic opportunities it needs to pursue. The implementation of these technologies will reshape the economy by strengthening China's international market. China needs to enhance its self-driven innovation capabilities through the 14th Five-Year Plan to achieve breakthroughs in critical technologies and lay the foundation for future advanced industrial development²⁶. Various researchers have conducted extensive studies on internet development, analyzing technological innovation, industrial structure transformation, and upgrading²⁷. Research has primarily focused on the effects of technological innovation on Internet growth, the implementation of big data, and the structural changes enabled by open innovation. This narrow focus limits the exploration of other significant influences that these technologies may have on broader industrial transformations. Further studies could illuminate their role in promoting economic growth and sustainability²⁸.

This study optimizes environmental challenges and business decision-making operations while providing critical knowledge and practical insights for organizations across all industry sectors²⁶. The complexity of the process and the uncertainty it entails pose significant challenges for governments and management teams seeking to implement green innovation practices in industrial operations. Governments must adopt long-term policies to actively protect the environment. Therefore, researching green, innovative technologies for enterprises is essential to reducing environmental harm, improving the quality of life, and supporting the country's economic development. VCC activities enable companies to develop the ability to deliver exceptional value. This study investigates Chinese manufacturing companies, using them as the primary research subjects to evaluate the influence of the EPRII on open green innovation. The research hypotheses for this study emerge from the theoretical foundation as follows:

H1a: The EPRII has a positive impact on AMT.

H1b: The EPRII has a positive effect on OGI.

H1c: The EPRII has a positive impact on VCC.

The mediation role of advanced manufacturing technology (AMT)

The term AMT refers to various computer-driven systems that improve industrial process performance. Production processes benefit from systems such as computer-aided design and computer-aided manufacturing, manufacturing resource planning, robotics, group technology, and flexible manufacturing systems to achieve higher efficiency and precision while increasing flexibility. These technologies aim to improve manufacturing efficiency, enhance product quality, and enable greater customization in the production process²⁹. Together, these technologies form the core framework of AMT, which provides strong support for the efficient operation of modern manufacturing³⁰. By applying these technologies, the digitalization, automation, and intelligence of the manufacturing process can be realized, thereby improving production efficiency, reducing costs, and enhancing enterprises' market competitiveness. The association with computer-integrated factory automation connects AMT as a multidimensional approach that uses various technological elements. This study divides AMT adoptive analysis into three distinct categories: design AMT, process AMT, and managed AMT. The design AMT category comprises technologies that support product planning and design, whereas process AMT provides technology controls to direct production activities and generate process-related information. Managed AMT comprises technologies that aid in the management and optimization of operations.

Modern manufacturing depends heavily on technologies such as robotics, artificial intelligence systems, computer-aided manufacturing, and control systems to boost industrial intelligence. Manufacturing companies improve production efficiency and product quality by adopting these advanced technologies. Studies have shown that AMT offers multiple benefits to manufacturers, including market expansion, higher profitability and flexibility, lower costs, faster delivery, and improved product quality—thereby increasing productivity and strengthening their competitive edge³¹. In recent decades, researchers have credited AMT with driving innovation in design, planning, and manufacturing³². Surprisingly, empirical evidence on the benefits of AMT for geographic information is limited. According to³³, Manufacturing companies urgently need to understand the effects of AMT before adopting geographic information technology solutions. Without an understanding of AMT's benefits, developing a classification system for manufacturing firms' geographic activities is hindered. Using AMT, businesses can reduce pollution, share management techniques, boost efficiency, and improve performance, gaining a competitive edge³⁴. In addition, organizations can engage in AMT-based innovation. AMT often brings dramatic changes to an organization's operations and technology. From the moment an organization starts adopting AMT, it gains process innovation and green products³⁵. As per the discussion of the critical role of these variables in promoting green innovation, this study proposes the following hypotheses:

H2A: AMT has a positive impact on OGI.

H2B: AMT has a positive effect on VCC.

H2C: AMT plays a mediating role between the EPRII and OGI.

The mediation role of value co-creation (VCC)

Value co-creation (VCC) is a collaborative process in which a business and its customers or stakeholders co-develop new products, services, or experiences³⁵. In the context of green innovation, VCC facilitates the development of environmentally friendly products and technologies through open innovation. Businesses collaborate with external partners, such as suppliers, competitors, and research institutes, to conduct activities that foster sustainable innovation, a form of open green innovation³⁶. Research evidence indicates that collaboration-driven value creation catalyzes open green innovation³⁷. When regulations tighten, companies must undertake more costly measures to maintain compliance, which may prompt them to develop novel partnership models to meet their environmental targets. Open innovation practices for creating green innovations become less necessary as regulations become less stringent³⁸. The beneficial effect of VCC extends to OGI, as companies recognize the advantages of collaborating on sustainability innovations to meet regulatory requirements.

Co-creation is the process of generating new value through association, collaboration, parallelism, and reciprocity, including material and symbolic values. The literature has engaged in an ongoing discussion of the distinction between co-creation and co-production, highlighting the importance of clearly differentiating between the two³⁹. Other perspectives on innovation research should also be considered when defining the boundaries of co-creation within management-related theories⁴⁰, which focus on collaborative and open processes involving both the company and the user. Information systems studies fall under this field and therefore focus on customer relationship management, customer engagement technology platforms, and open innovation. Under the OGI framework, companies collaborate with external partners, including suppliers, competitors, and research institutes, to develop sustainable innovations³⁶. This process emphasizes cross-border cooperation and resource sharing to promote the win-win development of environmental protection and the regional economy. VCC is a collaborative process in which a business and its customers or stakeholders co-develop a new product, service, or experience. In the context of green innovation, value co-creation fosters the development of environmentally friendly products and technologies through open innovation. Building on prior research, this study investigates how Chinese manufacturing enterprises influence the exploration of the industrial Internet to enhance open green innovation through the lens of value co-creation. Accordingly, this study proposes the following hypothesis:

H3a: VCC has a positive impact on OGI.

H3b: VCC plays a mediating role between EPRII and OGI.

The moderation role of firm resources (FR)

The industrial development of the Internet of Things (IoT) framework faces critical barriers due to resource constraints, mounting environmental concerns, and rising labor costs. The manufacturing sector faces these factors as significant barriers to its current development. Technological innovation is urgently needed in industry to advance sustainable industrial development through affordable production management methods that protect the environment⁴¹. Multiple innovative technologies and manufacturing processes at AMT lead to greater production efficiency, reduced waste, and minimized environmental impact⁴². However, companies rely heavily on their resources to successfully implement advanced manufacturing technologies and maximize their benefits⁴³. The success and performance of advanced manufacturing technology depend heavily on the firm's resource levels.

According to the Resource-Based View (RBV), a company's unique tangible and intangible resources are essential for leveraging new technologies to achieve competitive advantage and sustainable development⁴⁴. AMT requires physical resources, including state-of-the-art machinery and facilities, as well as financial capital to function correctly. Intangible resources, including organizational knowledge, technical expertise, and innovation capabilities, are essential for integrating AMT into green innovation practices. Research⁴⁵ highlights the importance of these resources in promoting technological progress and fostering a culture of innovation. Firm resources regulate the relationship between advanced manufacturing technology and open green innovation; the more resource-rich the enterprise, the greater the positive impact of its advanced manufacturing technology on open green innovation.

Various scholars have analyzed the development of the Internet, technological progress, and industrial structural evolution. Most academic studies primarily analyze how technological innovation affects Internet development and big data use, and how open green innovation aligns with industrial structural changes. An extensive research gap exists regarding how these technologies converge to shape industrial transformation and sustainable development⁴⁶. However, the extent to which companies can harness the full potential of the explorative industrial Internet for open green innovation depends mainly on their resources. According to the RBV theory, a company's tangible and intangible resources are essential for leveraging new technologies to pursue sustainable development and competitive advantage⁴⁴. Tangible resources, such as advanced information technology, infrastructure, capital investment, and cutting-edge machinery, provide a necessary foundation for integrating EPRII technology.

Simultaneously, intangible resources such as technical expertise, innovation culture, and organizational knowledge facilitate the effective absorption and utilization of these technologies^{47,48}. Enterprises with significant resources are better able to adopt and adapt explorative IIoT technologies, collaborating with external partners through open innovation practices to drive the development of environmentally friendly products and processes. By proposing this hypothesis, this study aims to examine how the allocation and utilization of firm resources can amplify the benefits of explorative industrial Internet technologies and, in turn, strengthen OGI practices, thereby promoting sustainable environmental and economic development in China. Such an innovative approach not only helps protect the environment but also provides a sustained impetus for long-term, stable economic growth. Studies examining firm performance under various economic conditions have failed to identify which resource dimensions have the greatest impact. Value co-creation is a fundamental process for developing environmentally friendly products and technologies through open innovation within the green innovation context. Therefore, this study proposes the following hypothesis:

H4a: FR has a moderating effect between AMT and OGI.

H4b: FR has a moderating effect between the EPRII and OGI.

H4c: FR has a moderating effect on the relationship between VCC and OGI.

Figure 1 shows the relationship of each hypothesis below.

Methodology

Research design and analytical approach

According to the proposed conceptual framework, this research paper employed a quantitative research design to empirically test whether explorative industrial Internet (EPRII) mediates open green innovation (OGI). The survey employed a structured questionnaire to collect firm-level information on manufacturing enterprises in China. Quantitative research was chosen to test the hypothesized relationships and to refine the proposed impact mechanism using rigorous statistical methods. We used Smart PLS software to bootstrap resamples of size 5000 in this study to test the hypothetical relationships.

