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Original Research

How Does Digital Transformation Promote Low-Carbon Technology Innovation? The Case of Chinese Manufacturing Companies

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Abstract

Under the Chinese government's carbon neutral target, digital transformation enabling low-carbon technology innovation has become an innovative starting point to promote the new development concept. We use data from a sample of 270 manufacturing companies in 30 provinces and cities in China, this paper constructs an analysis framework of low-carbon technology innovation in manufacturing driven by digital transformation with knowledge reconstruction as the intermediary variable and knowledge sharing as the regulating variable, and empirically explores the impact of digital transformation on low-carbon technology innovation. It is found that the digital transformation of the manufacturing industry has a significant positive impact on low-carbon technology innovation, and is an important power source to promote low-carbon technology innovation. Knowledge reconstruction plays a part of intermediary role between digital transformation and low-carbon technology innovation, and plays a key role as a bridge. Knowledge sharing plays a positive role in digital transformation, knowledge reconstruction and low-carbon technology innovation. The research clarified the differences and suitability in the process of low-carbon technology innovation in the digitally enabled manufacturing industry and answered the question of how to effectively use knowledge management to realize digitalization and help the industrial low-carbon innovation and upgrading in the digital economy era, which has important reference significance for guiding the green and high-quality development of the industry.

Keywords: digital transformation, low-carbon technology innovation, knowledge reconstruction, knowledge sharing, manufacturing companies

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Introduction

Global warming, pollution, and resource depletion are becoming increasingly severe, and the traditional economic development method of "high pollution, high emissions, and high consumption" has irreparably harmed humanity's survival (Yadav et al., 2021) [1]. Reducing carbon emissions and energy consumption has become an inevitable choice to alleviate environmental problems and achieve sustainable development (Lee ta al., 2018) [2]. The world's countries are becoming aware of this issue, which is a set of problems that can cause irreversible damage to the human planet. The Paris Agreement, signed by 196 parties, requires all parties to submit strategies to reduce greenhouse gas emissions by 2020. Each party needs to adopt measures adapted to its national context and its strengths to move into a sustainable growth mode (Wang et al., 2022) [3]. Based on the requirement to promote sustainable development and the responsibility to build a community of human destiny, China has proposed to the world a major strategic goal of carbon peaking and carbon neutrality. The Chinese government shall incorporate peak carbon and carbon neutrality into the overall planning of ecological civilization construction, promote major breakthroughs in green and low-carbon technologies, and deploy low-carbon frontier technology research urgently. "Double carbon" is the strategic goal of China's economic and social reform. Promoting the new development concept and realizing the leap of civilization is also essential. To ensure the smooth realization of the "double carbon" goal, we should attach importance to low-carbon technology innovation. China is the largest energy consumer and carbon dioxide emitter in the world. At present, China is in the middle and late stages of industrialization. The traditional "three high and one low" industries still account for a high proportion. The manufacturing industry of considerable scale is facing a series of challenges under the new situation, such as low energy resource utilization efficiency, low-carbon, zero carbon, and the development of negative carbon technologies has yet to mature. Therefore, as an essential subject to implement the new development concept and promote innovation-driven green, low-carbon, and high-quality development, the manufacturing industry is a critical practical path for China to achieve sustainable economic growth and address global climate change governance, which is crucial to ensure the smooth realization of the "double carbon" goal.

Big data, artificial intelligence, blockchain, and the innovative application of mobile network technology represented by 5G, the digital economy with digital information as a critical factor of production has flourished, giving rise to a new economic paradigm, and becoming a new high ground for significant countries around the world to compete for the layout. China has written a separate chapter on digital development in the " Fourteenth Five-Year Plan" for the first time. The "four-fold" framework of the digital economy digital industrialization, digitalization of industry, digital governance, and digital value is becoming a new engine of economic growth in China. Low-carbon technology innovation in the manufacturing industry is different from traditional innovation, it is difficult to integrate various types of low-carbon technology systems. The link composition is complex, the types of technology are a lot, and the cost is expensive. For different low-carbon technologies, there are significant differences in their technical characteristics, application areas, marginal abatement costs and abatement potential. It is necessary to integrate with digitalization and carry out digital transformation to achieve stability.

As the research progresses, against the backdrop of the era of the knowledge economy, the focus of scholars has steadily shifted to elucidate the antecedents of low-carbon technology innovation and the influence of knowledge in the digital transformation mechanism on company innovation. Pan et al. (2022) [4] noted that digital transformation has emerged as a new factor driving a company's technology innovation. In a similar vein, Verhoef et al. (2021) [5] suggested that organizations undergoing digital transformation require the support of hybrid advanced technologies, such as information technology, edge computing and so on., which also counteracts the rapid development of technology innovation. Moreover, according to Vial et al. (2019) [6], digital transformation is the process of accelerating the evolution of a business entity by prompting an organization to respond strategically through digital technologies, such as information, computing, and communication to change its structure, boundaries, and even value generation pathways. Zhang and Ren (2018) [7] suggested that technology innovation is the process of businesses connecting, reconfiguring, and regenerating internal and external knowledge elements into a new knowledge system. Consequently, numerous researchers have introduced "knowledge" to the subject of innovation management.

Literature research suggests that knowledge reconstruction, as a substantial change that deconstructs and reshapes existing knowledge systems (Tong, 2021) [10], plays a crucial role in the relationship between digital transformation and organizational innovation. Wang et al. (2020) [8] viewed knowledge restructuring as a crucial phase for businesses undergoing digital transformation in order to successfully integrate internal and external innovation resources, and sustain technology innovation. Fleming (2001) [9] noted that company innovation signifies that the old knowledge body produces a new, harmonious knowledge body through the steps of deconstruction, transformation, reconstruction, and coupling, a process of in-depth knowledge reconstruction. In addition, several researchers indicate that knowledge sharing is also a crucial component of low-carbon technology innovation in businesses. Tong (2021) [10] stated that in an environment of rapid renewal of digital transformation, a greater degree of information sharing could encourage open innovation and enhance the innovation performance of businesses. Xu et al. (2020) [11] argue that companies continuously acquire external knowledge through knowledge sharing, improve the degree of inter-companies trust and collaboration, and promote internal cohesion, which leads to the deep integration and reconstruction of knowledge elements and accelerates the rate of innovation. Evidently, in the digital transformation process, companies must continuously engage in knowledge reconstruction and sharing, realize the transmission, reconstruction, and sublimation of innovative knowledge, and lay the groundwork for enhancing the efficacy and quality of companies low-carbon technology innovation (Fleming, 2001) [9].

