systems

MDPI

Article

Digital Economy and Intelligent Manufacturing Coupling Coordination: Evidence from China

Wanyu Zhang and Fansheng Meng *

School of Economics and Management, Harbin Engineering University, Harbin 150001, China; zhangwy@hrbeu.edu.cn
* Correspondence: mengfanshen@hrbeu.edu.cn

Abstract: The digital economy uses its own digital information advantages to reduce the intensity of energy consumption brought by economic growth. Intelligent manufacturing achieves cost reduction and efficiency through the integration of manufacturing and intelligence as well as digitalization and information technology. The two have become a new engine for sustainable economic development at present, and they can promote and influence each other. However, there is a lack of research on the relationship between them. In this regard, this study aims to build a coupling coordination model of digital economy and intelligent manufacturing and to make an empirical analysis using the data of Chinese provincial administrative regions in order to provide a theoretical reference for promoting sustainable economic development. The research finds that (1) the digital economy and intelligent manufacturing are mainly cross-coupled from four aspects: infrastructure, technological innovation, product optimization and organizational change. The development level and speed of the former are significantly higher than those of the latter, and the gap does not decrease with time. The two have a strong correlation, but there is no high-quality coupling coordination. (2) The main obstacle factors to the digital economy lie in the imperfect supporting facilities, the short board of technological innovation and the lack of technological application capacity. Intelligent manufacturing lacks intelligent application and technological innovation. (3) Influencing factors such as opening to the outside world, economic development, high-level talent input, industrial structure and innovation emphasis have different effects on their coupling and coordinated development in different regions. (4) The spatial correlation test shows that the coupling coordination degree of each region is spatially positively correlated. This research helps to promote the coupling and coordinated development of the digital economy and intelligent manufacturing.

Keywords: digital economy; intelligent manufacturing; coupling coordination; obstacle factors; influencing factors; spatial correlation

Citation: Zhang, W.; Meng, F. Digital Economy and Intelligent Manufacturing Coupling Coordination: Evidence from China. *Systems* **2023**, *11*, 521. https://doi.org/10.3390/systems11100521

Academic Editor: William T. Scherer

Received: 26 September 2023
Revised: 16 October 2023
Accepted: 17 October 2023
Published: 19 October 2023

1. Introduction

The intensification of energy consumption and serious environmental pollution have aroused people's awareness of environmental protection. The intensive economic growth model has replaced the extensive one, and the governments of all countries have listed sustainable economic development as a long-term goal. Due to the popularization of informatization and market demand, the digital economy (*DE*) has emerged at a historic moment, providing new impetus for global economic development [1]. *DE* refers to the economic form that uses data directly or indirectly to guide resources to play a role and promote the development of productivity. As a branch of emerging economies, *DE* can significantly reduce the cost of searching, transmitting and copying information; reduce the energy consumption intensity brought by economic growth [2]; and is expected to achieve sustainable economic development [3].

China's economic situation is improving, but the increase in environmental pollution cannot be ignored [4]. The International Energy Agency (IEA) points out that China is one of the major energy producers and consumers, and its carbon emissions cannot be ignored [5]. In other words, China should not only rejoice in economic progress but also be wary of excessive environmental costs [6,7]. Without harming the environment under the premise of economic development, China must change the traditional economic development model and explore new paths to promote sustainable economic development.

The *DE* has entered many fields and has gradually become a "stabilizer" and "accelerator" for China's national economy, which can not only optimize the stock but also provide an increase. Although the *DE* is gaining momentum, it does not mean that the real economy is no longer important. The *DE* and the real economy are a correspondence between the new economy and the traditional economy. Healthy *DE* and the real economy should be integrated and promote each other [8]. As the main body of the real economy, the manufacturing industry is the key to whether China's economy can achieve high quality [9]. Therefore, promoting the integration of the *DE* and the real economy, especially the manufacturing industry, is of positive significance to China's sustainable economic development.

Industry 4.0 promotes the global manufacturing industry to move towards digitalization and intelligence. In order to improve their competitive advantage in the world, many developed countries compete to list intelligent manufacturing (*IM*) as the future of their own manufacturing industry [10]. In this regard, China has issued relevant policy guidance and other ways to achieve the purpose of accelerating the successful realization of *IM*. *IM* is a specific manifestation of manufacturing intelligence, which refers to a collaborative manufacturing system that realizes real-time response through manufacturing software systems and robots to meet the changing needs of factories, supply networks and customers. *IM* can improve production efficiency, reduce product costs, strengthen manufacturing flexibility and bring the possibility of sustainable manufacturing [11–13]. Enhancing China's competitive advantage in *IM* is an important strategic measure for China to meet various future challenges such as anti-globalization and trade frictions. Promoting the development of *IM* is not only the only way for China to achieve manufacturing power but also the main means of sustainable economic development.

China's 14th Five-Year Plan lists *IM* as a key task in the deep integration of the *DE* and the real industry. *IM* depends on the industrial ecology and industrial layout of the *DE* in the region, and the realization of *IM* is also conducive to the healthy development of the *DE* [14]. To sum up, this paper believes that *DE* and *IM* have two-way coupling advantages and coupling needs, and strengthening the coupling coordination of *DE* and *IM* is the focus of the integrated development of the *DE* and real economy and is also a new path to achieve sustainable economic development. There is a close relationship between *DE* and *IM*, which has been affirmed by many scholars [15–17], but most of them only generally point out that *DE* and *IM* provide a positive role for the development of the other side, and there are few literature studies on the specific relationship and how to facilitate their coupling and coordinated development. Based on this situation, we are committed to solving the following questions: (1) Is there a coupling coordination relationship between *DE* and *IM*? (2) How can the coupling and coordinated development of *DE* and *IM* be promoted? In order to solve these problems, we first calculated the development index of *DE* and *IM* and its coupling degree and coordination degree of each provincial administrative region in China and used the coupling evolution model and obstacle degree model to clarify the development trend and obstacle factors of the two subsystems, and we also studied the influencing factors and spatial correlation of the coupling coordination degree of *DE* and *IM*.

Realization Contribution: First, from the perspective of coupling coordination, it innovatively integrates *DE* and *IM* into the same framework, builds a theoretical model of the coupling and coordinated development of *DE* and *IM* through logical reasoning and reference to the existing literature and makes empirical analysis using the data at the provincial level in China. In the context of the rapid development of *DE* and *IM* and the requirements of sustainable economic development, from the perspective of coupling and coordination of

DE and *IM*, the theoretical research of *DE* and *IM* is enriched and provides a realistic basis for the sustainable economic development of China's provincial administrative regions as well as a reference for other countries to promote the coupling and coordinated development of *DE* and *IM*. Second, based on the internal perspective of the coupled system, the development trend and obstacle factors of *DE* and *IM* are analyzed, and the development obstacles of *DE* and *IM* are pointed out for each provincial administrative region in China. It not only deepens the application of the coupled system theory in the field of *DE* and *IM* but also helps the relevant provincial units in China to formulate the development strategy of *DE* and *IM*. Third, based on regional development and spatial interaction, explore the influencing factors and spatial correlation of the coupling coordination degree of the two and provide a path for the coupling and coordinated development of *DE* and *IM* from the perspective of regional development and the connection between regions. The research results not only enrich the research field on the relationship between *DE* and *IM* but also provide new ideas for promoting the coupling and coordinated development of *DE* and *IM*.

The arrangement of the remaining chapters is as follows: Section 2 reviews the current literature research status and builds a theoretical model. Section 3 describes the sample data, research variables and research models. Section 4 conducts empirical tests and discusses the research results. Section 5 is the conclusion and puts forward policy recommendations and limitations.