Measurement development and instrument design

The measurement scales used in this study were based on well-developed, extensively validated scales developed by internationally recognized scholars. The relevant literature review was carried out in order to guarantee construct validity and conceptual consistency. Minor contextual adjustments were also made where necessary to align the items with the research aims and the nature of Chinese manufacturing companies.

The original English-language questionnaire was professionally translated into Chinese to ensure linguistic precision and contextual appropriateness, with assistance from experienced personnel in innovation and research on the industrial Internet. The translation process focused on semantic equivalence and conceptual consistency rather than literal translation. Appendix 1 contains the complete list of questions and their wording in the questionnaire.

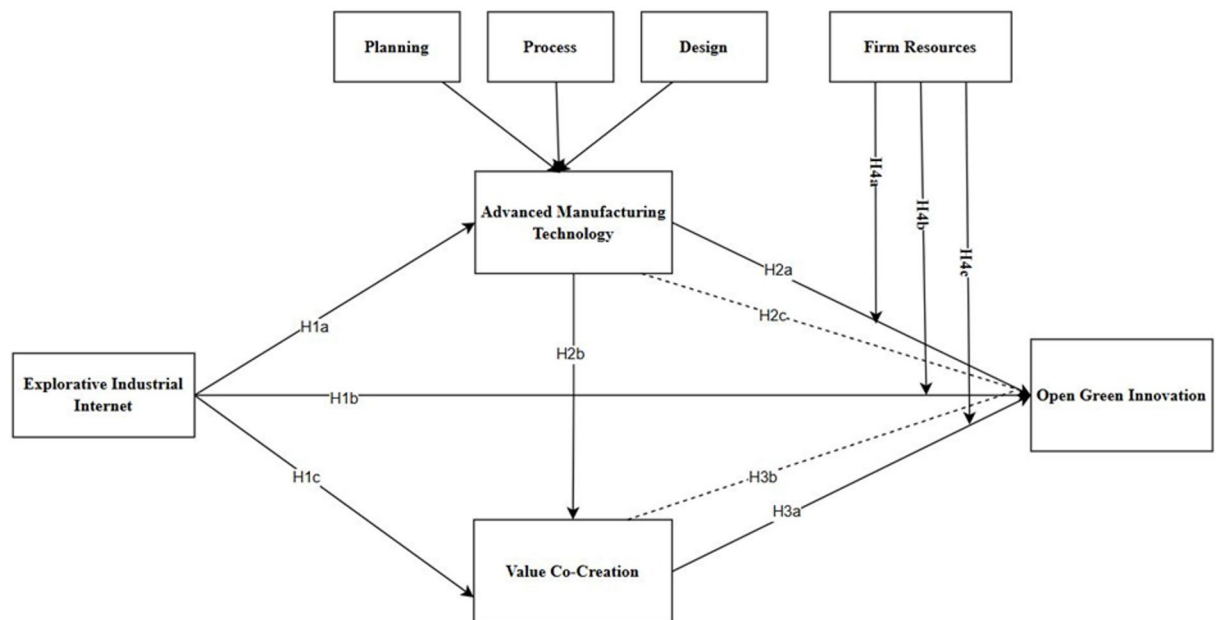


Fig. 1. Research framework of study.

The basic theoretical findings elucidate EPRII and its role in OGI. The four items of the Explorative Industrial Internet were derived from⁴⁹. This study used three dimensions of AMT: *design, planning, and process*. Which five items of design, four items of planning, and four items of process were adapted from the study of³³. The four items of value co-creation (VCC) are adapted from⁵⁰. Four items of the OGI were adapted from Chang⁵¹ to meet the research objectives. 7 items of Firm Resources excerpted from⁵².

Questionnaire refinement and content validity

To make the questionnaire more relevant to the current development stage of the Industrial Internet and to open green innovation practices, a focus group discussion was conducted. The focus group included two academic scholars specializing in innovation research and three doctoral students with methodological expertise. According to feedback, ambiguous wording was corrected, unnecessary questions were eliminated, and phrases were clarified, precise, and understandable to respondents. This enhanced the content validity and the situational relevance of the measurement tool.

Scale format

All perceptual measures utilized a seven-point Likert scale, with 1 indicating strongly disagree and 7 indicating strongly agree. The seven-point scale offers greater sensitivity than shorter scales, enabling respondents to express subtle attitudes and perceptions, thereby improving measurement accuracy and variability.

Sampling strategy and study context

This study employed a purposive sampling approach to target knowledgeable respondents from Chinese manufacturing enterprises. The respondents were managerial-level employees with adequate knowledge of the firm's technological and innovation practices. To manage firm heterogeneity, various organizational attributes have been collected, including ownership structure, industry, and enterprise size. The Chinese Securities Regulatory Commission (CSRC) standards were used to classify industries into agricultural manufacturing, petroleum manufacturing, electrical machinery and equipment manufacturing, pharmaceutical manufacturing, and other manufacturing industries. Enterprise size was categorized into small and micro enterprises, medium-sized enterprises and large enterprises, according to the predetermined Chinese enterprise classification criteria.

Data collection procedure and response rate

The data were collected through a structured questionnaire administered to respondents of qualifying manufacturing firms. The survey collected data on construct-level variables and demographics. Data on gender, work experience, education level, and respondents' roles were provided to enhance the analysis and provide further insights.

A structured survey was administered to approximately 600 manufacturing enterprises in China. The response rate was approximately 76.3%, with 458 questionnaires returned. During data screening and refinement, some responses were excluded to ensure data quality. First, 8 questionnaires were excluded due to a high number of missing or incomplete responses. Second, 11 responses were excluded due to straightlining, indicating no thoughtful participation in the survey. Additionally, 18 questionnaires were excluded due to inconsistent or illogical response patterns identified during reliability testing. In addition, 15 responses were excluded because respondents failed to meet the initial screening criteria, such as a lack of familiarity with their firm's industrial

Internet or innovation practices. After that, 406 were deemed valid following these refinement processes and were sent to the final empirical analysis. This data cleaning procedure is systematic, thereby increasing the reliability and validity of the results, as the retained responses are meaningful and support informed decisions.

Ethical considerations

The survey was conducted voluntarily, and respondents were informed of its academic purpose. All procedures carried out in this study involving human participants are in compliance with the ethical standards of the respective institutions and/or national research committees, as well as the 1964 “Helsinki Declaration” and its subsequent revisions or similar ethical standards. Although no experimental procedures were carried out and no human tissue samples were used, the study involved the participation of individuals through the application of an anonymous questionnaire. None of the participants was forced to participate in this study, and no rewards were offered. Confidentiality and anonymity were also guaranteed, and no information that could identify individuals was gathered. All responses were utilized solely for research purposes in line with the general ethical guidelines concerning social science research.

Demographic profile of respondents

The sample’s respondent profile is balanced and informative, which increases the analysis’s power as shown in Table 1. The proportion of male respondents is higher, reflecting the gender composition of China’s manufacturing industry. Most respondents have moderate to substantial work experience, indicating that the data were provided by individuals with sufficient exposure to organizational processes and technological practices. The educational level of the respondents is rather high, as most of them have an undergraduate degree, which implies enough cognitive abilities to evaluate the problems associated with the industrial Internet and innovation processes.

From an organizational perspective, responses are obtained nearly equally from middle and top management, enhancing the accuracy of information at the firm level because it reflects both strategic and operational positions. The sample is balanced across ownership types, allowing comparison of state-affiliated and privately owned enterprises. The data range spans a wide variety of manufacturing industries, with greater coverage of traditional and technology-intensive industries, thereby enhancing the data’s generalizability. Finally, there is a good representation of the firms of various sizes, and the findings are not limited to one size of an enterprise, and the conclusions represent the diversity of the Chinese manufacturing environment.

Results

Factor loading, reliability, and convergent validity test

In this study, inter-item reliability was assessed using factor loadings, with a threshold of 0.70⁵³. Table 2 presents the loading values of each factor. All values were above the threshold of 0.70. This study employed Smart PLS-4 to analyze the data, using the measurement model shown in Table 2. The key indicators included Cronbach’s α , composite reliability (CR), and mean-variance extraction rate (AVE). Cronbach’s α was used to assess internal consistency reliability, which reflects the degree of correlation among the items comprising the scale. Composite reliability also measures internal consistency and assesses the consistency between the multiple items

Name	Category	Frequency	Percentage
Gender of the respondent	Male	282	69.5
	Female	124	30.5
Work experience (years)	1 to 3	83	20.4
	3 to 6	194	47.8
	6 to 9	61	15
	More than 9	68	16.7
Educational background	College degree or below	94	23.2
	Undergraduate	180	44.3
	Master’s degree or above	132	32.5
Respondent’s position	Middle management	208	51.2
	Top management	198	48.8
Enterprise nature	State-owned/state-controlled	211	52
	Private/privately held	195	48
Industry type	Agricultural manufacturing enterprises	104	25.6
	Petroleum manufacturing enterprises	110	27.1
	Electrical machinery and equipment manufacturing enterprises	82	20.2
	Pharmaceutical manufacturing enterprises	37	9.1
	Other manufacturing enterprises	73	18
Enterprise size	Small and micro enterprises (less than 300 Employees)	152	37.4
	Medium-sized enterprises (300–1000 employees)	142	35
	Large enterprises (more than 1000 employees)	112	27.6

Table 1. Demographic profile.