Based on this, for the "double carbon" constraint escalation factor, governance of digital transformation dilemmas still falls short. Especially the heterogeneous evolutionary process of digital transformation paths in different ways to affect the manufacturing industry low-carbon technology innovation, what should be the driving path is still no definite answer. To this end, this study poses the following scientific questions: Under the "double carbon" purpose, what are digital transformation's driving effects and endogenous differences on low-carbon technology innovation in manufacturing? What is the diverse impact of corporate knowledge reconfiguration capacities on the role of low-carbon technology innovation driven by digital transformation? Which pathway mechanism may be selected to alleviate the transformation reality challenges more effectively, accelerate the success of old and new dynamics, construct an intelligent industrial system, and steer industries' green and high-quality development? In this paper, these are the questions that must be addressed.

In conclusion, the innovations and contributions of this paper are as follows: first, the research on the impact of integrating low-carbon technology innovation systems under the "double carbon" target has not yet been strengthened, and most studies have focused on the broad calculation of regional and industrial green development efficiency. This study uses the limits imposed by the "double carbon" target as a starting point to address the path optimization and realistic problem resolution mechanism for low-carbon technology innovation. Second, as there are few studies matching the real-life dilemmas and heterogeneous evolutionary paths of digital transformation in the new situation, and as there are many factors affecting low-carbon technology innovation, this paper selects the real-life trend of digital transformation as a critical source of power for low-carbon technology innovation, focuses on its internal mechanism of action, and provides manufacturing companies with new dynamic energy and innovation strategies. Thirdly, the paper creatively introduces a knowledge perspective, considering the mediating factor of knowledge reconstruction and the moderating role of knowledge sharing, thoroughly deciphers the heterogeneous influence mechanism of digital transformation driving low-carbon technology innovation in manufacturing industries, and clarifies the differences, appropriateness, and dependence of the process of digitally enabled low-carbon technology innovation in manufacturing industries. It addresses how to effectively employ knowledge management to achieve digitization and assist companies in upgrading their low-carbon creation. This issue is of theoretical and practical importance to the industry in building a long-term sustainable driving mechanism.

Theoretical Framework

Digital Transformation

Digital transformation is the product of mutual promotion between information technology integration and business innovation, which produces great technological and economic resonance effects. It runs through the whole process of company's operation and product production. It is also changing the economy, government and society by applying continuous innovative digital technology and growing digital resources. At its core is a holistic and comprehensive transformation using new digital technologies such as mobile internet, artificial intelligence and blockchain. In addition to this, it is also about improving production processes, changing management models, optimizing marketing methods and improving the customer experience. Its purpose is to unleash the amplifying, superimposing, and multiplying effects of digital on economic development (Yin, 2021) [12]. From this perspective, digital transformation transcends changes in business procedures and enables the emergence of a new type of organization. It is a transformation at a higher level, accompanied by modifications to organizational culture, connections, value generation, customer coverage, and market position. Digital transformation of a company's products, services, and processes can help businesses better manage their limited resources, and increase their both flexibility and efficiency. Businesses generate differentiated value and enhance competitive advantage by leveraging digital resources (Proksch, 2021, Yang and Wang, 2021) [13, 14]. Therefore, digital transformation is necessary for companies to survive, build core competitiveness, and achieve sustainable development. It is also a crucial engine for fostering high-quality economic growth (Yang and Wang, 2021) [14].

Low-Carbon Technology Innovation

Low-carbon technology innovation aims to achieve low-carbon production methods through technological innovation, with "green" as the goal and "low-carbon" as the orientation. The aim is to protect the ecological environment and promote green development and economic growth (Yang and Wang, 2021) [14]. To achieve innovation-driven outcomes, China must boost the intensity of low-carbon technology innovation and enhance the quality of green innovation. Compared to conventional technologies, low-carbon technology is characterized by strong externalities, high complexity, high input and risk. Their innovative development requires the collaboration of multiple actors, multidisciplinary integration, and complementary knowledge from various sources (Chen and Zeng, 2019, Dong and Bi, 2020) [15, 16]. Low-carbon technology innovation is characterized by originality and key technological change. It is a series of creative activities that reduce the disruption of ecological resources and create maximum value demand in a low-carbon form (Dong and Bi, 2020) [16]. The focus is on promoting technology innovation and upgrading industries related to carbon reduction. This will improve the country's living environment and achieve its emission abatement targets (Cui, Zhu and Wang, 2020) [17]. The green innovation of the manufacturing industry, as an important factor to achieve the win-win goal of environmental protection and technological progress, its technological innovation and low-carbon transformation has become a key link affecting the development of China's low-carbon economy. Low-carbon technology innovation can change the traditional industrial model from the source, distinguishing it from the limitations of traditional technology innovation, and is a critical path to break through the bottleneck of development and promote the transformation and upgrading of the manufacturing industry (Bi, Fu and Li, 2017) [18]. In addition, if the manufacturing companies carrying out low-carbon technology innovation can finally increase income, it means that the full diffusion of low-carbon technology will further improve the economic efficiency and development quality of companies, which is impossible for traditional technology innovation (Lv, Xu and Xu, 2019) [19]. At the same time, low-carbon technology innovation as the most critical economic factor of production, is of great importance to the development of a low-carbon economy in China. To achieve a qualitative shift in economic growth, the contribution of low-carbon technology innovation to total economic output must be enhanced. Under the existing environment, maximizing growth with minimal environmental costs.

Digital Transformation and Low-Carbon Technology Innovation

As the study on low-carbon technology innovation has intensified in recent years, many academics have discovered that the impact of digital transformation on innovation is unknown, and in some situations, the two also exhibit heterogeneous changes and may even function non-linearly: Zhou et al. (2021) [20] introduced the level of digitalization and analyzed its impact on green innovation performance in three dimensions of digital transformation in manufacturing, confirming the positive moderating effect of digitalization level between digital transformation and its path. Not coincidentally, Wang et al. (2022) [21] divided the level of digitization into five dimensions and studied the impact and intrinsic mechanism of each of the five sub-indicators on green technology innovation in resource-based companies. The results of the study show that the comprehensive level of regional digitization and its four sub-indicators of digital foundation, digital input, digital economy and digital application all have significant "∩-type" effects on resource-based companies' green technology innovation, and the digital transformation-driven low-carbon technology innovation is affected by the non-linearities of the evolutionary paths of different regions and industries.