2. Literature Review and Mechanism Construction

2.1. Literature Review

The digital economy theory points out that the key elements of the *DE* are data resources, and the emergence of the *DE* as the optimal allocation of resources provided may promote fairness and a more unified efficiency. *DE* has brought new forms of business and new business models [1] and can also promote low-carbon emission reduction through digital and intelligent development [14,18]. Along with the *DE* of the environmental impact of heat, the academic circles about the relationship between the two influences have increased [19]. Balcerzak et al. (2017) indicated that the *DE* is an effective way to achieve sustainable development and accelerate regional coordinated development [3]. Furthermore, scholars have verified the positive effects of the *DE* on environmentally sustainable development from the perspectives of curbing carbon emissions, promoting green innovation and energy structure transformation. Zhang et al. (2022) proved through empirical analysis that the *DE* can achieve regional low-carbon development [20]. Wang et al. (2022) highlighted that the *DE*, which includes digital infrastructure, innovative application, economic growth and employment, can promote green technology innovation and thus curb carbon dioxide emissions [21]. Yi et al. (2022) once again supported this view from a spatial perspective [22]. Zhang et al. (2022) showed that the *DE* is optimistic about the scale of energy consumption and urban greening [23]. Shahbaz et al. (2022) emphasized that the *DE* improves the governance capacity of the government, thereby improving the renewable energy structure and contributing to the global energy transition [24]. Luo et al. (2023) pointed out that the *DE* can enhance green innovation [25]. Wu et al. (2023) found that the *DE* can improve energy efficiency and promote sustainable urban development [26]. Ren and Zhang (2023) also gave recognition to this view from the Chinese provincial level [27].

The importance of manufacturing in the real economy is self-evident, since Industry 4.0, as China will use *IM* as the future development goal of manufacturing but also to strengthen the international competitive advantage of the manufacturing industry as a new engine [28,29]. Fisher et al. (2020) said the manufacturing industry with advanced technology, to help manufacturing from linear transformation for circulation, is the effective way to sustainable manufacturing [13]. The intelligent manufacturing theory points out that *IM* uses digitalization, networking, intelligence and other means to realize the automation, visualization, traceability and other modern manufacturing methods of the production process, which are indispensable parts of Industry 4.0 and provide new ideas for reducing resource consumption and environmental pollution [30]. Many scholars also understand the importance of *IM* for sustainable development. Zhou et al. (2018) found that *IM* represents the integration of manufacturing and advanced technology, which is conducive to improving product quality, reducing resource consumption and moving toward sustainable manufacturing [10]. He et al. (2021) believes that *IM* can achieve higher quality assurance and production efficiency at a lower cost [11]. Chen et al. (2021) proposed that *IM* optimizes the product design and manufacturing process, reduces resource and energy consumption and is in line with sustainable manufacturing [12]. Kim et al. (2022) believe that *IM* enables flexible, efficient and sustainable product manufacturing [31]. Lan and Chen (2023) said that the realization of *IM* can shorten production time, reduce power consumption, help enterprises rationally allocate resources and achieve green and sustainable development [32]. Sun and Diao (2023) argue that *IM* utilizes advanced technologies that help determine the energy needs of internal and external users and integrate with production systems to achieve sustainable production and outcomes [33]. Further, Yang and Shen (2023) found that accelerating the transformation of *IM* is an opportunity for the green development of manufacturing [34].

For *DE* and *IM*, scholars not only proved the positive role of *DE* and *IM* for energy conservation and emission reduction but also discussed their relationship. In 2018, Kovacs pointed out the complex relationship between the *DE* and Industry 4.0 [15]. *IM*, which plays a key role in industry 4.0, is also inextricably linked to the *DE*. A good *DE* development situation provides a basic guarantee to realize *IM* and endogenous power [8,35] and, at the same time, the implementation of *IM* technology transformation in favour of *DE* [9,35]. Rajput and Singh (2020) proposed that digital transformation paves the way for data-driven, intelligent, networked and resilient manufacturing systems [16]. Jiao et al. (2021) pointed out that digital development plays an important role in promoting the realization of Industry 4.0 [36]. Martin-Gomez et al. (2021) proposed that digitization and informatization are important factors for realizing the intelligent, connected and sustainable development of manufacturing industry [37]. Yin et al. (2022) and Garcia et al. (2022) agree with this statement [9,38]. Fang and Chen (2022) showed that *DE* can promote the manufacturing industry to solve information access barriers, improve production efficiency and accelerate transformation and upgrading [17]. Turner et al. (2022) explained the close connection between digitalization and industrial upgrading from the perspective of digital production equipment and intelligent products [39]. Based on the measurement and analysis of the relevant literature on *IM* and digitalization, Barbosa et al. (2022) found that many studies pointed out that improving digital infrastructure and strengthening the application of digital technology could support the evaluation and market supervision of *IM* [40]. Liu et al. (2023) analyzed the thought of *DE* and found that it can drive the intelligent transformation and upgrading of traditional manufacturing industry [41].

To sum up, the *DE* and *IM* for energy conservation and emission reduction improve production capacity. Hence, accelerating the realization of *DE* and *IM* has become a new path for China to promote sustainable economic development. Scholars have demonstrated the positive role of the *DE* and *IM* in achieving sustainable development from reducing pollution emissions to strengthening green innovation. Therefore, exploring the path of accelerating the development of *DE* and *IM* is not only of great theoretical significance for enriching the theory of digital economy and intelligent manufacturing but also of great practical significance for promoting China's sustainable economic development. At present, many scholars have found that there is a complex interaction between *DE* and *IM*, which seems to be inspiring and providing a new way to promote the progress of *DE* and *IM*. However, the excessive focus on theoretical analysis and the relationship between the two are limited to vague description, which also makes the complex interaction between them lack systematic research. In the face of the growing demand for resources and environmental pollution, the rapid development of *DE* and *IM* has been put forward in order to further achieve sustainable economic development. In the existing literature, it is pointed out that *DE* and *IM* have a mutually promoting and mutually supporting relationship, which means that *DE* and *IM* are likely to have a complex coupling relationship of interdependence and mutual promotion in the development process. If the coupled and coordinated development of *DE* and *IM* can be promoted, it will be more conducive to the realization of economic sustainability. In this regard, based on the coupling and coordination theory, this paper innovatively puts *DE* and *IM* in the same research framework, verifies the coupling and coordination relationship between *DE* and *IM* and explores the path to realize the coupling and coordination development of *DE* and *IM*. The aim is to promote the cross-integration of digital economy and intelligent manufacturing theories, enrich the application of coupling and coordination theory and also provide a reference for achieving sustainable economic development.

2.2. Coupling Coordination Mechanisms of DE and IM

The *DE* relies on information technology to break the space constraint and strengthen regional economic linkage [23]. This advantage is used to strengthen cooperation and sharing of innovation resources among regions, reduce innovation costs [1], push the transformation of energy consumption and reduce carbon emission intensity [42]. *IM* is an integral part of Industry 4.0 and a new option for sustainable manufacturing [12]. By integrating information technology with manufacturing, *IM* has become a leading force in the implementation of clean strategies [43].