Constructs	Items	Factor loadings	CB-Alpha	CR_A	AVE
Advance Manufacturing Design	DAMT1	0.913	0.927	0.929	0.774
	DAMT2	0.905			
	DAMT3	0.861			
	DAMT4	0.866			
	DAMT5	0.851			
Explorative industrial internet	EPRII1	0.850	0.904	0.904	0.776
	EPRII2	0.866			
	EPRII3	0.893			
	EPRII4	0.915			
Firm resources	FR1	0.893	0.947	0.949	0.758
	FR2	0.842			
	FR3	0.892			
	FR4	0.837			
	FR5	0.870			
	FR6	0.878			
	FR7	0.878			
Open green innovation	OGI1	0.822	0.890	0.890	0.753
	OGI2	0.892			
	OGI3	0.904			
	OGI4	0.852			
Planning advanced manufacturing technology	PLAMT1	0.828	0.869	0.873	0.720
	PLAMT2	0.905			
	PLAMT3	0.884			
	PLAMT4	0.770			
Process advance manufacturing technology	PrAMT1	0.894	0.896	0.898	0.763
	PrAMT2	0.873			
	PrAMT3	0.900			
	PrAMT4	0.825			
Value-co creation	VCC1	0.867	0.916	0.917	0.799
	VCC2	0.894			
	VCC3	0.910			
	VCC4	0.904			

Table 2. Factor loading, reliability, and convergent validity.

that comprise a structure. The AVE assesses convergent validity by quantifying the proportion of variance in structural items attributable to measurement error. The thresholds for Cronbach α , CR, and AVE were $\alpha > 0.7$, $CR > 0.7$, and $AVE > 0.5^{54,55}$. According to the results shown in the below, the Cronbach α values for advanced manufacturing technology *design* are $DAMT = 0.927$, $EPRII = 0.904$, $FR = 0.947$ for firm resources, $OGI = 0.890$ for open green innovation, $PLAMT = 0.869$ for *planning* advanced manufacturing technology, $PrAMT = 0.896$ for *process* advanced manufacturing technology, and (VCC) for value co-creation 0.916. These results show that the reliability and validity values meet the threshold requirements.

Discriminant validity

HTMT-matrix

To characterize the differences among the benchmarks, we developed a new measurement method: the HTMT Ratio Standard. An HTMT ratio close to 1 indicates insufficient discriminant validity in the path results⁵⁶. HTMT calculates the impact of a variable (specifically, its upper limit). To clearly distinguish between the two factors, the HTMT should be less than 1⁵⁷. Therefore, within the scope of this investigation, the HTMT ratios were accepted as valid. The HTMT ratios in Table 3 range from 0.000 to 0.846, with a maximum of 0.846. Notably, all values were below the established thresholds, suggesting that discriminant validity was generally accepted in this study.

Cross loadings

The results in Table 4 show that the project loads for each construct exceed the cross-loads for other potential constructs. This conclusion meets the requirements for discriminant validity, indicating that the measurement tool can distinguish between the constructs.

Constructs	DAMT	EPRII	FRI	OGI	PLAMT	PrAMT
EPRII	0.611					
FRI	0.522	0.596				
OGI	0.753	0.760	0.701			
PLAMT	0.737	0.721	0.631	0.831		
PrAMT	0.716	0.661	0.573	0.762	0.846	
VCC	0.560	0.632	0.541	0.696	0.689	0.583

Table 3. Heterotrait-Monotrait ratio (HTMT).

Items	DAMT	EPRII	FRI	OGI	PLAMT	PrAMT	VCC
DAMT1	0.913	0.543	0.497	0.669	0.635	0.610	0.487
DAMT2	0.905	0.453	0.427	0.578	0.555	0.565	0.420
DAMT3	0.861	0.497	0.424	0.592	0.571	0.566	0.488
DAMT4	0.866	0.488	0.393	0.555	0.532	0.551	0.445
DAMT5	0.851	0.479	0.410	0.612	0.611	0.581	0.437
EPRII1	0.513	0.850	0.482	0.597	0.577	0.520	0.525
EPRII2	0.513	0.850	0.482	0.597	0.577	0.520	0.525
EPRII3	0.494	0.866	0.454	0.591	0.539	0.528	0.503
EPRII4	0.485	0.893	0.511	0.614	0.575	0.519	0.485
EPRII5	0.484	0.915	0.490	0.600	0.556	0.532	0.519
FR1	0.449	0.490	0.893	0.609	0.502	0.474	0.459
FR2	0.407	0.486	0.842	0.528	0.497	0.458	0.406
FR3	0.450	0.501	0.892	0.605	0.525	0.489	0.462
FR4	0.432	0.497	0.837	0.497	0.465	0.420	0.387
FR5	0.421	0.447	0.870	0.530	0.500	0.453	0.450
FR6	0.411	0.445	0.878	0.598	0.508	0.478	0.464
FR7	0.422	0.490	0.878	0.555	0.489	0.446	0.445
OGI1	0.588	0.584	0.540	0.822	0.641	0.587	0.533
OGI2	0.617	0.600	0.546	0.892	0.624	0.583	0.543
OGI3	0.588	0.600	0.554	0.904	0.643	0.586	0.562
OGI4	0.587	0.582	0.603	0.852	0.626	0.608	0.545
PLAMT1	0.546	0.526	0.442	0.576	0.828	0.615	0.492
PLAMT2	0.552	0.558	0.500	0.642	0.905	0.656	0.553
PLAMT3	0.588	0.566	0.530	0.659	0.884	0.647	0.563
PLAMT4	0.559	0.513	0.466	0.596	0.770	0.610	0.481
PrAMT1	0.574	0.517	0.450	0.577	0.657	0.894	0.452
PrAMT2	0.542	0.495	0.432	0.594	0.662	0.873	0.450
PrAMT3	0.606	0.548	0.504	0.638	0.681	0.900	0.512
PrAMT4	0.561	0.518	0.460	0.567	0.601	0.825	0.439
VCC1	0.480	0.531	0.455	0.573	0.582	0.503	0.867
VCC2	0.460	0.530	0.481	0.575	0.546	0.451	0.894
VCC3	0.428	0.459	0.426	0.542	0.510	0.428	0.910
VCC4	0.481	0.535	0.443	0.557	0.562	0.511	0.904

Table 4. Items cross loadings.

Common method bias and collinearity statistics

In this study, a Structural Equation Model (PLS-SEM) and Common Method Deviation (CMB) were used, which are systematic errors arising from factors such as a shared data source or measurement environment. This usually occurs when data are collected from a single source at the same point in time. CMB may affect the study's validity. The most common method for testing CMB is Harman's one-way test⁵⁸, particularly in social science research. Therefore, in this study, the researchers used Harman's univariate test in SPSS v26 to identify potential problems with CMB, and the analysis indicated that the first factor accounted for approximately 48.44% of the variance. According to the social science literature, the threshold for CMB is typically set at less than 50%⁵⁹. The Kaiser-Meyer-Olkin Sampling Adequacy Index (KMO) was also used, yielding a value of 0.000.

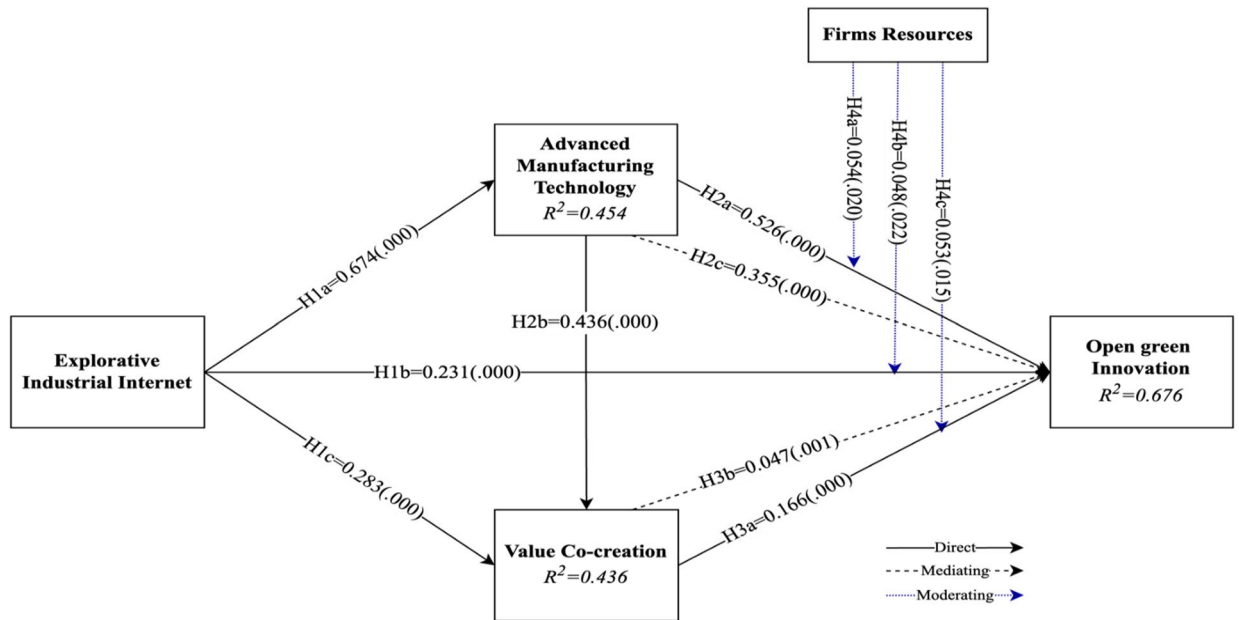


Fig. 2. SEM results.