However, more scholars believe that digitalization is the endogenous driving force to promote low-carbon technology innovation (Wang et al., 2022) [21] from the perspective of promoting high-tech industrial innovation, Yin and Tian (2021) [12] studied the relationship between digital transformation and high-tech industrial innovation efficiency through the Tobit model, indicating that digital transformation has a significant role in promoting the innovation and development efficiency of high-quality industries in the region in the same direction, Fichman et al. (2014) [23] found that product data management and other technologies used in the digital transformation of companies support the standardization and optimization of companies processes, shorten the time to market or delivery, and greatly improve the efficiency of low-carbon technology innovation, In addition, the digital transformation process gradually changes the shape of products and services, corporate organization and industrial organization (Liu, Dong and Wei, 2020) [24], resulting in important and even disruptive changes to the innovation process (Nambisan et al., 2017) [25]. Accelerating the digital transformation and upgrading of high-tech industries has become the way to achieve quality change, efficiency change, dynamic change, and better innovation efficiency and effectiveness. At the same time, digitalization has great potential to monitor environmental change and facilitate the uptake of low-carbon and energy-efficient technologies, and considering digitalization as an important part of the transformation could be a key driver for low-carbon technology innovation. It follows that its relevant research findings need to be further expanded (Sareen and Haarstad, 2017) [26]. This leads to the hypothesis that:

H1: Digital transformation is positively influencing low-carbon technology innovation.

The Mediating Role of Knowledge Reconstruction

In the process of digital transformation, the basis on which the technology innovation of companies is supported is the knowledge reconstruction capability. The essence of knowledge reconstruction lies in knowledge exchange under the premise of knowledge diversity and heterogeneity. Knowledge exchange is the basis for manufacturing companies to carry out knowledge innovation reconstruction (Prieto, Revilla and Rodríguez-Prado, 2009) [27]. Knowledge is the inexhaustible power for the sustainable development of manufacturing companies. Manufacturing companies should not only "manufacture", but also "create", develop and create wisdom for their existing products, operation and management. This requires manufacturing companies to have a certain stock of knowledge. At the same time, it also puts forward certain requirements on the knowledge flow of companies, and companies need to continuously exchange knowledge to improve the knowledge flow of companies (Zhang and Hao, 2018) [7]. In addition, manufacturing companies should actively source external knowledge, continuously improve the marginal value of knowledge elements, and lay the foundation for companies to reconstruct knowledge and create new knowledge (Prieto et al., 2009) [27]. The core of digital transformation is a holistic and comprehensive transformation using new digital technologies, including mobile internet, artificial intelligence and blockchain. In this process, companies need to break the traditional innovative knowledge system, integrate new digital technologies, and carry out knowledge reconstruction. In the era of digital connectivity, the frequency and speed of knowledge flow have been accelerated. Knowledge is embedded and coupled with each other, generating many knowledge flows and facilitating knowledge reconstruction for companies (Fleming, 2001, Li et al., 2022) [9, 28]. Knowledge reconstruction means breaking down and starting over. A company can continuously absorb and utilize new knowledge elements, actively change the original knowledge system and form a new, more valuable knowledge system. It is also a source of technology innovation for companies. The ability to reconstruct knowledge is crucial to the effectiveness of a company in integrating internal and external innovation resources (Li et al., 2022) [28]. The digitalization process, whether it is improving production processes, changing management models or optimizing operations, has to a certain extent accelerated the pace of knowledge reconfiguration in companies, thus promoting low-carbon technology innovation (Prieto et al., 2009) [27]. Knowledge reconstruction not only achieves the purposeful diffusion and dissemination of heterogeneous knowledge among different organizations, but also promotes the intermingling of knowledge in the process of knowledge reconstruction, realizing knowledge optimization and generating new knowledge that can be used by companies to carry out technology innovation (Lv et al., 2019, Laursen and Salter, 2006) [19, 29]. When a company has a strong ability to reconstruct knowledge, it means that it can continuously absorb and use new knowledge elements, or even break the inherent knowledge system, reshape new knowledge structures, form more valuable innovation resources, and improve the level of low-carbon technology innovation in the companies (Wang et al., 2020) [8]. Therefore, the following assumptions are proposed:

H2: Digital transformation is positively affecting knowledge reconstruction.

H3: Knowledge reconstruction plays a mediating role in the impact of digital transformation on low-carbon technology innovation.

The Moderating Role of Knowledge Sharing

Knowledge sharing is seen as the process of knowledge diffusion from sender to receiver (Hooff, Schouten and Simonovski, 2012) [30], i.e. the process of mutual knowledge exchange, experience exchange and cooperation between companies (Ma, Tang and Zheng, 2021) [31]. The rapid development and application of digital technologies and new models have enabled knowledge sharing across geographical boundaries, and companies can exchange knowledge online with companies in other regions through the network at lower costs and faster speeds to acquire new knowledge, i.e. the process of digital transformation has led to the expansion of the scope, frequency, and extent of knowledge sharing between companies, which in turn promotes the reconstruction of knowledge (Chen and Shen, 2020) [32]. In addition, knowledge sharing makes the diversity and heterogeneity of knowledge increase, and the more likely it is to generate knowledge reconstruction behaviors. In the process of digital transformation, knowledge sharing can facilitate the exchange and interaction between internal and external knowledge elements and deepen knowledge reconstruction. Knowledge not only needs to be shared but also needs to be integrated efficiently to enhance the degree of knowledge interaction and increase the breadth and thickness of knowledge, thus further enhancing innovation performance (Hilbert and López, 2011) [33]. This leads to the hypothesis that:

H4: Knowledge sharing positively moderates the positive relationship between digital transformation and knowledge reconfiguration.

During the digital transformation process, the degree of collaboration and trust between companies feels the impact of willingness to share knowledge, which affects low-carbon technology innovation. A higher level of knowledge sharing encourages the formation of shared values and cooperation norms among collaborating companies, improving trust and communication between employees on both sides and enhancing organizational cohesion, thereby assisting companies in promoting low-carbon technology innovation (Fleming, 2001) [9]. Digital transformation is disrupting traditional knowledge-sharing mechanisms, which can facilitate knowledge-sharing between innovation agents within and outside the company.