DE and *IM* are two complex nonlinear systems, both of which are important means to achieve sustainable economic development. The two systems also have a complex coupling relationship that depends on each other and promotes each other. The *DE* provides the development guarantee and impetus for *IM* [8,9], and *IM* promotes the transformation of the technological achievements of the *DE* [44,45]. Promoting the coupling and coordination of the *DE* and *IM* has promoted the combination of the *DE* and the industrial field, accelerated the realization of *IM* and further contributed to the outbreak of a global dual revolution in which the scientific and technological revolution and the new industrial revolution complement each other. Based on the coupling of internal and external innovation environment and system elements, this study analyzes the coupling coordination mechanism of *DE* and *IM*.

At the infrastructure level, *DE* integrates hardware and software. The improvement of *DE* infrastructure provides strong system support and reliable network guarantee for information construction in various fields, facilitates the sharing and integration of innovation resources in various industries and regions [9], realizes cross-border integration, and promotes the integration of the *DE* and the real economy. *DE* infrastructure, through the realization of data collection, storage, etc., and through the supply chain and sales chain design, manufacturing and sales and other links, not only greatly reduce business friction but also reduce the search, transmission and replication of information costs [1], providing conditions for the realization of *IM*. *IM* is conducive to the high integration of digitalization, networking, intelligence and industrial modernization [46], and it can fully and widely share and utilize the globally distributed production resources and manufacturing resources so as to maximize the value of digital infrastructure, promote the reuse of resources and achieve sustainable economic development.

At the technical level, *IM* means that enterprises use digital technology to realize digital, networking and intelligent transformation of traditional manufacturing methods and management modes, from cross-departmental transformation to intelligent upgrading, and realize the transformation of the path and mechanism of manufacturing upgrading. The main reason for this fundamental change is that the wide application of digital technology in traditional manufacturing enterprises has made the technical versatility between various industries continue to improve, has made the industrial boundaries continue to blur, and the trend of industrial integration continues to strengthen. The *DE* and digital technology can solve the difficulties and pain points of *IM* by cracking the technical bottleneck of *IM*, improving the competitive advantage and production efficiency of the manufacturing industry [47], and accelerating the realization of *IM*. As a new economic form, the matching and support degree of various industrial sectors has a great impact on the development of the *DE*. The manufacturing industry, through digital information technology, completes machine replacement and value-added value chain, improves the total factor productivity of traditional industries, realizes automated capacity optimization, quality optimization and efficiency optimization and enhances the competitive advantage in the era of *DE* [14,48].

At the product level, *DE* can guide enterprise innovation and product development through digital technology, enhance product quality and create new value [23], improve production efficiency and change consumption patterns. *DE* makes it so that the demand side and supply side of production data can be connected at the same time, so that enterprises can gain accurate insight and rapid response in the face of consumption upgrading, the rapid change of the market and the personalized needs of massive customers, provide pertinence and directivity for enterprise product production, and improve the willingness of enterprises to *IM*. The product production link of *IM* belongs to the application layer of *DE* to a certain extent, enabling the traditional manufacturing industry, and new technologies are applied to the entire process of product design, production, service and so on in the value chain, improving product quality and production efficiency [49]. This also promotes product customization and diversified production, achieves economies of scale and all-round service and provides consumers with value services of the whole life cycle through all-round service and customized production, improving consumer product experience [50] and thus promoting the development of *DE*.

At the organizational level, *DE* optimizes the organizational structure within and between enterprises, flattening the platform organizational structure and eliminating the need for traditional middlemen, which can significantly reduce transaction costs [17], promote large-scale innovation collaboration and achievement transformation, and accelerate the realization of *IM*. Meanwhile, the *DE* also improves the willingness of enterprises to realize the transformation of *IM*, improves the development ecology of *IM*, and further promotes the rapid development of new efficient organizational forms such as flexible production and personalized production in the manufacturing industry. Personalized production refers to on-demand manufacturing and customized production to improve production accuracy [9,51], thus greatly saving social resources and avoiding the emergence of economic excess. The efficient organization of the manufacturing industry has also accelerated the formation of industrial digitization, vigorously improved the energy efficiency of production management, reduced resource consumption, enhanced the value creation ability of the *DE* and formed a new balance between productivity improvement and environmental friendliness.

To sum up, this paper believes that *DE* and *IM* complement each other in infrastructure, technological innovation, product optimization, organizational change and other aspects, and they rely on each other to jointly promote the sustainable economic development of various regions. See Figure 1 for the theoretical model.

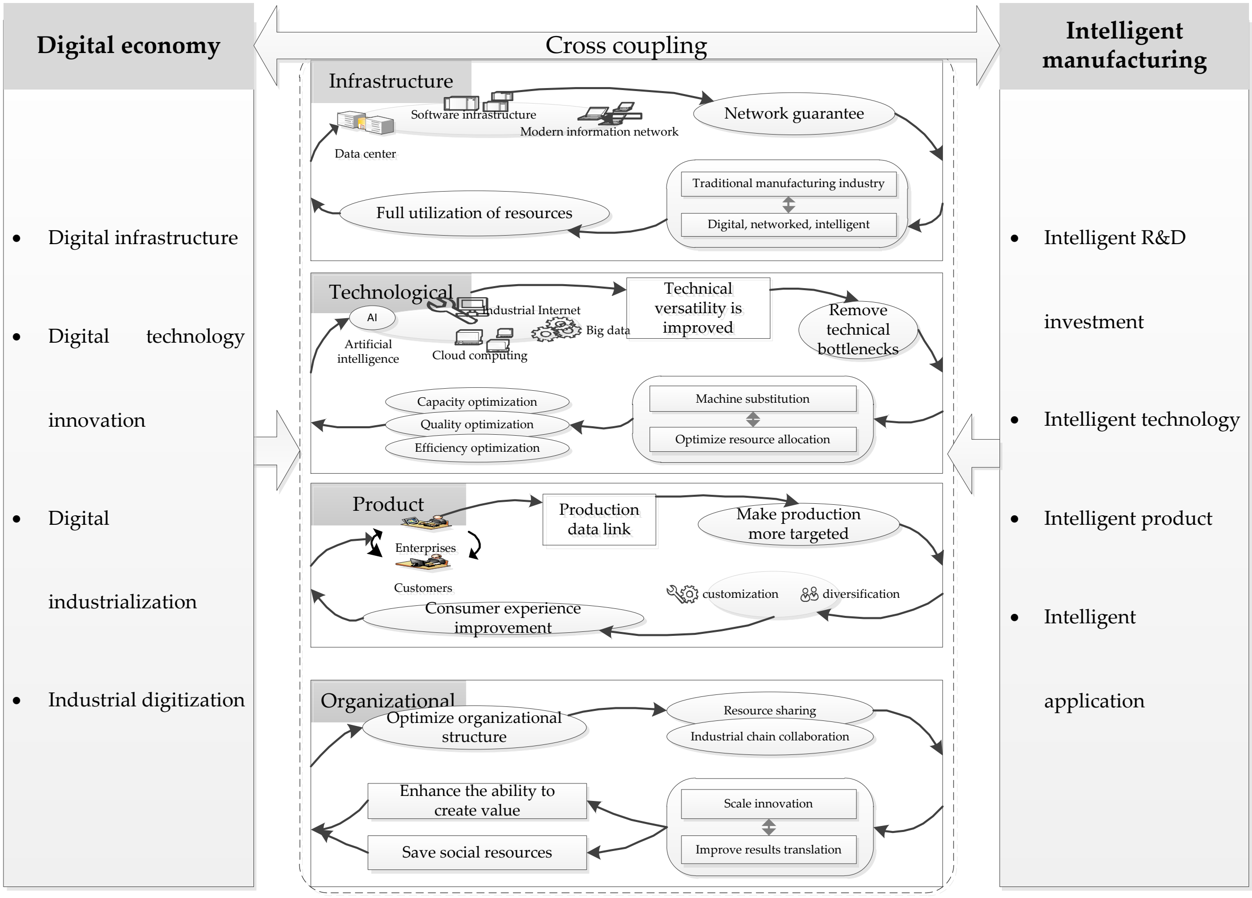

Figure 1. Theoretical model.