Hypothesis	Original sample	Standard deviation	T-statistic	P-value
H1a: EPRII→AMT	0.674	0.047	14.343	0.000
H1b: EPRII→OGI	0.231	0.045	5.119	0.000
H1c: EPRII→VCC	0.283	0.052	5.484	0.000
H2a: AMT→OGI	0.526	0.042	12.477	0.000
H2b: AMT→VCC	0.436	0.053	8.187	0.000
H3a: VCC→OGI	0.166	0.037	4.530	0.000

Table 5. Direct effects.

Furthermore, to assess collinearity and multicollinearity, we conducted a full collinearity analysis by examining the variance inflation factor (VIF) for the models. Outer-model VIF values ranged from 1.609 to 4.219 across all indicators. None exceeded the threshold of 5.0, indicating that multicollinearity is not an issue and that these indicators offer unique explanatory power. Similarly, inner-model VIF values of the latent variables ranged from 1.704 to 3.064, indicating acceptable levels. The highest correlations were between platform-level and process-level advanced manufacturing technology, but remained well below the critical threshold of 3.3. These results show that neither CMB nor multicollinearity threatens the validity of the models. This confirms the robustness of the path coefficients and supports the credibility of hypothesis tests and conclusions.

Structural model results

Direct path model results

After conducting an empirical analysis to test the hypothetical structural model, we obtained the structural model path analysis as shown in Fig. 2.

Table 5 below explains the results of the algorithm and guided test, including the effect size (coefficient β) and the corresponding effect significance (t-value and p-value). The results showed that EPRII was positively correlated with AMT ($\beta = 0.647$, $t = 14.343$, $p = 0.000$). Similar to EPRII, IT was positively correlated with OGI ($\beta = 0.231$, $t = 5.119$, $p = 0.000$). In this study, EPRII was also positively correlated with VCC ($\beta = 0.283$, $t = 5.484$, $p = 0.000$), indicating a significant positive association. The study also found a positive correlation between AMT and OGI ($\beta = 0.526$, $t = 12.477$, $p = 0.000$). There was also a positive correlation between AMT and VCC with $\beta = 0.436$, $T = 8.187$, and $p = 0.000$. Finally, the study found that VCC and OGI were positively correlated ($\beta = 0.166$, $t = 4.53$, $p = 0.001$).

Mediation results

The path analysis of the specific indirect effects showed that AMT mediated the relationship between EPRII and OGI ($\beta = 0.355$, $t = 8.633$, $p = 0.000$). These values confirm the significant mediating role of AMT in the relationship between EPRII and OGI. The values for the mediating role of VCC between EPRII and OGI were $\beta = 0.047$, $t = 3.378$, and $p = 0.001$, confirming VCC's mediating role. As shown in Table 6.

Hypothesis	Original sample	Standard deviation	T-statistic	P-value	Bias-corrected confidence intervals		
					Deviation	2.5%	97.5%
H2c: EPRII→AMT→OGI	0.355	0.041	8.633	0.000	-0.001	0.275	0.435
H3b: EPRII→VCC→OGI	0.047	0.014	3.378	0.001	0.000	0.024	0.079

Table 6. Mediation results.

Hypothesis	Original sample	Standard deviation	t statistics	p-Value	Bias-corrected confidence intervals		
					Deviation	2.5%	97.5%
H4a: FR x AMT→OGI	0.054	0.023	2.336	0.020	-0.001	0.010	0.101
H4b: FR x EPRII→OGI	0.048	0.021	2.284	0.022	0.001	0.011	0.094
H4c: FR x VCC→OGI	0.053	0.022	2.425	0.015	-0.001	0.010	0.096

Table 7. Moderation results.

Moderation results

The results showed that FR played a moderating role in EPRII and OGI, with $\beta=0.048$, $t=2.284$, and $p=0.022$. FR moderated the relationship between VCC and OGI ($\beta=0.053$, $t=2.425$, $p=0.015$). FR played a significant regulatory role between AMT and OGI ($\beta=0.054$, $t=2.336$, $p=0.020$). Table 7 shows the list.

Figure 3 shows the moderating effects of FR on the EPRII and OGI. Specifically, the positive impact of EPRII on OGI is reinforced by higher FR levels; companies aiming to improve OGI through EPRII may achieve better results by focusing on increasing FR.

Figure 4 shows the moderating effect of FR on VCC and OGI, indicating that OGI increases as FR increases, regardless of the VCC level. This suggests that the higher the FR level, the greater the positive effects on VCC and OGI values.

Figure 5 shows the moderating effect of FR on AMT and OGI, indicating that OGI increases with an increase in FR, regardless of the AMT level. This suggests that the higher the FR level, the greater the positive impact of AMT and OGI.

Structural cross-validation redundancy

Table 8 presents the cross-validation redundancy values used in the model. The table presents the results for Q^2 and R^2 . For the AMT construct, Q^2 was 0.354, and R^2 was 0.454, indicating that the model accounts for moderate predictive correlations and variance. VCC had a Q^2 of 0.342 and an R^2 of 0.436, indicating a moderate degree of predictive correlation and a substantial proportion of explained variance. The predictive correlation of the OGI values was the highest ($Q^2=0.524$), and the interpretable variance was the largest ($R^2=0.676$). Therefore, AMT, VCC, and OGI showed varying degrees of predictive relevance and explanatory power in the study models⁶⁰.

IPMA results

The IPMA analysis in this study showed the total effect (the X-axis represents importance) and the latent variable's exponential value (the Y-axis represents performance). According to Fig. 6, the “explorative Industrial Internet” is the most important factor because of its high importance score. This indicates that the “explorative industrial Internet” has a significant impact on this study and is currently performing well. In addition, manufacturing companies must invest time and resources to enhance the utilization of the Industrial Internet to improve the enterprise's overall performance.

Discussion

The results of this study support the hypothesis that H1a—the EPRII—has a significant positive impact on AMT. The analysis in this chapter shows that EPRII has a positive, direct effect on AMT and that the two are positively correlated, indicating that enterprises using EPRII technology have made significant progress in manufacturing. This discovery provides a theoretical basis for understanding how EPRII produces technological innovations. The latest data analytics and digital tools enable companies to optimize their manufacturing processes, thereby improving production efficiency. The positive impact demonstrates that explorative Industrial Internet initiatives help organizations by enabling them to integrate innovative technologies into their manufacturing operations. Industrial Internet research has revolutionized manufacturing technology, enabling companies to develop more robust connectivity systems, make data-driven decisions, and integrate new technologies.

This study validates H1b (explorative industrial Internet) and its positive effect on OGI. The results indicate that explorative industrial Internet use positively boosts open green innovation processes. Organizations can use new digital tools, along with data analytics, to enhance manufacturing processes, as this discovery confirms the explorative industrial internet as an innovation catalyst, consistent with theoretical models⁶¹. The industrial Internet promotes OGI by enhancing data collection and analysis capabilities, thereby demonstrating its explorative impact in enabling open green innovation. OGI receives a primary boost from explorative industrial

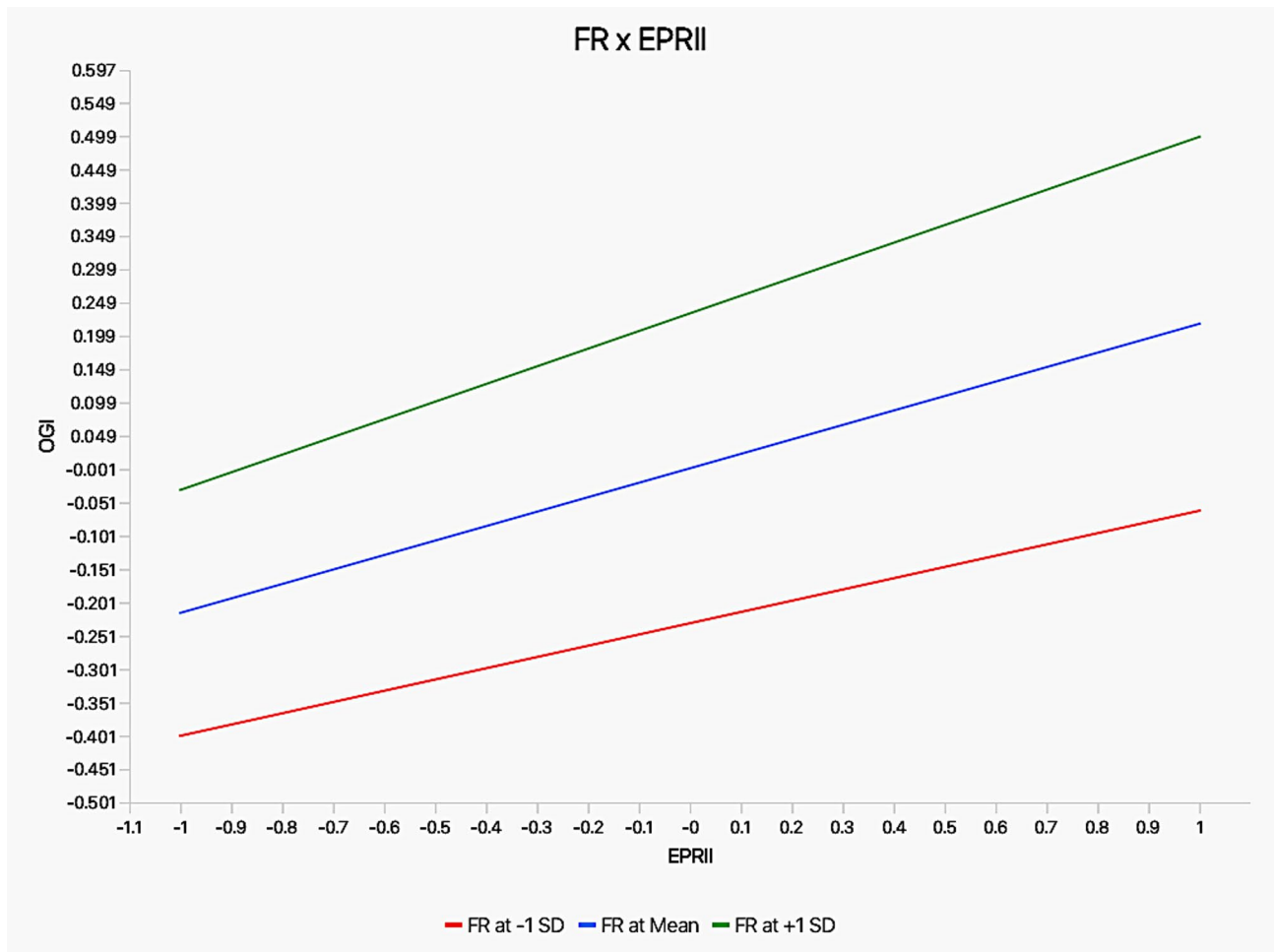


Fig. 3. The moderating role of FR between EPRII and OGI.