Each innovation subject uses knowledge sharing to gain more knowledge and establish a mechanism for knowledge integration, leading to improved company's technology innovation performance through systematic development. With the rapid development of the Internet and digital economy, numerous interactive innovation communities have emerged relying on Internet platforms. These communities provide a convenient and effective integration of knowledge sharing, the use of external resources to facilitate cross-organizational knowledge sharing, and value-added knowledge and open innovation for companies. Through these approaches, innovation costs are shared, innovation risks are reduced, complementary strengths are formed and innovation efficiency is improved (Chen and Shen, 2020, Hilbert and López, 2011) [32, 33].

This leads to the following hypothesis:

H5: Knowledge sharing plays a moderating effect in the relationship between the impact of digital transformation on low-carbon technology innovation

Experimental

Samples and Data

More than 2,000 pilot carbon trading companies in 30 Chinese provinces and cities were chosen for this paper, based on the carbon emissions trading website and the National Companies-Information Publicity System, with ST and *ST companies with missing data and financial anomalies excluded. The study included 270 companies in the carbon and related manufacturing industries (general equipment, pharmaceuticals, chemical fibers, special equipment, and other industries that use high-carbon or low-carbon technology in their production). These businesses are involved in developing high- or low-carbon technology. This paper uses a questionnaire to obtain research data. The respondents are mainly middle and senior management and some R and D personnel of Chinese manufacturing companies, who have been working in the surveyed companies for more than three years, and have a general understanding of the overall situation of the company and the quality of innovation. In designing the questionnaire, reference was made to more established national and international scales. Additionally, questionnaires were distributed to MBA and EMBA students, amended based on relevant feedback, and finally used in the formal research.

Due to the impact of the COVID-19, The data was collected mainly by telephone and mail, with 68 valid data obtained from telephone interviews and 324 valid data obtained from emails. Of these, 94 questionnaires were distributed to senior managers, with 48 validly returned, 322 questionnaires were distributed to middle managers, with 237 validly returned, and 198 questionnaires were distributed to R and D staff, with 107 validly returned. This data collection involved the distribution of 614 questionnaires, of which 392 were validly returned (return rate of 63.8%). Considering the use of individual-level sample data (managers and employees) to study the organizational level, the data were tested and aggregated (aggregated validity greater than 0.60) before the empirical analysis. In addition, a factor analysis of all questionnaire items yielded a loading of 37.09% for the first unrotated factor, which is not a severe homophily bias and can be investigated further.

Measurement of Variables

Explained variable: low-carbon technology innovation. Low-carbon technology innovation, as the most critical economic production factor, is mainly aimed at reducing carbon emissions in the production process. In this paper, by drawing on the relevant studies of Chen and Zeng (2019) [15], Fang et al. (2016) [34] and considering the existing situation of low-carbon manufacturing companies, we designed the questions mainly from the perspective of companies' investment in low-carbon technology innovation, which contains six questions in total. For example, "companies are investing an increasing proportion of their total equipment asset investment in low-carbon technology

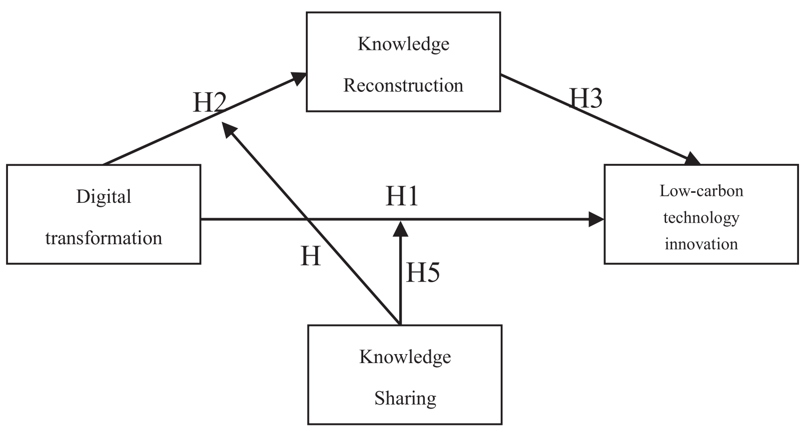

Fig. 1. The impact model of knowledge sharing, knowledge reconstruction, digital transformation and low-carbon technology innovation.

innovation equipment", " companies are using digital technology to transform and upgrade existing business processes."

Explanatory variable: digital transformation. The core of digital transformation is to use new digital technologies such as mobile internet, artificial intelligence, and blockchain to carry out the holistic and comprehensive transformation, improve production processes, change management models, optimize marketing methods and improve customer experience. These are to unleash the amplifying, superimposing and multiplying effects of digital on economic development (Yin and Tian, 2021) [12]. Based on the actual situation of manufacturing companies in China, the scale of Yang and Wang (2021) [14] and Chi et al. (2020) [35] was used to design five questions, mainly based on the application of digital transformation in manufacturing companies in China. For example, "Companies are developing digital products and services" and "Companies are using digital technologies to transform and upgrade existing business processes."

Mediating variable: knowledge reconstruction. The essence of knowledge reconstruction lies in the absorption, deconstruction, reconstruction, coupling, and interaction of knowledge. Knowledge reconstruction is a continuous and dynamic process. Drawing on the studies of Li et al. (2022) [28], Karim et al. (2000) [36] and Zhou et al. (2012) [37], five questions are designed from three aspects of knowledge expansion, knowledge integration and knowledge reconstruction based on the perspective of knowledge resources view. For example, "Companies actively integrate key ideas and technical knowledge" and "Can expand and integrate knowledge from multiple perspectives and channels."

Moderating variable: knowledge sharing. Knowledge sharing is the process of knowledge exchange between companies. Based on the studies of Alavi and Leidner (2001) [38] and Xu et al. (2020) [11], this paper designed four questions: knowledge-sharing degree, willingness to share, sharing efficiency and sharing effectiveness. For example, "High willingness to share knowledge among companies" and "Significant knowledge sharing effect among companies."

In addition, using Xu et al. (2020) [11] and Li et al. (2022) [28] as references, this paper selected firm age, frequency of interaction, R&D investment, and companies-scale as its control variables. Companies age has existed may impact its management philosophy and adaptability, thus its support for low-carbon technology innovation (2022) [28]. Variations in firm size may differentiate innovation resources, innovation base, and innovation talent pool, which affects the capacity and quality of low-carbon technology innovation (Fleming, 2001, Li et al., 2022) [9, 28], measured by the number of employees. The frequency of interactions affects the efficiency of innovation by influencing the interaction between departments and employees within the company (Fleming, 2001) [9]. R&D investments significantly contribute directly to firms low-carbon technology innovation (Li et al., 2022) [28]. All latent variables were measured using a Likert Level 5 Scale except for the control variables.