3. Empirical Design

This section introduces the research design of this paper, including research data, research variables and a research model. In this part, we choose quantitative analysis to solve the problems in this paper. The main reason is that qualitative research is applicable to unfamiliar social systems. At the same time, the research process needs to rely on the experience and interview skills of the investigators. The authenticity of the attitudes expressed by the interviewees also needs to be considered, and they are committed to solving the problem of "what is" [52]. Quantitative research can be used for large-scale surveys with a large amount of data to solve the problem of "how much" [22]. Based on various regions of China (at the provincial level), this paper not only needs to determine the relationship between China's *DE* and *IM* but also needs to clarify the extent to which the two are coupled and coordinated and point out how to promote the coupling and coordinated development of the two through objective data. The use of qualitative research for this kind of research will inevitably lead to incomplete coverage of interviewees. Therefore, qualitative and quantitative research methods are not applicable in this paper. Instead, we prefer to systematically analyze the existing research basis through logical reasoning, then build a research theoretical model (Section 2.2) and complete the research through quantitative means.

3.1. Sample and Data Collection

China has a total of 34 provincial administrative regions, and each provincial administrative region has a large political, economic, cultural differences. Its *DE* and *IM* development foundation and development status are also different, and the provincial-level data time series is longer, with less missing value and wider coverage. Therefore, exploring the coupling and coordination of *DE* and *IM* based on provincial-level data are of great significance for realizing the coordinated development of *DE* and *IM* in the region and promoting economic sustainability.

In 2020, due to the COVID-19 epidemic, regional economic statistics show abnormal deviations. There are many indicators involved in this paper, and some important indicators lag seriously and are not updated in a timely manner (such as intelligent technology innovation, intelligent technology accumulation, intelligent project application, etc.). Therefore, based on the overall data quality and availability, the panel data of 30 provincial-level administrative regions from 2013 to 2019 (due to the serious lack of data, the sample data does not include Hong Kong, Macao, Taiwan and Tibet) are selected as investigation samples. The original data mainly come from the National Bureau of Statistics, China Tertiary Industry Statistical Yearbook, China Information Industry Yearbook, China Science and Technology Statistical Yearbook and Provincial Statistical Yearbook, etc. The Digital Financial Inclusion Index of Peking University's Digital Finance Research Center serves as a source of digital finance measurement [53]. The statistics of the manufacturing industry are based on the caliber of industry above the designated size.

3.2. Index System Construction and Measurement

3.2.1. Index Composition

In the coupling coordination and evaluation of *DE* and *IM*, the first thing is to measure *DE* and *IM*. In this paper, Zhou et al. (2022) refer to as the construction process of the selection index system of a coupled system, which follows the principles of science, operation and system [54], considers the theoretical basis and practical situation, relies on the existing theoretical achievements of *DE* and *IM* measurement in the academic circle, integrates the availability and quality of data and builds the theoretical construction based on the coupled model, setting the index system of a *DE* and *IM* coupling system.

In academia, the measure of the *DE* standard is not unified, but most of the research points out that the *DE* is the economic development and social structure evolution of complex system and that using a single measure is not reasonable [55–58]. Yi et al. (2022) confides that the measurement of *DE* should include three dimensions: infrastructure, industrial scale and user scale [22]. Pan et al. (2022) also believe that infrastructure is an important component of *DE* [1]. Chen and Wu (2022) analyzed that the innovation capability of digital technology is also one of the measurement indicators of *DE* [57]. In addition, the China Academy of Information and Communications Technology (CAICT) pointed out that digital industrialization and industrial digitization are the main components of the *DE*. Based on the analysis of existing academic research and the theoretical model of *DE* and *IM* coupling coordination systems constructed in this paper, combined with the premise of data availability and quantification, the *DE* development level of each provincial administrative region is comprehensively evaluated from the four aspects of digital infrastructure, digital technology innovation, digital industrialization and industrial digitalization in order to ensure comprehensive and reasonable measurement indicators of *DE*.

The quantitative research on regional *IM* is few, and the index system of *IM* is lacking. Compared with the analysis of the connotation of *IM* [10,29,59,60] and the theoretical model of a coupled coordination system between *DE* and *IM* constructed in this paper, the development level of *IM* in each provincial administrative region is comprehensively calculated from four dimensions of intelligent R&D investment, intelligent technology, intelligent products and intelligent application, considering the availability and quality of data. Finally, the index system of the *DE* and *IM* coupling systems with 8 factor layers and 24 index layers is selected. Concrete are shown in Table 1, all the indicators are positive.

Table 1. *DE* and *IM* evaluation index system of manufacturing industry.

Element Level		Index Level	Measure Index and Unit
Digital Economy X	Digital infrastructure X1	Cable length X11	Cable length (km)
		Internet penetration X12	Broadband Internet users accounted for (%)
		Telephone penetration rate X13	Mobile phone part number per 100 people (units)
		Number of Internet domain names X14	Number of Internet domain names (thousands)
	Digital technology innovation X2	Technological innovation level X21	Number of patent applications (pieces)
		Proportion of enterprises with e-commerce transactions X22	The proportion of e-commerce enterprises
	Digital industrialization X3	Output value of information service industry X31	Information transmission, software and information technology services business income (CNY 100 million)
		Digital industry employees X32	Employees in information transmission, software and information technology service enterprises (10,000)
		Total telecommunications business X33	Telecommunications business volume (CNY 100 million)
	Industrial digitization X4	Digital Financial Inclusion Index X41	Peking University Digital Financial Inclusion Index
		Digital transaction X42	E-commerce sales (CNY 100 million)
		Corporate website coverage X43	Websites per million businesses (number)
		The proportion of computers used by enterprises X44	Every one hundred people use the computer number (units)
Intelligent manufacturing Y	Intelligent R&D investment Y1	R&D funds are invested in Y11	Manufacturing R&D funding (CNY ten thousand)
		Talent input Y12	Manufacturing R&D personnel equivalent to full-time
		Technological innovation input Y13	Manufacturing technology transformation spending (CNY ten thousand)
	Intelligent technology Y2	Intelligent technology innovation Y21	Number of patent applications for manufacturing inventions (pieces)
		Intelligent technology accumulation Y22	Manufacturing invention patent number effectively (pieces)
		Smart project request Y23	Manufacturing R&D project topics (items)
	Intelligent product Y3	Intelligent product development project Y31	Manufacturing a new product development project (items)
		Intelligent product sales revenue Y32	Sales revenue of manufacturing new products (CNY ten thousand)
	Intelligent application Y4	Intelligent equipment application Y41	Imports of computers, electronic components, instruments, etc. (USD 10,000)
		Industrial robot application Y42	Embedded system software (foundation, embed, support and application software) (CNY ten thousand)
		Software usage Y43	Software business revenue (CNY ten thousand)

3.2.2. Measuring Method

Entropy method can effectively overcome the disorder of multi-index information and the subjectivity of artificial determination [61,62] and can be used in the evaluation and calculation of comprehensive indicators. Thus, it is selected to calculate the *DE* and *IM* comprehensive index of each provincial administrative region. The steps include the following:

(1) Index standardization: $x'_{cdj} = (x_{cdj} - x_{\min})/(x_{\max} - x_{\min})$.