internet applications. The technology infrastructure, along with data-driven insights, collaborative platforms, and flexible solutions from this system, helps manufacturers establish sustainable methods and technologies.

The findings of this study confirm H1c, demonstrating that EPRII functions as a positive factor for VCC. The EPRII demonstrates a substantial direct role in VCC processes that revolutionize traditional business practices and establish new inter-enterprise, customer, and technology-provider collaboration systems. Multiple industries demonstrate this influence in both manufacturing and service industry operations. Studies have shown that the Industrial Internet generates VCC through enhanced information sharing and greater operational efficiency, while facilitating different collaboration methods and delivering improved customer service. Industrial processes have become more efficient because digital technologies enable real-time system monitoring, optimized operations, and rapid information transfer. Improved connectivity enables businesses to allocate resources more effectively, thereby enhancing collaboration. Open innovation occurs through digital platforms that connect different value-creation participants to combine decentralized resources for more effective solutions and benefits.

The study found that AMT has positive effects on OGI and VCC. Advanced manufacturing technologies have played an essential role in promoting OGI and VCC development. The results of this investigation contribute to the academic understanding and provide quantitative assessments of advanced manufacturing techniques for implementing open green innovations. The current study produced findings similar to those of prior studies^{33,62}, in which industrial Internet adoption by enterprises promotes the use of advanced manufacturing technologies. The researchers assumed that the validation of H2a and H2b was complete. Research data show that VCC is positively correlated with OGI. Companies that achieve better OGI results tend to actively engage in value co-creation through partnerships with customers, suppliers, and other business partners. VCC activities strengthen firms' ability to develop and implement sustainable innovations through their positive relationships. The study supports the notion that joint ventures facilitate knowledge dissemination through resource and idea sharing, thereby driving sustainable innovation³⁵. Open innovation succeeds by integrating stakeholders who provide external knowledge to develop better green solutions. According to these findings, OGI requires VCC methods as essential enablers. The research findings support the hypothesis that H3a is valid.

Path analysis revealed that advanced manufacturing technology functions as an intermediary connection between the explanatory industrial Internet and OGI. Its numerical values indicate that this technology serves

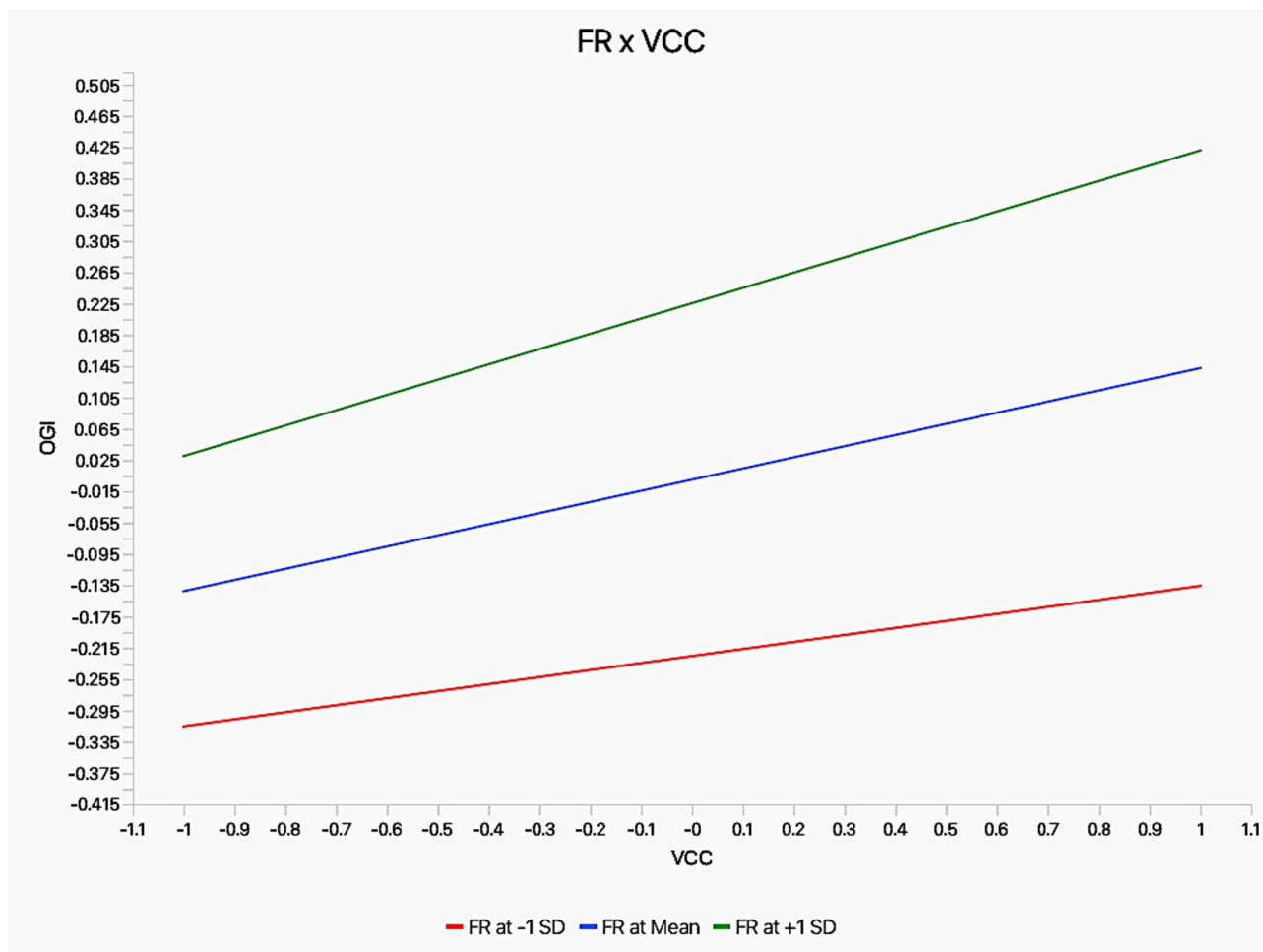


Fig. 4. The moderating role of FR between VCC and OGI.

as a potent mediator between the two elements. OGI success is attainable for companies that use explorative IIoT technologies to discover and apply new digital tools. The deployment of these technologies allows companies to apply innovative green solutions, including automation and intelligent systems, more efficiently. According to the mediating effect, AMT plays a vital role in converting explorative digital practices into actual green innovations. Therefore, H2c is validated. The statistical analysis in this study revealed that VCC functions as a mediating factor linking the explorative industrial Internet and open green innovation. The obtained values of $\beta = 0.047$, $t = 3.378$, and $p = 0.001$ indicate that VCC acts as a key intervening factor in this relationship. OGI success increases for enterprises that use EXPRII through VCC. According to the mediating effect, VCC mediates the relationship between digital exploration practices and actual green innovation outcomes. The relationships between these variables are as follows: EXPRII \rightarrow VCC \rightarrow OGI. Therefore, H3b was validated.