Results and Discussion

Reliability and Validity Tests

In terms of structural validity, the models of digital transformation, knowledge reconfiguration, knowledge sharing, and low-carbon technology innovation were well-fitted ($X^2/df = 1.730$, NFI = 0.949, CFI = 0.978, TLI = 0.974, RMSEA = 0.043), in terms of convergent validity, it shows that digital transformation, knowledge reconfiguration, knowledge sharing, and low-carbon technology innovation correspond to the same constructs, all topic factor loadings exceed 0.5, indicating that the topics mentioned in each latent variable are highly representative. In addition, the mean-variance AVE of each latent variable is more significant than 0.5, and the combined reliability CR is greater than 0.7, indicating that the convergent validity is ideal (Table 1), from the KMO and Bartlett's tests, the KMO statistics of each scale are more significant than 0.7, which is suitable for factor analysis, and Bartlett's spherical test the original hypothesis. Each variable has a strong correlation, from the reliability, the formal survey in terms of reliability, the Cronbach Alpha reliability coefficients of the subscales represented by each questionnaire factor are all greater than 0.80 and based on the criteria above. From the reliability coefficient table, it can be concluded that the questionnaire's reliability is optimal. In conclusion, the reliability and validity of this study are high.

Correlation Analysis and Covariance Testing

The correlation coefficients between digital transformation, knowledge reconfiguration, low-carbon technology innovation, and knowledge-sharing models are all less than the square root of the respective AVE (Table 2), indicating that each latent variable is correlated with and differentiated from the others, i.e. demonstrating the rationality of the discriminant validity of the scale data. In addition, it reveals that digital transformation is significantly positively correlated with knowledge reconfiguration and low-carbon technology innovation (β = 0.449, $p<0.01$,β = 0.427, $p<0.01$),but not with knowledge sharing (β = 0.024), knowledge reconfiguration is significantly positively correlated with low-carbon technology innovation (β = 0.416, $p<0.01$) but not with knowledge sharing (β = -0.026). Based on the Max-VIF values of less than 10 (Table 2 and Table 3), it is evident that multiple co-linearity is not a significant issue. The relationship between the variables in this study can be initially supported, and the research hypothesis can be tested further.

Table 1. Checksum test.

Dimensionality	Title content and sources	Factor load	AVE	CR	KMO	α
Digitalization Transformation	There is a consensus within companies that the use of digital technology can facilitate business development 14	0.834	0.693	0.918	0.89	0.918
	Full diffusion of digital technology within the companies [14, 35]	0.853				
	Companies are operating business processes based on digital technology 35	0.842				
	Companies are using digital technologies to transform and upgrade existing business processes 35	0.803				
	Companies are developing digital products and services 14	0.828				
Knowledge Reconstruction	Firms can bring in external knowledge 28	0.834	0.678	0.913	0.889	0.891
	Firms have the ability canal sources of knowledge 28	0.87				
	Companies have the ability cany the use external knowledge 28	0.824				
	Companies can exchange rate knowledge from multiple perspectives and channels 36	0.809				
	Companies actively engage in the integration of key ideas and technical knowledge 37	0.777				
Knowledge Sharing	The level of social capital between firms influences the degree of knowledge sharing 11	0.756	0.633	0.873	0.808	0.872
	High willingness to share knowledge among companies 11	0.775				
	The degree of knowledge sharing at the early stage of cooperation between companies a flow-carbon effects the efficiency of sharing at the later stage of cooperation 11	0.818				
	Significant inter-company knowledge sharing [11, 38]	0.831				
Low-carbon technology innovation	An increasing proportion of total sales of products developed by companies with low-carbon technologies [15, 34]	0.804	0.689	0.93	0.918	0.917
	The number of valid invention patents granted to companies for low-carbon technologies is increasing as a proportion of the number of patents granted to companies 15	0.846				
	The proportion of corporate investment in low-carbon technology innovation to total corporate R&D investment is gradually increasing [15, 34]	0.833				
	The number of corporate personnel for low-carbon technology innovation as a proportion of R&D personnel is gradually increasing [15, 34]	0.807				
	Companies are investing an increasing proportion of their total equipment asset investment in low-carbon technology innovation equipment 15	0.835				
	Increasing replacement of legacy production models by firms due to low-carbon technology innovation 15	0.853				

Main Effects Test

Test of principal effects. The first hypothesis asserts that digital transformation positively influences the development of low-carbon manufacturing technologies. To test this hypothesis, this paper first examines the impact of control variables on disruptive green technology innovation and then incorporates the independent variable (digital transformation) into the regression equation. The model Ma4 (Table 3) demonstrates that digital transformation has a statistically significant positive effect on low-carbon technology innovation ($\beta = 0.414$, $p<0.001$), confirming H1. According to Puzyrny et al. (2021) [22], digitalization is an endogenous driver of innovation in low-carbon technologies. In the meantime, model Ma2 demonstrates that digital transformation positively influences the reconfiguration of corporate knowledge ($\beta = 0.435$, $p<0.001$), thus confirming hypothesis H2.

Testing for Intermediation Effects

In model Ma6, after controlling for the independent variable digital transformation, the effect of the

Table 2. Correlation analysis.

	1	2	3	4	5	6	7	8
1 age	1							
2 Frequency of interactions	-0.082	1						
3 R&D investment	0.041	-0.038	1					
4 Companies size	0.044	-0.030	0.011	1				
5 Digital transformation	0.002	-0.092	-0.036	-0.066	**0.832**			
6 Knowledge Reconstruction	0.056	0.012	-0.107*	-0.056	0.449**	**0.823**		
7 Knowledge Sharing	0.108*	-0.036	0.033	-0.048	0.024	-0.026	**0.796**	
8 Low-carbon technology innovation	-0.082	-0.015	0.017	0.075	0.427**	0.416**	0.083	**0.830**

Note: * denotes P<0.05, ** denotes P<0.01, *** denotes P<0.001, bold values are the root mean square of AVE for each scale.

mediating variable knowledge reconstruction on the dependent variable low-carbon technology innovation passed the significance test at the level of 0.001 with a coefficient of 0.290, and the coefficient of digital transformation decreased from 0.414 to 0.288 after adding the mediating variable (Table 3). According to the stepwise test of mediating effect, in the first step, the model Ma4, the effect of the independent variable digital transformation on the dependent variable was significant ($\beta = 0.414$, $p<0.001$). In the second step, in model Ma2, the effect of the independent variable digital transformation on the mediating variable was significant ($\beta = 0.435$, $p<0.001$). In the third step, after adding the independent variable, the effect of the mediating variable knowledge reconstruction on the dependent variable was significant ($\beta = 0.290$, $p<0.001$), indicating that knowledge reconfiguration plays a partially mediating role between digital transformation and low-carbon technology innovation, so H3 is proved. The reason for this is that in the process of low-carbon technology innovation in manufacturing companies, it takes time to split and reorganize knowledge, and the factors affecting low-carbon technology innovation are influenced by other factors such as the digitalization process and the industry innovation environment in addition to the ability to reconstruct knowledge, therefore, knowledge reconstruction only plays a partial mediating role.