(2) Index normalization: $P_{cdj} = x'_{cdj}/(\sum_{c=1}^{C}\sum_{d=1}^{D} x'_{cdj})$.

(3) Entropy of each index: $e_j = -q\sum_{c=1}^{C}\sum_{d=1}^{D} P_{cdj}\ln P_{cdj}$, among which, $q = 1/\ln(C \times D)$.

(4) Weights of indicators: $w_j = (1 - e_j)/\sum_{j=1}^{h}(1 - e_j)$.

(5) Scores for each provincial administrative region: $S_{cd} = \sum_{j=1}^{h} w_j P_{cdj}$.

3.3. Model Specification

3.3.1. Coupling Coordination Degree Model

Coupling degree and coupling coordination degree originated from the concept of physics, which refers to the phenomenon of coordination and interaction between multiple systems. The coupling coordination theory finds that the development trend and interrelation of elements can be studied using the coupling system coordination degree model, which has the advantage of realizing accurate and complete information [54]. The theoretical model constructed above (Figure 1) shows that *DE* and *IM* interact and relate to each other at the levels of infrastructure, technology, product and organization. In order to reflect the development level and coordination effect of regional *DE* and *IM* as a whole, the coordination degree model of the *DE-IM* coupling system is constructed on the basis of calculating the subsystems of *DE* and *IM*, respectively:

$$cd\_DEMI = \sqrt{Cd \times Ts} \tag{1}$$

Among them, $Cd = \left\{ \frac{f(de) \times f(im)}{\left[\frac{f(de) \times f(im)}{2}\right]^2} \right\}^{\frac{1}{2}}$

$$Ts = \alpha f(de) + \beta f(im) \tag{2}$$

cd_DEMI is the coupling coordination degree, *cd* is the coupling degree, *Ts* is the comprehensive development index of the subsystem, $f(de)$ is the *DE* subsystem development index and $f(im)$ is *IM*. In the theoretical model (Figure 1), it is pointed out that the development of *DE* realizes the sharing of innovative resources, the cost of local production, and the improvement of competitive advantage and production efficiency by providing network guarantee, improving the versatility of technology, promoting the link of production data, and reducing transaction costs. *IM*, through the integration of traditional manufacturing with digital, networked and intelligent systems, improves product quality, saves social resources and achieves capacity optimization, quality optimization and efficiency optimization. Therefore, we believe that the *DE* and *IM* are equally important for the development of society. Hence, values α and β are 0.5 [63].

Although, according to our theoretical model (Figure 1), while *DE* and *IM* are equally important for social development, there may still be differences in the development level and speed of the two. To explore the development difference degree of *DE* and *IM* subsystems and to build a relative development model to explore the relative development degree of digital *DE* and *IM* in administrative regions at all levels, the model is as follows:

$$\lambda = f(im)/f(de) \tag{3}$$

where λ is the relative development degree, when $\lambda \in (0, 0.9]$, indicating that in the constructed theoretical model (Figure 1) in the actual situation, *IM* lags behind the *DE* (MS). When $\lambda \in (0.9, 1.1]$, this indicates that in the constructed theoretical model (Figure 1) in the actual situation, *IM* is equivalent to the *DE* (DM). When $\lambda \in (1.1, +\infty)$, this indicates that in the constructed theoretical model (Figure 1) in the actual situation, *DE* lags behind *IM* (DS).

3.3.2. Coupling Evolution Model

In the theoretical model (Figure 1), it can be found that *DE* and *IM* interact and connect through multiple levels. With the development of society and technological progress, the development of *DE* and *IM* subsystems is not static. Exploring the evolution of *DE* and *IM* can further clarify the development situation and development gap between them. According to the general system theory, the subsystem evolution equation is constructed to describe the evolution process of *DE* and *IM*:

$$f(de, t) = df(de)/dt \tag{4}$$

$$f(im,t) = df(im)/dt \tag{5}$$

Among them, $f(u_1, t)$ and $f(u_2, t)$ are the evolution states of the *DE* subsystem and the *IM* subsystem influenced by themselves and the outside world, respectively, and the subsystem evolution rate is as follows:

$$v(de) = df(de,t)/dt \tag{6}$$

$$v(im) = df(im,t)/dt \tag{7}$$

where $v(de)$ and $v(im)$, respectively, represent the evolution speed of the *DE* and *IM* subsystems. The evolution trajectory is projected onto the same two-dimensional plane. For a certain time point, the angle between curves $v(de)$ and $v(im)$ is β, which can be expressed as $\text{Tan}\beta = v(de)/v(im)$, $\beta = \arctan[v(de)/v(im)]$, and the angle β reflects the characteristics and differences between the two systems' changing trends [64].

3.3.3. Obstacle Degree Model

The theoretical model (Figure 1) shows that the *DE* and *IM* not only interact and connect at multiple levels but also that the paths of interaction at each level are complex and changeable. The development of the two subsystems is not the same at all levels, which also means that the obstacles to their development are not clear. As the name suggests, obstacle factors refer to the factors that hinder the development and progress of things, and in this study, they are the factors that hinder the high-quality coupling of *DE* and *IM*. Exploring the obstacles to the development of *DE* and *IM* is helpful to point out the key points for their future development. The obstacles that affect the development of things can be studied using the obstacle degree model [65]. Based on this, with the help of his research to explore the barrier factors of coupling coordination between *DE* and *IM*, the model is built with reference to the study of He and Liu (2022) [66]:

$$I_{ij} = 1 - x'_{vij} \tag{8}$$

$$z_j = \left(\frac{F_j I_{ij}}{\sum\limits_{j=1}^{h} F_j I_{ij}}\right) \times 100\% \tag{9}$$

Among them, $F_j = \lambda_i w_{ij}$, $Z_j = \sum z_j$.

Here, λ_i is the i system weight, w_{ij} is the weight of the j index in the i system, I_{ij} is the deviation degree of the index, F_j is the factor contribution degree and z_j and Z_j are the obstacle degrees between the index layer and the factor layer.

3.3.4. Fixed Effects Model

The theoretical model (Figure 1) argues that the coupling and coordination of *DE* and *IM* can complement each other in infrastructure, technological innovation, product optimization and organizational change. Whether these levels can achieve mutual promotion, and the degree of mutual promotion are closely related to the actual regional development situation. Influencing factors are the reasons or conditions that determine the success or failure of things. In this study, it refers to the factors that promote or inhibit the coupling and coordinated development of *DE* and *IM* within the region. Considering the influencing factors of coupling coordination between *DE* and *IM* from the perspective of regional development is conducive to providing reference for improving the coupling coordination degree of the two from the perspective of regional development. Regional opening helps local communities absorb more advanced technological knowledge and promote innovation [67]. The level of economic development reflects the local ability to accept new knowledge and skills [68], which affects the development basis of *DE* and *IM*. Human capital is not only the carrier of knowledge but also an important support for regional innovation, economic transformation and sustainable development [69–71]. *DE* and *IM* have increased the demand for high-quality and high-level talents in the region. Irrational industrial structure will aggravate resource consumption and environmental pollution and realize the transformation and upgrading of regional industrial structure, which is conducive to promoting sustainable economic development [72]. In addition, the regional emphasis on innovation reflects the local support for innovation and development, which is conducive to activating the technological innovation vitality of innovation subjects [73], improving digital technology and intelligent technology, thus promoting the development of *DE* and *IM*. Based on this, we selected the degree of openness of the region (*op*), economic development (*gdp*), high-level talent input (*hhc*), industrial structure (*is*) and regional innovation emphasis (*ixf*) as the influencing factors of the coupling coordination degree of *DE* and *IM*. After the Hausman test, the P value was less than 0.01, and the fixed effect model was selected for empirical test [74]. In addition, the fixed effects model constructed includes time and individual fixation, which can reduce the influence of missing variables. The model is as follows:

$$cd\_DEMI_{i,t} = \alpha + \beta_1 op_{i,t} + \beta_2 gdp_{i,t} + \beta_3 hhc_{i,t} + \beta_4 is_{i,t} + \beta_5 ixf_{i,t} + \lambda_i + \mu_t + \varepsilon_{i,t} \tag{10}$$