Research has demonstrated that firm resources are a major factor influencing the link between advanced manufacturing technologies and open green innovation. The study found that firm resources significantly modify the relationship between EXPRII and OGI. Simultaneously, firm resources shape the relationship between value co-creation and OGI and moderate it. Enterprises with robust resources demonstrate greater capacity to deploy innovative manufacturing technologies to develop novel, green solutions. Having significant corporate resources can enhance the implementation and scaling of advanced technologies, thereby contributing to OGI's greater success. This result underscores the importance of adequate resources to maximize AMT use and foster sustainable innovation, consistent with the resource-based perspective, which emphasizes the role of internal capabilities in achieving competitive advantage. However, since the questionnaire survey data used in this study are cross-sectional and cannot capture patterns of change over time, they are susceptible to sample selection bias and common trends. Further longitudinal and multi-industry studies are needed to validate these findings and apply them to different settings. Therefore, H4a was supported. This study shows that enterprises with sufficient resources are better able to effectively deploy explorative industrial Internet technologies for OGI development. The presence of significant corporate resources supports the implementation and expansion of innovative digital tools, thereby amplifying the impact of explorative use on green innovation outcomes⁴⁷. This finding highlights the critical role of firm resources in effectively deploying new digital technologies to foster sustainable innovation, consistent with the view that resource availability affects the ability to capitalize on new technological

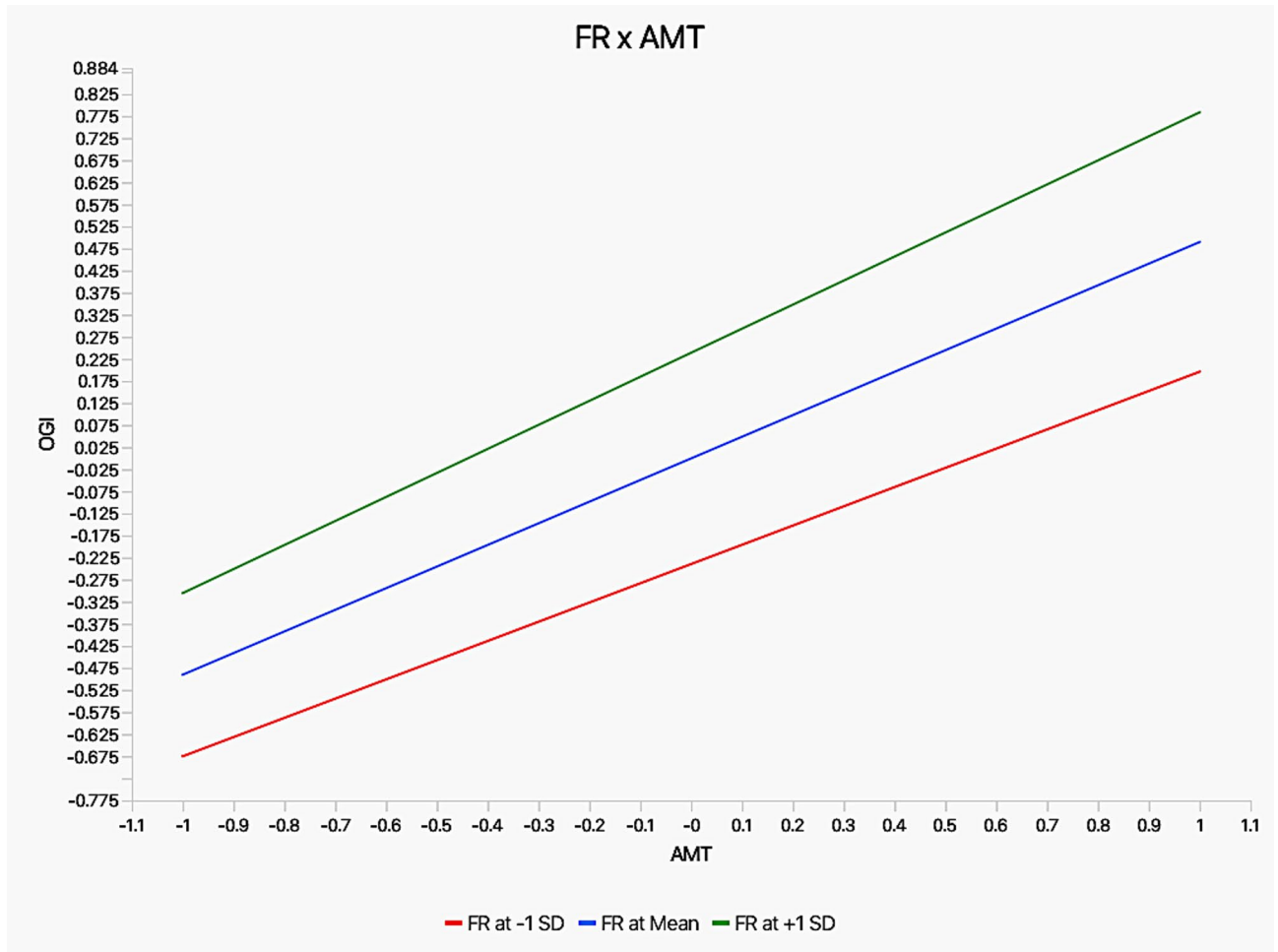


Fig. 5. The moderating role of FR between AMT and OGI.

Construct	SSO	SSE	Q ² (= 1-SSE/SSO)	R ²
AMT	1218.000	787.1620	0.354	0.454
EPRII	1624.000	1624.000	–	–
FRI	2842.000	2842.000	–	–
VCC	1624.000	1068.542	0.342	0.436
OGI	1624.000	772.5720	0.524	0.676

Table 8. Cross-validated redundancy.

opportunities. These findings highlight the need for companies to strategically invest in and manage resources to maximize the benefits of the explorative industrial Internet. Therefore, H4b is supported.

The analysis shows that the positive impact of VCC on OGI is significantly greater in enterprises with greater financial, human, and technological resources. This indicates that companies with sufficient resources are better able to leverage stakeholder collaboration to achieve better OGI results. The strong availability of resources enhances firms’ ability to invest and implement partnership programs effectively, thereby reinforcing the impact of VCC on the development and scale of green innovation. This finding highlights the role of corporate resources in supporting the successful integration of stakeholder input and collaborative efforts into innovative green solutions, consistent with the resource-based view, which holds that organizational resources are essential for businesses to capitalize on opportunities for collaborative innovation. Therefore, we assume that H4c is supported.

Theoretical implication

This study enhances our understanding of how the explorative industrial Internet (EPRII) drives open green innovation and contributes to sustainable industrial practices. Theoretically, it clarifies the mechanism by which the EPRII Program impacts open green innovation, demonstrating that digital transformation in traditional

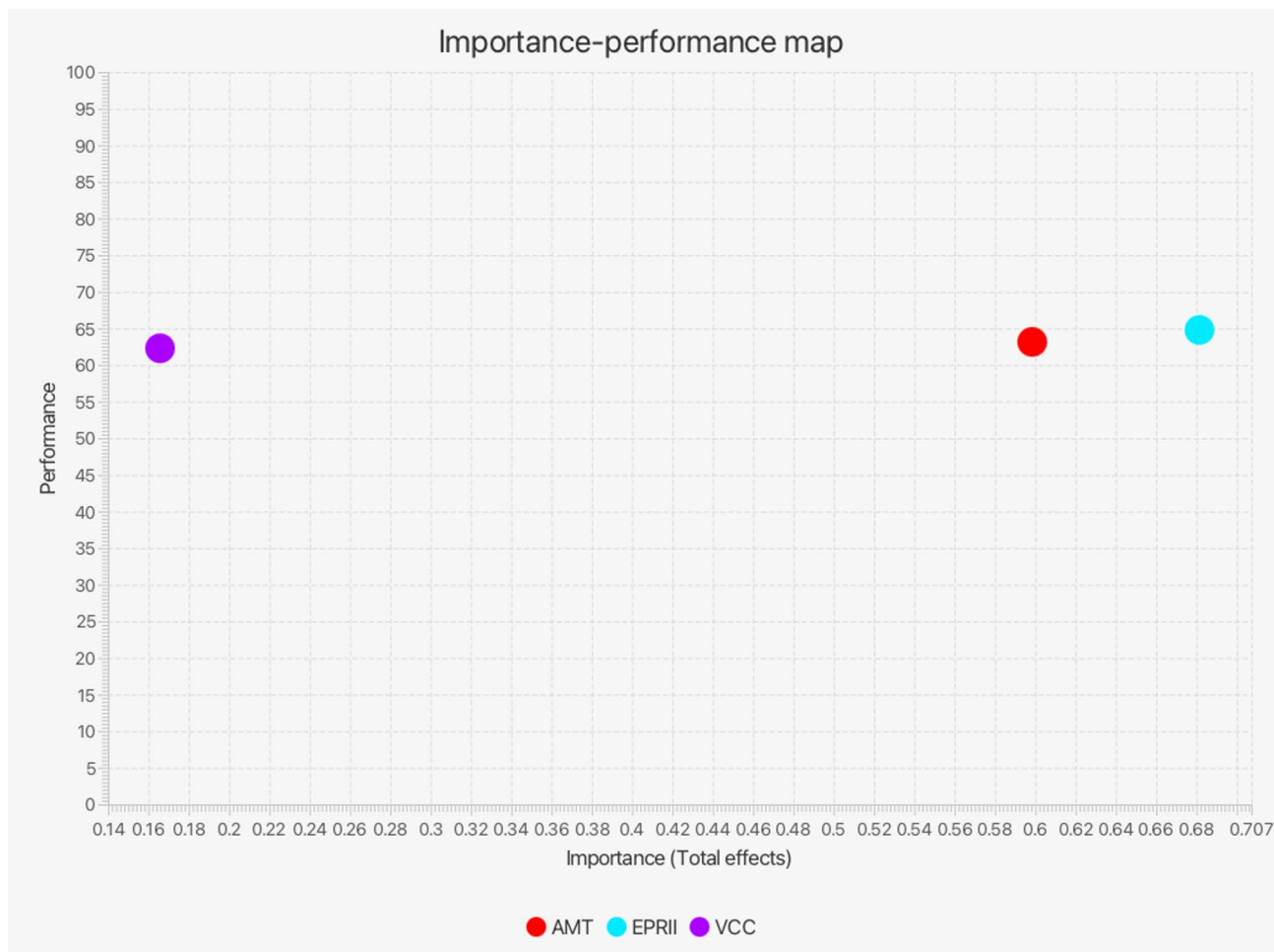


Fig. 6. IPMA of OGI.

industries enhances technological innovation and collaboration. By exploring the mediating roles of advanced manufacturing technology (AMT) and value co-creation, this study highlights the essential pathways through which EPRII facilitates green innovation. This study also addresses the moderating role of firm resources, showing that companies with greater resources are better positioned to leverage digital technologies for sustainability. This study enriches platform theory by demonstrating how EPRII acts as a digital platform that facilitates value creation and open green innovation. Traditional platform theory emphasizes the role of platforms in connecting different stakeholders (e.g., customers, suppliers, and firms) to create value for the platform. This study extends this view by showing that platforms such as the EPRII not only enable collaboration but also drive technological innovation and sustainability.