Additionally, the Bootstrap test demonstrates that the confidence interval of the path where the indirect effect is located does not contain zero, supporting the idea that knowledge reconstruction mediates the impact of digital transformation and low-carbon technology innovation. The non-parametric estimation's confidence interval is 95%, and the Bootstrap sample size is set at 5000. The test results showed a significant indirect effect coefficient ($\beta = 0.126$) with a 95% confidence interval of [0.081, 0.178], excluding the null (Table 4). This provides more evidence in favor of the theory

Table 3. Table of regression coefficients of knowledge reconfiguration in digital transformation and low-carbon technology innovation

	Knowledge Reconstruction		Low-carbon technology innovation			
	Ma1	Ma2	Ma3	Ma4	Ma5	Ma6
Age	-0.008	-0.046	0.176*	0.140	0.180*	0.154
Frequency of interactions	0.011	0.081	-0.030	0.036	-0.035	0.013
R&D investment	-0.157*	-0.134*	0.035	0.056	0.101	0.095
Companies size	-0.079	-0.033	0.100	0.144*	0.133*	0.153*
Digital transformation		0.435***		0.414***		0.288***
Knowledge Reconstruction					0.423***	0.290***
R^2	0.014	0.213	0.018	0.202	0.199	0.270
Adj. R^2	0.004	0.203	0.007	0.192	0.188	0.258
F	1.419	20.899	1.731	19.509	19.088	23.653
D-W	2.209	2.136	2.035	1.988	1.995	1.985
Max-VIF	1.013	1.018	1.013	1.018	1.020	1.275

Table 4. Mediating Effects of Knowledge Reconstruction (Bootstrapping Test).

	Effect	BootSE	BootLLCI	BootULCI
Total effect	0.414	0. 044	0.328	0.500
Direct effects	0.288	0.047	0.195	0.380
Indirect effects	0.126	0.025	0.081	0.178

Note: Sample size = 392, coefficients are unstandardized, Bootstrap sample size is 5000.

that knowledge reconstruction functions as a partial intermediary between digital transformation and low-carbon technology innovation.

Testing for Moderating Effects

Before testing the mediated moderating model, to prevent the problem of multicollinearity between variables, the independent and moderating variables were first centralized. An interaction term was introduced between digital transformation and knowledge sharing to investigate the moderating effect of knowledge sharing. In addition, firm age, interaction frequency, R&D investment, and firm size were included as control variables in this study's comprehensive model. The correlation coefficients between digital transformation, low-carbon technology innovation, and knowledge reconstruction are all positive, and the model fit indicators RMSEA, CFI, and TLI all meet the requirements, i.e., the model fits well, validating H1 and H2 once more. From model Mb3 (Table 5), knowledge sharing plays a positive moderating role in the correlation coefficient between digital transformation and knowledge reconstruction ($\beta = 0.098$, $p<0.01$), indicating that the higher the degree of knowledge sharing, the stronger the positive relationship between digital transformation and knowledge reconstruction, supporting H4, which is consistent with Chen and Shen's study (2020) [32]. Similarly, low-carbon technology innovation is used as the dependent variable, followed by independent variables, moderating variables, and interaction terms, to verify hypothesis 5. The results of model Mb6 show that knowledge sharing positively modifies the correlation coefficient between digital transformation and low-carbon technology innovation ($\beta = 0.102$, $p<0.01$). That is, knowledge sharing enhances the correlation coefficient of digital transformation on low-carbon technology innovation, and when the degree of knowledge sharing is higher, the correlation of digital transformation on knowing low-carbon technology innovation will also increase, H5 obtained evidence. Based on the above results, theoretically speaking: First, the digital transformation process of companies has facilitated inter-firm knowledge sharing, which significantly influences the extraction and application of innovation knowledge by companies. In the digital economy driven by big data, cloud computing and artificial intelligence, the open innovation environment has built a knowledge-sharing platform for companies (Tong, 2021) [10] and facilitated inter-companies knowledge sharing. Second, inter-companies knowledge

Table 5. Adjustment analysis.

	Knowledge Reconstruction			Low-carbon technology innovation		
	Mb1	Mb2	Mb3	Mb4	Mb5	Mb6
Age	-0.046	-0.043	-0.052	0.140	0.133	0.124
Frequency of interactions	0.081	0.079	0.081	0.036	0.040	0.043
R&D investment	-0.134	-0.132*	-0.123	0.056	0.053	0.062
Companies size	-0.033	-0.035	-0.038	0.144*	0.149*	0.146*
Digital transformation	0.435***	0.436***	0.440***	0.414***	0.413***	0.417***
Knowledge Reconstruction		-0.034	-0.011		0.076	0.100*
Digital Transformation* Knowledge Sharing			0.098**			0.102**
R^2	0.213	0.214	0.237	0.202	0.207	0.232
Adj. R^2	0.203	0.202	0.223	0.192	0.195	0.218
F	20.899	17.475	16.997	19.509	16.742	16.532
D-W	2.136	2.139	2.120	1.988	1.995	1.968
Max-VIF	1.013	1.016	1.030	1.013	1.016	1.030

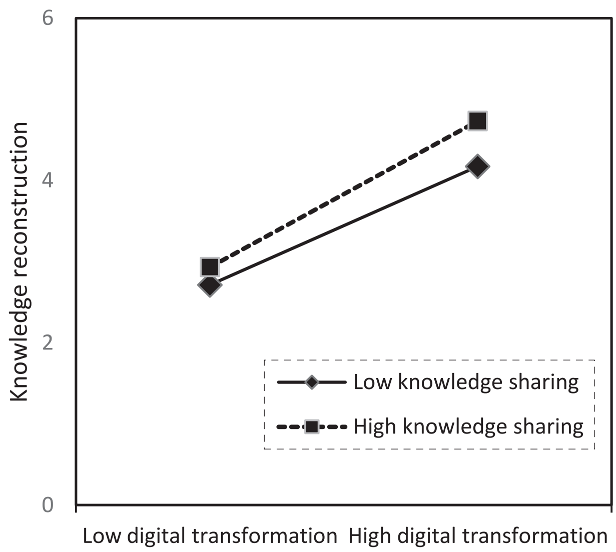

Fig. 2. Moderating effects of knowledge sharing.