Among them, *cd_DEMI* is the coordination degree between *DE* and *IM*, *i* is the province and *t* is the year. *op* is the degree of openness to the outside world, expressed by the proportion of total imports and exports to GDP [75]. *eco* is economic development, and logarithm of GDP per capita is the proxy variable. *hhc* is invested in high-level talents, and the number of PhDs, masters and bachelors degree graduates in research and development (R&D) is the proxy variables. Due to outliers in the number data, the three groups of data were, respectively, Winsorize by 1%. In addition, in order to eliminate dimensional differences, maximum processing was performed. *is* is the industrial structure, which is the ratio of tertiary production to secondary production [76]. *ixf* is the regional innovation emphasis, expressed as the ratio of internal spending on research and experimental development (R&D) to GDP. λ_i represents the individual fixed effect, μ_t represents the time fixed effect and $\varepsilon_{i,t}$ is the random disturbance term. At the same time, in order to make the statistical inference more robust, the robust standard misestimation regression model is adopted.

3.3.5. Exploratory Spatial Data Analysis

In the theoretical model constructed (Figure 1), it is found that the coupling coordination between *DE* and *IM* involves resource sharing and industrial chain collaboration, etc. Under the background of digitalization and intelligence, the coupling coordination paths such as resource sharing and industrial chain collaboration are not limited to each provincial administrative region but also have a correlation at the spatial level of each provincial administrative region. Spatial correlation refers to the connection between a certain phenomenon in a specific geographical unit and other surrounding phenomena. In this paper, it refers to the correlation between the coupling coordination degree of *DE* and *IM* in each provincial administrative region and the coupling coordination degree of the other provinces around. The application of the exploratory spatial data analysis method to explore the spatial correlation of the coupling coordination degree of each region is conducive to clarifying the spatial distribution characteristics of the coupling coordination degree of *DE* and *IM* [77] and providing a reference for realizing regional complementarity. Moran's index (Moran's I) test is commonly used, which can realize the global and local spatial correlation test. The formula includes the following:

Global Moran index calculation formula:

$$Moran'I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(cd\_DEMI_i - \overline{cd\_DEMI})(cd\_DEMI_j - \overline{cd\_DEMI})}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \tag{11}$$

Local Moran index calculation formula:

$$I_i = \frac{n(cd\_DEMI_i - \overline{cd\_DEMI})\sum_{j=1}^{n} W_{ij}(cd\_DEMI_j - \overline{cd\_DEMI})^2}{\sum_{i=1}^{n}(cd\_DEMI - \overline{cd\_DEMI})^2} \quad (12)$$

Among them, $\overline{cd\_DEMI}$ represents the corresponding average value, cd_DEMI_i is the coordination degree of *DE* and *IM* in region i, cd_DEMI_j stands for region j, n represents 30 provincial administrative regions and W_{ij} represents the spatial weight matrix of geographical distance.

4. Empirical Results

4.1. Subsystem Development Index and Coupling Coordination Degree

The development index of the two subsystems of *DE* and *IM* in different provincial administrative regions (Figure 2) was calculated. Each provincial administrative region contains the 2013–2019 *DE* and *IM* subsystem development index. Nationwide, the digital economy and intelligent manufacturing in most regions are in the initial stage of development, especially in the central and western regions, such as Heilongjiang, Jilin, Gansu, Qinghai, Ningxia, etc. Both have a growth trend over time, but the growth trend in individual regions is slower, especially intelligent manufacturing, such as Inner Mongolia, Guangxi, Guizhou, Yunnan, etc. However, from the change of subsystem development index in each year, the former development is better than the latter. Although the development level of *DE* and *IM* has risen over time, the gap has not narrowed, which indicates that the growth rate of *DE* is greater than the growth rate of *IM*. Therefore, it is not only necessary to improve the support of the two, but also to increase the attention to *IM*, narrow the gap with the *DE* and promote the high-level evolution of coupled systems. Locally, the development index of the two subsystems in the east is better than that in the central and western regions, but the difference between different provinces in the east is also the largest, indicating that the development of *DE* and *IM* is synchronized, but the speed is different, mainly because the *DE* and *IM* development basis of different provincial administrative regions is different. This is also consistent with the studies of Pan et al. (2022) [1] and Yang and Shen (2023) [34]. Pan et al. (2022) also found regional differences in the development of *DE* when estimating the *DE* of various provincial administrative regions in China and pointed out that the development of *DE* in the east is in a leading position in the country due to better policies, systems and innovation environment [1]. Although Yang and Shen (2023) did not analyze the development differences of *IM* in China's provincial administrative regions in detail, they found that there were large regional differences in the data during the descriptive statistical analysis of the sample data [34].

Formulas (1) and (2) are used to calculate the coupling degree and coordination degree of *DE* and *IM*. The numerator represents the coupling degree, and the denominator is the coordination degree. Due to space limitations, all provincial administrative regions are not listed (Table 2). With further reference to Zhou et al. (2022) [54], the mean coordination degree between *DE* and *IM* in various regions was calculated and graded, and their relative development types were analyzed (Table 3). As far as the country is concerned, the coupling degree of each year is basically stable at more than 0.8, and the coupling degree is good, which can be inferred from the fact that the relationship between the *DE* and *IM* is relatively close and has a strong correlation. In other words, we once again demonstrate the strong connection between the *DE* and *IM* based on the coupled coordination perspective [15–17]. From the regional point of view, the coupling degree of *DE* and *IM* in the eastern region and the central region is high; there is no significant difference, but the western region is lower than the national average level, indicating that the interaction between *DE* and *IM* in the western region is low, which means that the western region needs to increase its support for the development of *DE* and *IM*. However, to evaluate whether the two can develop harmonically at a high level, the comprehensive development index of subsystems cannot be ignored. The coordination degree of the two subsystems (Table 2) and the results of the coordination degree division of provincial administrative regions (Table 3) show that the coordination degree of provincial administrative regions is generally low, and most of them are in mild, moderate and severe disorders. Only a few provincial-level administrative regions, such as Beijing, Zhejiang, Guangdong, Shandong and Jiangsu have entered the stage of systematic coordination, and there is still a gap between high-quality coordination. As for the time trend, the coordination degree of each region is increasing year by year, and the overall development trend is good. Locally, the coupling degree and coordination degree are highest in the east, reflecting that the evolution direction of the *DE* and *IM* subsystems is more consistent, and the coordination level of the two is also higher when the correlation is high. From the perspective of relative development type, most of the provincial administrative regions are in *IM*, lagging behind the *DE*. Only a small number of provincial administrative regions belong to *DE* and *IM* equivalents or *DE* lagging behind *IM*, consistent with the above analysis.