Practical implication

In practice, this study offers insights for policymakers and business leaders seeking to optimize the integration of EPRII to encourage green innovation. This emphasizes the importance of resource investment, stakeholder collaboration, and technological infrastructure in driving an effective digital transformation. The findings suggest that targeted innovation policies and management practices should consider regional heterogeneity and the complexity of industrial Internet applications to maximize sustainability and economic growth. From a financial perspective, the findings suggest that leveraging the EPRII accelerates industrial modernization while promoting sustainability. This study provides a roadmap for policymakers to invest in digital infrastructure and collaborative innovation platforms to facilitate green industrial practice. Businesses can capitalize on these results by aligning resource allocation with green goals, thereby advancing China's vision of high-quality, environmentally sustainable economic development.

Conclusion

To reveal the impact mechanism of the explorative industrial Internet (EPRII) on the open green innovation (OGI) of manufacturing enterprises, this study considers the changes in the global manufacturing pattern, the transformation and upgrading needs of China's manufacturing industry, and the joint promotion of ecological civilization construction as the background to understand how the industrial Internet promotes the green, open,

and innovative development of the manufacturing industry by promoting open green innovation, and reveals the mechanism and influencing factors by taking China's manufacturing enterprises as the research object. A theoretical model of the impact mechanism of EPRII on the OGI of manufacturing enterprises was constructed, and questionnaire survey data from 406 Chinese manufacturing enterprises were used to empirically test the model using structural equation modeling. The results show that EPRII has a positive and significant impact on the OGI of manufacturing enterprises in China. Simultaneously, advanced manufacturing technology and value co-creation serve as intermediaries between the explorative industrial Internet and open green innovation in manufacturing enterprises. The company's resources play a significantly positive moderating role in the impact of explorative industrial Internet, advanced manufacturing technology, and value co-creation on open green innovation.

Limitations and future research

The research analysis has various significant limitations. The findings from cross-sectional research preclude investigators from determining temporal cause-and-effect relationships, underscoring the need for future studies to use longitudinal methods. The specific geographic region and business sectors emphasized in this study limit the generalizability of the results to other contexts, as cultural and economic factors may shape the digital and green innovations that businesses adopt. Self-reported questionnaires as data sources introduce potential risks associated with standard methods and social desirability bias, which require additional credible information to enhance validity. Researchers should develop more intricate definitions of complex constructs, such as "open green innovation" and "explorative industrial internet," to capture the essential subtleties of these concepts.

Data availability

This study used first-hand data collected through questionnaires. The datasets analyzed in the current study are available from the corresponding author upon reasonable request.

Code availability

No custom code or proprietary softwares were developed for this study. All analyses were conducted using standard and publicly available statistical software.

Received: 19 November 2025; Accepted: 12 February 2026

Published online: 27 February 2026

References

- Liao, F., Hu, Y., Chen, M. & Xu, S. Digital transformation and corporate green supply chain efficiency: evidence from China. *Econ. Anal. Policy*. <https://doi.org/10.1016/j.eap.2023.11.033> (2024).
- Zheng, H., Dai, J., Li, B. & Shou, Y. The impact of anticipation of new technologies on operational and environmental performance: a strategy-structure-capabilities-performance perspective. *Int. J. Logistics Res. Appl.* <https://doi.org/10.1080/13675567.2023.2260312> (2023).
- Zhao, S., Zhang, L., Peng, L., Zhou, H. & Hu, F. Enterprise pollution reduction through digital transformation? Evidence from Chinese manufacturing enterprises. *Technol. Soc.* <https://doi.org/10.1016/j.techsoc.2024.102520> (2024).
- Tao, Y., Lu, H., Ye, Y. & Wu, H. Does the firms' digital transformation drive environmental innovation in china? *Sustain. Dev.* <https://doi.org/10.1002/sd.2769> (2024).
- Moravec, V., Hynek, N., Skare, M., Gavurova, B. & Kubak, M. Human or machine? The perception of artificial intelligence in journalism, its socio-economic conditions, and technological developments toward the digital future. *Technol. Forecast. Soc. Change.* <https://doi.org/10.1016/j.techfore.2023.123162> (2024).
- Liu, Y., Yang, Y., Li, H. & Zhong, K. Digital economy Development, industrial structure upgrading and green total factor productivity: empirical evidence from china's cities. *Int. J. Environ. Res. Public Health.* <https://doi.org/10.3390/ijerph19042414> (2022).
- Sui, B. & Yao, L. The impact of digital transformation on corporate financialization: the mediating effect of green technology innovation. *Innov. Green. Dev.* <https://doi.org/10.1016/j.igd.2022.100032> (2023).
- Wang, B., Ma, M., Zhang, Z. & Li, C. How do the key capabilities of the industrial internet platform support its growth? A longitudinal case study based on the resource orchestration perspective. *Technol. Forecast. Soc. Change.* <https://doi.org/10.1016/j.techfore.2023.123186> (2024).
- Narkhede, G., Mahajan, S., Narkhede, R. & Chaudhari, T. Significance of industry 4.0 technologies in major work functions of manufacturing for sustainable development of small and medium-sized enterprises. *Bus. Strategy Dev.* <https://doi.org/10.1002/bsd.2.325> (2024).
- Shishakly, R., Almaiah, M. A., Lutfi, A. & Alrawd, M. The influence of using smart technologies for sustainable development in higher education institutions. *Int. J. Data Netw. Sci.* <https://doi.org/10.5267/j.ijdns.2023.10.015> (2024).
- Kulkov, I. et al. Artificial intelligence - driven sustainable development: examining organizational, technical, and processing approaches to achieving global goals. *Sustain. Dev.* **32**, 2253–2267 (2024).
- Zhang, K., Liu, H., Li, Y. & Wu, X. Effects of social media usage on exploratory innovation, exploitative innovation and organizational agility: the moderating role of learning goal orientation. *Internet Res.* <https://doi.org/10.1108/INTR-07-2021-0503> (2024).
- Wang, X., Qin, C., Liu, Y., Tanasescu, C. & Bao, J. Emerging enablers of green low-carbon development: do digital economy and open innovation matter? *Energy Econ.* <https://doi.org/10.1016/j.eneco.2023.107065> (2023).
- Gawer, A. & Cusumano, M. A. Industry platforms and ecosystem innovation. *J. Prod. Innov. Manage.* **31**, 417–433 (2014).
- Dong, Y., Yao, X. & Wei, Z. Research on the process of knowledge value co-creation between manufacturing enterprises and internet enterprises. *Knowl. Manage. Res. Pract.* **1–16** <https://doi.org/10.1080/14778238.2023.2189170> (2023).
- Sang, Y. & Han, E. A win-win way for corporate and stakeholders to achieve sustainable development: corporate social responsibility value co-creation scale development and validation. *Corp. Soc. Responsib. Environ. Manag.* **30**, 1177–1190 (2023).
- Caputo, F., Garcia-Perez, A., Cillo, V. & Giacosa, E. A knowledge-based view of people and technology: directions for a value co-creation-based learning organisation. *J. Knowl. Manage.* **23**, 1314–1334 (2019).
- Vargo, S. L. & Lusch, R. F. Institutions and axioms: an extension and update of service-dominant logic. *J. Acad. Mark. Sci.* <https://doi.org/10.1007/s11747-015-0456-3> (2016).