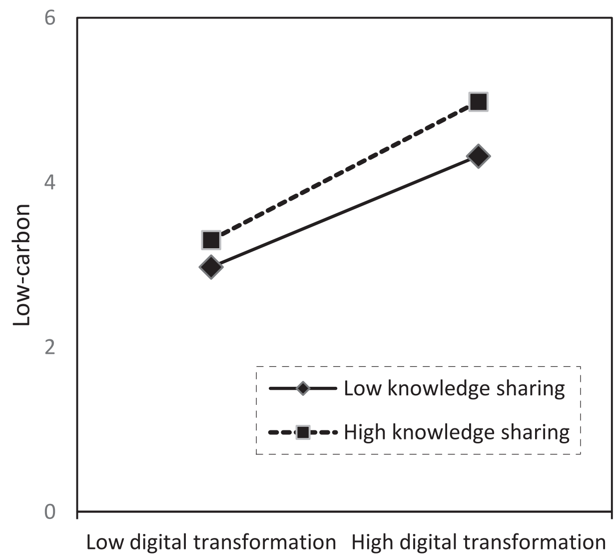

Fig. 3. Moderating effects of knowledge sharing.

sharing enhances not only companies' ability to acquire and perceive low-carbon technologies and information but also realizes efficient diffusion, absorption and integration of knowledge, which in turn enhances companies' knowledge reconfiguration while promoting low-carbon technology innovation. Thirdly, the differences in the width and depth of knowledge sharing result in different effects of knowledge reconstruction and low-carbon technology innovation. According to the theory of increasing marginal utility of knowledge, knowledge resources are more valuable than other resources because not only does the law of diminishing marginal returns not appear in the repeated use and large-scale application of knowledge, but also the value potential of knowledge will be fully stimulated due to extensive use. Therefore, the greater the width and depth of knowledge sharing, the higher the frequency of knowledge reconstruction and innovation efficiency of companies.

To further verify the moderating effect of knowledge sharing on digital transformation and knowledge reconstruction, the following conclusions are drawn: with the increase of knowledge sharing, the positive impact of digital transformation on knowledge reconstruction is rising (Fig. 2). With a high degree of knowledge sharing, the positive impact of digital transformation on knowledge reconstruction will continue to increase (Fig. 3).

Analyzing the indirect effect of digital transformation and low carbon technology innovation under different knowledge sharing, the data processing and hypothesis testing (Table 6) shows that under low knowledge sharing, the 95% CI is [0.037, 0.126], which does not contain 0, and the effect value is 0.078, indicating a significant mediating effect. Under high knowledge sharing the 95% CI is [0.101, 0.225], which does not contain 0, and the effect value is 0.160, and the difference in indirect effects between the high and low conditions does not contain 0, indicating a significant mediating effect, suggesting that there is an enhanced indirect effect of digital transformation on low-carbon technology innovation through knowledge sharing, and that the higher the knowledge sharing, the stronger the mediating effect. This is because in the process of digital transformation, company's products, technologies and management methods will develop in a diversified direction. Knowledge sharing makes knowledge and knowledge, technology and knowledge promote and integrate with each other. It deepens the low-carbon technology innovation of manufacturing companies, and the higher the knowledge sharing, the stronger its role in promoting innovation. However, after companies have acquired the required resources through social relationships, they may face the problem of "low efficiency in resource transformation". The differences in companies' knowledge absorption,

Table 6. Intermediary analysis with reconciliation.

	Effect	BootSE	BootLLCI	BootULCI
Low adjustment	0.078	0.023	0.037	0.126
High adjustment	0.160	0.032	0.101	0.225
Difference	0.082	0.009	0.011	0.047

knowledge transformation and knowledge development capabilities lead to companies heterogeneity in the moderating effect of knowledge sharing.

Conclusions

Research Findings

Knowledge has become the first productive force for the sustainable development of manufacturing companies in digital transformation. An increasing number of manufacturing companies have embarked on the path of digital transformation to achieve low-carbon technology innovation through digital transformation. In the context of the "double carbon" target, can the digital transformation of manufacturing companies effectively promote low-carbon technology innovation? How can knowledge reconstruction, an innovation source, be applied to developing low-carbon technologies? Can the exchange and interaction of knowledge and coupled reconfiguration truly drive low-carbon technology innovation? How does knowledge sharing contribute to knowledge reconfiguration and low-carbon technology innovation in conjunction with digital transformation? To investigate the above issues, this study explores the impact of digital transformation of manufacturing on low-carbon technology innovation based on the "double carbon" objective. From a knowledge perspective, the impact of inter-firm knowledge sharing and intra-firm knowledge reconfiguration behavior on low-carbon technology innovation is analyzed. It also answers the question of how knowledge management can be effectively used to digitize, and help industries upgrade their low-carbon innovation in the digital economy.

This study provides new insights into the factors and impact effects that influence the relationship between digital transformation and low-carbon technology innovation. The following are the main findings: First, digital transformation influences low-carbon technology innovation significantly, indicating that digital transformation is an essential source of motivation to promote low-carbon technology innovation. Second, knowledge reconfiguration mediates the relationship between the impact of digital transformation and the creation of low-carbon technology. The level of knowledge reconstruction capability is the determining factor in whether organizations can transfer, recreate, and sublimate knowledge more effectively. Companies with rapid digital transformation processes often have higher knowledge reconstruction ability. In the process of low-carbon technology innovation, innovative knowledge can be transformed into low-carbon technology achievements with higher efficiency. The positive relationship between digital transformation, knowledge reconstruction, and low-carbon technology innovation is strengthened by knowledge sharing. Third, knowledge sharing has strengthened the positive correlation between digital transformation, knowledge reconstruction and low-carbon technology innovation. The efficient diffusion and flow of innovation elements is the key to low-carbon technology innovation and an essential factor in starting the knowledge reconstruction process. In the dynamic environment of digital transformation, companies with high knowledge sharing can quickly understand foreign knowledge and internalize it, and then promote the efficiency of knowledge reconstruction and low-carbon technology innovation.