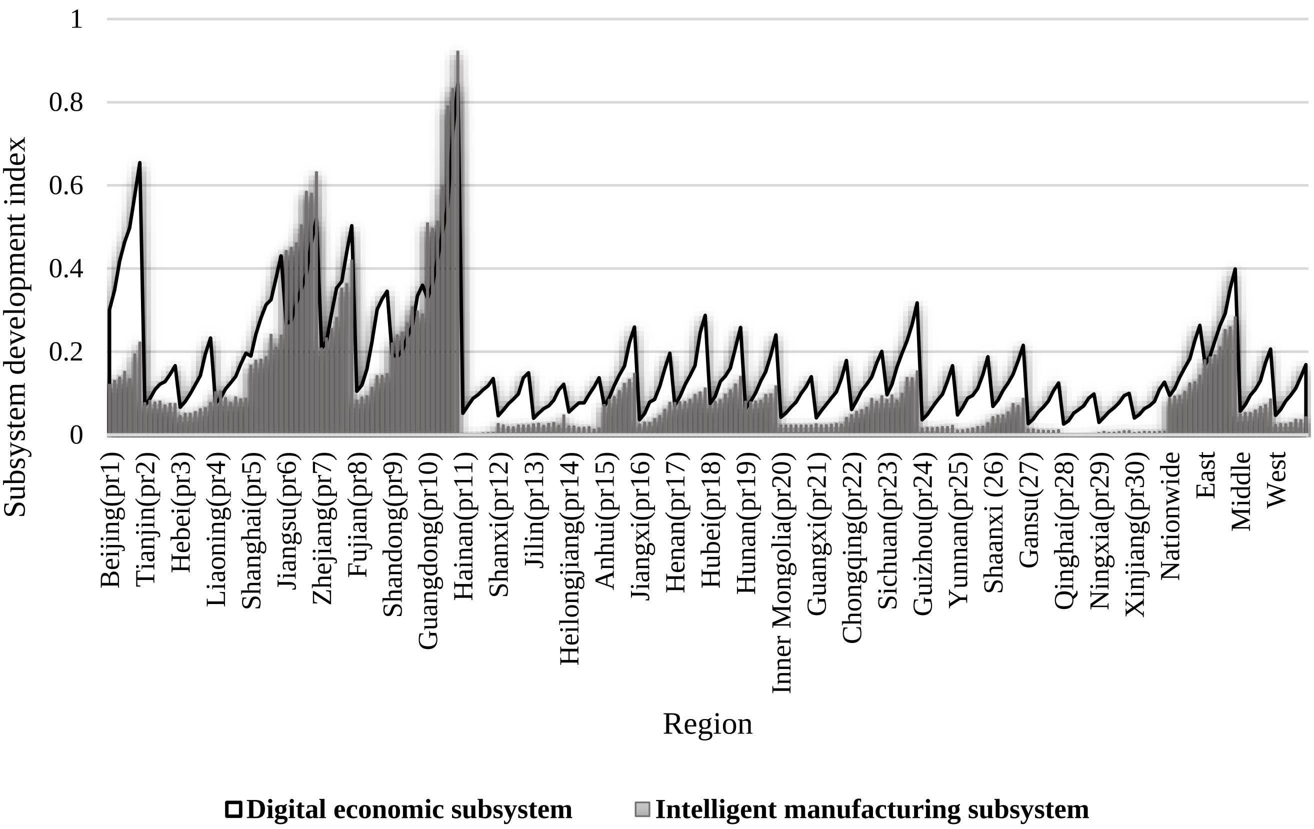

Figure 2. *DE* and *IM* subsystem development index.

Table 2. The degree of coupling and coordination of *DE* and *IM*.

Region	2013	2014	2015	2016	2017	2018	2019
Nationwide	0.903/0.262	0.886/0.278	0.848/0.294	0.838/0.313	0.832/0.333	0.797/0.357	0.801/0.384
East	0.934/0.384	0.925/0.400	0.912/0.420	0.905/0.445	0.903/0.478	0.898/0.503	0.892/0.529
Middle	0.976/0.225	0.958/0.243	0.912/0.257	0.911/0.273	0.902/0.287	0.845/0.320	0.861/0.351
West	0.818/0.166	0.794/0.183	0.739/0.196	0.718/0.209	0.712/0.222	0.661/0.239	0.666/0.264

Table 3. Coordination degree and relative development types of *DE* and *IM*.

Region Code	Coordination Degree	Rank Division	Relative Development Type
pr1	0.516	Bare coordination	MS
pr2	0.307	Mild imbalance	MS
pr3	0.291	Moderate imbalance	MS
pr4	0.326	Mild imbalance	MS
pr5	0.496	Little imbalance	MS
pr6	0.662	Primary coordination	DS
pr7	0.561	Bare coordination	MS
pr8	0.395	Mild imbalance	MS
pr9	0.508	Bare coordination	DM
pr10	0.765	Intermediate coordination	DS
pr11	0.134	Severe imbalance	MS
pr12	0.212	Moderate imbalance	MS
pr13	0.213	Moderate imbalance	MS
pr14	0.196	Severe imbalance	MS
pr15	0.351	Mild imbalance	MS
pr16	0.251	Moderate imbalance	MS
pr17	0.339	Mild imbalance	MS
pr18	0.346	Mild imbalance	MS
pr19	0.327	Mild imbalance	MS
pr20	0.185	Severe imbalance	MS
pr21	0.221	Moderate imbalance	MS
pr22	0.302	Mild imbalance	MS
pr23	0.381	Mild imbalance	MS
pr24	0.196	Severe imbalance	MS
pr25	0.202	Moderate imbalance	MS
pr26	0.295	Moderate imbalance	MS
pr27	0.164	Severe imbalance	MS
pr28	0.083	Extreme imbalance	MS
pr29	0.144	Severe imbalance	MS
pr30	0.151	Severe imbalance	MS

4.2. Coupling Evolution Analysis

Sequential fitting of *DE* and *IM* subsystems was carried out, respectively. Through repeated trial calculation and comparative analysis, the goodness of fit of quadratic function was 0.996 and 0.968, respectively. Accordingly, the evolution equations of *DE* and *IM* were obtained:

$$f(de,t) = 0.002083\ t^2 + 0.01130\ t + 0.08143$$

$$f(im,t) = 0.0009524\ t^2 + 0.001667\ t + 0.08457$$

The evolution equations of the two subsystems were derived, respectively, and the evolution velocity function of each subsystem was obtained as follows:

$$v(de) = 0.002083\ t + 0.01130$$

$$v(im) = 0.0009524\ t + 0.001667$$

The evolution trend and evolution speed of *DE* and *IM* are represented in Figure 3; it is drawn and the predicted value for 2020–2022 is shown. It can be seen that the actual curve is basically consistent with the fitted curve, which proves that the evolution trend of the fitted curve can basically shows the evolution law of *DE* and *IM*.