19. Rusly, F. H., Taliba, Y. Y. A., Abd Mutaliba, H. & Hussina, M. R. A. Developing a Digital Adaptation Model for Malaysian Manufacturing SMEs. In *Proceedings of the 4th UUM International Qualitative Research Conference (QRC)* (2020).
20. Hu, R., Shahzad, F., Abbas, A. & Liu, X. Decoupling the influence of eco-sustainability motivations in the adoption of the green industrial IoT and the impact of advanced manufacturing technologies. *J. Clean. Prod.* <https://doi.org/10.1016/j.jclepro.2022.130708> (2022).
21. Abbas, A., Luo, X., Shahzad, F. & Wattoo, M. U. Optimizing organizational performance in manufacturing: the role of IT capability, green supply chain integration, and green innovation. *J. Clean. Prod.* **423**, 138848 (2023).
22. Abbas, A., Luo, X., Wattoo, M. U., Hu, R. & Corrigendum Organizational Behavior in Green Supply Chain Integration: Nexus Between Information Technology Capability, Green Innovation, and Organizational Performance. *Front. Psychol.* **13**, 874639. <https://doi.org/10.3389/fpsyg.2022.874639> (2022).
23. Shahzad, F., Du, J., Khan, I. & Wang, J. Decoupling institutional pressure on green supply chain management efforts to boost organizational performance: moderating impact of big data analytics capabilities. *Front. Environ. Sci.* <https://doi.org/10.3389/fenvs.2022.911392> (2022).
24. Natarajan, T., Pragma, P. & Dhalmahapatra, K. Uses and gratifications of metaverse: Understanding the user adoption factors through a mixed method approach. *Asia Pac. J. Mark. Logistics.* <https://doi.org/10.1108/APJML-03-2024-0395> (2024).
25. Yi, Y. Interactions among energy consumption per GDP, technological innovation input and energy consumption structure in China during the 14th Five-Year plan period. *Highlights Bus. Econ. Manage.* <https://doi.org/10.54097/njg0v985> (2024).
26. Xu, N., Shahzad, F. & Hu, R. Unveiling environmental excellence: the confluence of green industrial internet of Things, circular economy practices and dynamic capabilities in manufacturing firms. *J. Manuf. Technol. Manage.* **36**, 479–503 (2025).
27. Yuan, F., Xiong, X., Xu, Z. & Yu, L. Spatial differentiation and driving factors of economic resilience in the Yangtze river economic Belt, China. *Progress Geogr.* <https://doi.org/10.18306/dlkxjz.2023.02.004> (2023).
28. Shahbaz, M., Gao, C., Zhai, L. L., Shahzad, F. & Khan, I. Environmental air pollution management system: predicting user adoption behavior of big data analytics. *Technol. Soc.* <https://doi.org/10.1016/j.techsoc.2020.101473> (2021).
29. Wang, G., Zhang, L. & Guo, J. The impact of advanced manufacturing technology (AMT) application on product innovation performance: a model of mediated moderated effect. *Int. J. Innov. Sci.* <https://doi.org/10.1108/IJIS-06-2021-0108> (2023).
30. Bhise, D. V., Choudhari, S. A., Kumbhalkar, M. A. & Sardeshmukh, M. M. Assimilation of advanced manufacturing technologies in small and medium sized enterprises: an empirical analysis. *Multidisciplinary Sci. J.* <https://doi.org/10.31893/multiscience.2023041> (2023).
31. Singh, R. K. & Gurtu, A. Embracing advanced manufacturing technologies for performance improvement: an empirical study. *Benchmarking* <https://doi.org/10.1108/BIJ-02-2021-0110> (2022). doi:10.1108/BIJ-02-2021-0110.
32. Wong, D. T. W. & Ngai, E. W. T. The impact of advanced manufacturing technology, sensing and analytics capabilities, and planning comprehensiveness on sustained competitive advantage: the moderating role of environmental uncertainty. *Int. J. Prod. Econ.* <https://doi.org/10.1016/j.ijpe.2023.109007> (2023).
33. Kong, T., Feng, T. & Ye, C. Advanced manufacturing technologies and green innovation: the role of internal environmental collaboration. *Sustainability* **8**, 1056 (2016).
34. Sukathong, S., Suksawang, P. & Naenna, T. Analyzing the importance of critical success factors for the adoption of advanced manufacturing technologies. *International J. Eng. Bus. Management Preprint at.* <https://doi.org/10.1177/18479790211055057> (2021).
35. Prahalad, C. K. & Ramaswamy, V. Co-creation experiences: the next practice in value creation. *J. Interact. Mark.* <https://doi.org/10.1002/dir.20015> (2004).
36. Yousaf, Z. Go for green: green innovation through green dynamic capabilities: accessing the mediating role of green practices and green value co-creation. *Environ. Sci. Pollut. Res.* <https://doi.org/10.1007/s11356-021-14343-1> (2021).
37. Almansour, M. How do green intellectual and co-creational capitals drive artificial intelligence innovation and green innovation in start-ups? *Eur. J. Innov. Manage.* <https://doi.org/10.1108/EJIM-09-2023-0791> (2024).
38. Li, G., Shi, X., Yang, Y. & Lee, P. K. C. Green co-creation strategies among supply chain partners: A value co-creation perspective. *Sustain. (Switzerland)*. <https://doi.org/10.3390/su12104305> (2020).
39. Grönroos, C. & Voima, P. Critical service logic: making sense of value creation and co-creation. *J. Acad. Mark. Sci.* <https://doi.org/10.1007/s11747-012-0308-3> (2013).
40. Chesbrough, H. & Bogers, M. Explicating open innovation: clarifying an emerging paradigm for Understanding innovation keywords. *New Front. Open. Innovation* (2014).
41. Luo, W., Wang, H. & Zheng, S. Internet infrastructure and industrial development in China. *SSRN Electron. J.* <https://doi.org/10.2139/ssrn.3484081> (2019).
42. Xie, W., Zheng, D., Li, Z., Wang, Y. & Wang, L. Digital technology and manufacturing industrial change: evidence from the Chinese manufacturing industry. *Comput. Ind. Eng.* <https://doi.org/10.1016/j.cie.2023.109825> (2024).
43. He, Q., Ribeiro-Navarrete, S. & Botella-Carrubi, D. A matter of motivation: the impact of enterprise digital transformation on green innovation. *Rev. Managerial Sci.* <https://doi.org/10.1007/s11846-023-00665-6> (2024).
44. Barney, J. Firm resources and sustained competitive advantage. *J. Manage.* <https://doi.org/10.1177/014920639101700108> (1991).
45. Galbreath, J. Which resources matter the most to firm success? An exploratory study of resource-based theory. *Technovation* (2005). <https://doi.org/10.1016/j.technovation.2004.02.008> doi:10.1016/j.technovation.2004.02.008.
46. Wang, Y. & Yang, Y. Analyzing the green innovation practices based on sustainability performance indicators: a Chinese manufacturing industry case. *Environ. Sci. Pollut. Res.* <https://doi.org/10.1007/s11356-020-10531-7> (2021).
47. Ogiemwonyi, O. et al. Green innovation behaviour: impact of industry 4.0 and open innovation. *Heliyon* **9**, e16524 (2023).
48. Ahmad, A., Madi, Y., Abuhashesh, M., Nusairat, N. M. & Masa'adeh, R. The knowledge, attitude, and practice of the adoption of green fashion innovation. *J. Open. Innovation: Technol. Market Complex.* **6**, 1–20 (2020).
49. He, Z. L. & Wong, P. K. Exploration vs. exploitation: an empirical test of the ambidexterity hypothesis. *Organization Science Preprint at.* <https://doi.org/10.1287/orsc.1040.0078> (2004).
50. Hsu, Y. A value cocreation strategy model for improving product development performance. *J. Bus. Industrial Mark.* <https://doi.org/10.1108/JBIM-11-2014-0221> (2016).
51. Chang, C. H. Green open innovation activities and green co-innovation performance in taiwan's manufacturing sector. *Int. J. Environ. Res. Public Health.* <https://doi.org/10.3390/ijerph17186677> (2020).
52. Aragón-Correa, J. A. & Sharma, S. A. Contingent Resource-Based view of proactive corporate environmental strategy. *Acad. Manage. Rev.* **28**, 71–88 (2003).
53. Hair, J. F., Sarstedt, M., Hopkins, L. & Kuppelwieser, V. G. Partial least squares structural equation modeling (PLS-SEM): an emerging tool in business research. *Eur. Bus. Rev.* **26**, 106–121 (2014).
54. Hair et al. *Multivariate Data Analysis, Eighth Edition.* Annabel Ainscow (2019).
55. Kock, N. Common method bias in PLS-SEM: A full collinearity assessment approach. *Int. J. e-Collaboration.* **11**, 1–10 (2015).
56. Fornell, C. & Larcker, D. F. Structural equation models with unobservable variables and measurement error: algebra and statistics. *J. Mark. Res.* **18**, 382 (1981).
57. Henseler, J., Ringle, C. M. & Sarstedt, M. A new criterion for assessing discriminant validity in variance-based structural equation modeling. *J. Acad. Mark. Sci.* **43**, 115–135 (2015).
58. Podsakoff, P. M., MacKenzie, S. B. & Podsakoff, N. P. Sources of method bias in social science research and recommendations on how to control it. *Annu. Rev. Psychol.* **63**, 539–569 (2012).

59. Podsakoff, P. M., MacKenzie, S. B., Lee, J. Y. & Podsakoff, N. P. Common method biases in behavioral research: A critical review of the literature and recommended remedies. *Journal Appl. Psychology Preprint at*. <https://doi.org/10.1037/0021-9010.88.5.879> (2003).
60. Chin, W. The Partial Least Squares Approach to SEM chapter. *Modern Methods for Business Research* (1998).
61. Brynjolfsson, E. & McElheran, K. The rapid adoption of data-driven decision-making. *American Economic Review*. <https://doi.org/10.1257/aer.p20161016> (2016).
62. Hu, R., Shahzad, F., Abbas, A. & Liu, X. Decoupling the influence of eco-sustainability motivations in the adoption of the green industrial IoT and the impact of advanced manufacturing technologies. *J. Clean. Prod.* **339**, 130708 (2022).

Acknowledgements

We would like to express our sincere gratitude to all those who have supported and contributed to the completion of this research.

Author contributions

Rui Hu : Conceptualization, methodology, data curation, and writing- original draft; Ma Guoyong: Supervision, visualization, funding acquisition, and writing – review & editing; Adnan Abbas : Software, formal analysis, investigation, and writing – review & editing; Muhammad Umair Wattoo: Conceptualization, data curation, validation, and writing- original draft.

Funding

This research was supported by the Natural Science Foundation of Heilongjiang Province, China (Project No. LH2023G003: “Assessment and Realization of Forest Ecosystem Services in Northeast State-owned Forest Areas”). The second author, Prof. Ma Guoyong, received funding from Heilongjiang Province.

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

Ethical approval for this study was obtained from the Human Research Ethics Committee of Northeast Forestry University.

Consent for publication

All participants consented to the anonymous use of their responses for academic purposes. No personally identifiable information is disclosed in this manuscript.

Consent to participate

All respondents were informed of the study’s purpose, and participation was voluntary. Informed consent was obtained from all the participants included in the study.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-026-40439-0>.

Correspondence and requests for materials should be addressed to M.G.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2026