The theoretical contributions of this paper are listed below.

First, it confirms that digital transformation significantly promotes low-carbon technology innovation. Under the wave of digital economy and "Internet+", digitalization, VR, AI and intelligent systems are deeply integrated with the manufacturing industry, and smart product technologies are constantly being introduced, bringing economic benefits to companies. The impact of research on digitalization is theoretical primarily analysis and case studies related to financial performance, and few studies directly verify how digital transformation promotes low-carbon technology innovation. This study focuses on this issue, considering the new "double carbon" target environment, and aims to fill this gap by investigating the internal mechanisms of digital transformation as a critical driver of low-carbon technology innovation in companies. To some extent, digitalization is inherently low-carbon, transforming the paper era, and the use of intelligent OA and ERP systems is a true reflection of low-carbon technology. The company's digital transformation connects all aspects of the product, manufacturing, marketing, and management, promoting low-carbon technology innovation based on low energy consumption and high efficiency. This supports Wang's (2022) [21] study. It also adds to Zhou's (2021) [20] research, which demonstrates the inner workings of digital transformation driving low-carbon technology innovation. The digital transformation of companies has accelerated the momentum of transforming old knowledge into new knowledge and accelerated the pace of low-carbon technology innovation.

Second, only a few studies have combined digital transformation, knowledge reconfiguration, and low-carbon technology innovation into a single analytical framework. Through the mediating effect of knowledge reconfiguration, this paper delves more deeply into the mechanisms driving digital transformation for low-carbon technology innovation. Knowledge reconstruction acts as a buffer between the impact of digital change and low-carbon technology innovation. The level of knowledge reconfiguration capability is an indicator of a companies' knowledge absorption and integration effectiveness. Companies undergoing digital transformation will face internal management and operations restructuring, and such companies have high knowledge reconstruction ability and potential.

Companies with a high level of digital transformation can more efficiently reorganize knowledge and, with the help of digital technology, can often carry out low-carbon technology innovation activities effectively. As a result, there is a greater likelihood that innovative knowledge will be transformed into low-carbon technologies and products during the process of low-carbon technology innovation, which can improve product quality, enrich product features, reduce product costs, and bring more significant benefits to companies. However, due to the complexity and high requirements of low-carbon technology innovation, knowledge reconstruction only plays a part of intermediary role in the relationship between them.

Third, the essential factor of knowledge sharing is included in the theoretical framework under the mediating role of knowledge reconfiguration and the moderating effect of knowledge sharing in it is analyzed. Knowledge sharing reinforces the positive relationship between digital transformation, knowledge reconfiguration, and low-carbon technology innovation. The act of sharing knowledge across organizations increases the diversity and complexity of knowledge in the companies. building a solid knowledge base for knowledge restructuring and innovation in companies. In the digital transformation process, company's products, technologies, and management methods will develop in a diversified direction. Knowledge sharing enables knowledge and knowledge, technology and knowledge to promote and integrate, accelerating the pace of knowledge reconstruction and deepening low-carbon technology innovation in manufacturing companies.

Practical Insights

The practical implications of this paper are as follows: first, to achieve the "double carbon" goal, digital transformation is a critical path to promote low-carbon technology innovation in manufacturing companies. Manufacturing companies should actively promote digital development, as represented by big data, artificial intelligence, and 5G technology, as the driving force in achieving the "double carbon" goal to comprehensively improve their production processes, change their management modes, optimize their marketing methods, and continuously improve their customer service experience. Digital transformation and low-carbon technology innovation are intertwined and mutually beneficial processes. Taking full advantage of the digital transformation dividend to reduce the technical costs of low-carbon innovation and improve innovation efficiency can promote companies' green, low-carbon and high-quality development. Secondly, in the process of digital transformation, the stronger the knowledge reconstruction ability of companies, the better they can integrate new digital technologies and carry out low-carbon technology innovation. In the process of digital transformation, companies will face the splitting and restructuring of their original knowledge structure. At this time, companies should focus on the interaction and restructuring between heterogeneous knowledge to form more valuable knowledge resources. In addition, companies should not only increase their investment in low-carbon technology research and development and talents to improve their knowledge reconstruction capability, but also divide the knowledge reconstruction into a series of sub-divisions, so as to improve the efficiency of the whole process of knowledge reconstruction mechanism from the details, efficiently integrate internal and external knowledge and source external knowledge, so as to build up strength for low-carbon technology innovation of companies. Thirdly, in the process of digital transformation, companies should actively build a high-quality knowledge sharing relationship network and create a digital transformation knowledge ecosystem to facilitate better low-carbon technology innovation activities. Digitization facilitates knowledge sharing among companies. Companies should actively engage in knowledge sharing, mutual knowledge exchange, experience sharing and cooperation for mutual success, promote the establishment of an industry knowledge ecosystem, continuously broaden the breadth, depth and width of knowledge sharing, and increase knowledge diversity and complexity. From the core companies as the center, we will drive the marginal companies and promote the parallel progress of large, medium and small companies, so as to promote the low-carbon technology innovation of companies and even industries, so as to achieve the sustainable development of China's economy and guarantee the smooth realization of the "double carbon" target. In addition to strengthening knowledge sharing with external companies, companies should also promote knowledge sharing among employees and departments within the companies by adopting a shared leadership style or creating a shared atmosphere, to lay the foundation for low-carbon technology innovation.

Limitations and Prospects

This study has some remaining flaws and will need to be improved in the future. First, due to data availability and changes in objective scenarios, the data in this study are collected in questionnaires, which may lead to standard methodological deviations. Future research can expand different data levels for robust analysis. Second, this paper's empirical research focuses on the Chinese manufacturing industry. Future research could expand the scope of the sample data to include other sectors or differences between sectors as samples to empirically validate the theoretical model and make the research more generalizable. Finally, in addition to the intermediary effect of knowledge reconstruction and the regulating effect of knowledge sharing that this paper focuses on, low-carbon technology innovation may also be affected by other heterogeneity factors, such as innovative human capital, industrial structure, etc., which is the focus of further research in the future.

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Conflict of Interest

The authors declare no conflict of interest.

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