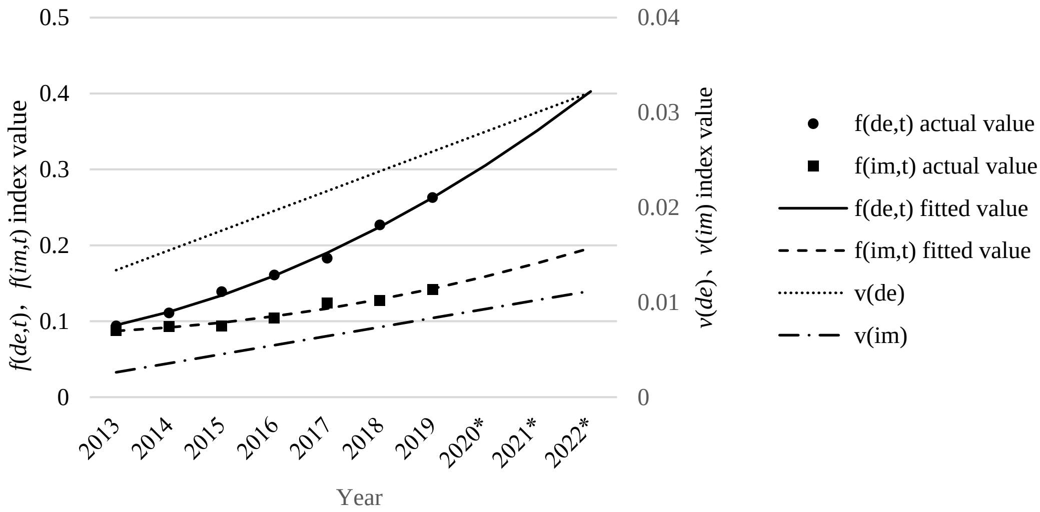

Figure 3. *DE* and *IM* evolution trend and evolution speed ("*" stands for forecast year).

It can be seen that the development of *DE* and *IM* has progressed with the passage of time, and the forecast period "2022" is relatively fast. However, the *DE* has been higher than *IM*, consistent with the conclusion above that the *DE* is stronger than *IM*. Meanwhile, the rapid development of *DE* growth in *IM*, and the widening gap in the process of evolution, is not conducive to a high-order coupling coordination system. Although the *DE* and *IM* have two-way coupling needs, the development goals and requirements of the two are still quite different. Furthermore, the included angles between the evolution velocity were calculated, which were, respectively, 78.926°, 76.996°, 75.544°, 74.413°, 73.508°, 72.768° and 72.151°, and the included angles were between 45° and 90°. It shows that the coupling system of *DE* and *IM* is in a coordinated coupling state. Thanks to the state's strong support for the in-depth promotion of *DE* and *IM* in recent years, it has provided them with more funds and technical support, during which the *DE* and *IM* have maintained rapid growth momentum. This conclusion coincides with Zhang et al. (2022) [23], who also found that although there are obvious regional differences in China's *DE*, it is undeniable that the *DE* has experienced rapid growth in recent years. At the same time, Zhou et al. (2018) also pointed out that China has vigorously promoted the development of *IM* in recent years [10], which also provides opportunities for accelerating the realization of *IM*. In addition, we also found that the evolution speed of the *DE* is greater than that of the *IM*. Although the current coupled system gradually tends to be benign coupled coordination, more vigilance should be increased to prevent the *DE* from overheating, in real to virtual and other situations.

4.3. Subsystem Development Index and Coupling Coordination Degree

The obstacle degree of *DE* and *IM* is calculated, respectively, the obstacle factors are sorted according to the obstacle degree and the top three obstacle factors are taken as the main obstacle factors. Due to limited space, only some years are shown, as shown in Table 4. Among them, the obstacle factors of each provincial administrative region are not consistent and change over time. For example, the main obstacle factors of Beijing's *DE* in 2013 were X14/X21/X33, in 2016 they were X21/X22/X11 and in 2019 they were X21/X33/X11. The main obstacle factor of *IM* in Shandong in 2013 was Y41/Y22/Y43, the order was Y41/Y22/Y42 in 2016 and the order was Y41/Y22/Y21 in 2019. The reason for the change may be that the focus of *DE* construction and *IM* development in various provincial administrative regions is different in recent years. This also confirms once again that Pan et al. (2022) [1] and Yang and Shen (2023) [34] found that the development of *DE* and *IM* in China's provincial administrative regions is different. As for the specific obstacle factors, the index layer of the *DE*, the obstacles mainly lie in the few e-commerce transaction activities of enterprises, insufficient technological innovation and the incomplete popularization of enterprise computer use. This shows that the supporting facilities of enterprises still need to be further improved, and there are shortcomings in technological innovation and the lack of ability to integrate technology with business activities. The development obstacles of *IM* mainly lie in the insufficient application of intelligent equipment, industrial robots and software and the lack of technology innovation and accumulation, which reflects that the intelligent core technology of manufacturing industry still lags behind and that the technology transformation and application ability still needs to be strengthened. From the factor level, the main obstacle factors of the *DE* are X2 > X4 > X1 > X3 and for IM are Y4 > Y2 > Y3 > Y1.

Table 4. Obstacle factors of *DE* and *IM*.

Region	2013	2016	2019
pr1	X14/X21/X33; Y41/Y22/Y21	X21/X22/X11; Y41/Y22/Y21	X21/X33/X11; Y41/Y22/Y21
pr2	X22/X21/X11; Y41/Y22/Y42	X22/X21/X11; Y41/Y22/Y42	X22/X21/X11; Y41/Y22/Y42
pr3	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y42/Y22	X22/X21/X42; Y41/Y42/Y22
pr4	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y42/Y22
pr5	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42	X22/X21/X42; Y41/Y22/Y42
pr6	X22/X21/X44; Y41/Y22/Y21	X22/X21/X44; Y41/Y22/Y42	X22/X21/X42; Y41/Y22/Y42
pr7	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42	X22/X21/X42; Y41/Y22/Y42
pr8	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42	X22/X21/X42; Y41/Y22/Y42
pr9	X22/X21/X11; Y41/Y22/Y42	X21/X22/X33; Y41/Y22/Y21	X22/X21/X33; Y41/Y22/Y21
pr10	X22/X44/X21; Y41/Y22/Y21	X22/X44/X21; Y41/Y22/Y42	X22/X44/X42; Y41/Y22/Y42
pr11	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42	X22/X44/X21; Y41/Y22/Y42
pr12	X22/X21/X44; Y41/Y42/Y22	X21/X22/X44; Y41/Y42/Y43	X21/X22/X44; Y41/Y42/Y43
pr13	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42
pr14	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42
pr15	X22/X21/X44; Y41/Y22/Y43	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y21
pr16	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y42/Y22	X22/X21/X44; Y41/Y42/Y43
pr17	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y43	X22/X21/X44; Y41/Y22/Y42
pr18	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y42/Y22	X22/X21/X44; Y41/Y42/Y43
pr19	X22/X21/X44; Y22/Y43/Y31	X22/X44/X21; Y42/Y31/Y23	X22/X44/X12; Y42/Y41/Y13
pr20	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42
pr21	X22/X21/X42; Y41/Y22/Y42	X21/X42/X22; Y41/Y22/Y42	X21/X22/X42; Y41/Y22/Y42
pr22	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42
pr23	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42
pr24	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42
pr25	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42	X22/X21/X42; Y41/Y42/Y22
pr26	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42	X22/X21/X42; Y41/Y22/Y42
pr27	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42
pr28	X22/X21/X11; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42	X22/X21/X42; Y41/Y22/Y42
pr29	X22/X21/X44; Y41/Y22/Y42	X21/X22/X44; Y41/Y22/Y42	X22/X21/X11; Y41/Y22/Y42
pr30	X22/X21/X44; Y41/Y22/Y42	X22/X21/X44; Y41/Y22/Y42	X22/X21/X43; Y41/Y22/Y42

4.4. Influence Factors Analysis

Table 5 is the *DE* and *IM* coupling coordination degree (*cd_DEMI*), external openness degree (*op*), economic development level (*gdp*), high-level talent input (*hhc*), industrial structure (*is*) and regional innovation emphasis degree (*ixf*) descriptive statistics. The correlation coefficient matrix and variance inflation factor of each variable are calculated, and the results show that there is no multicollinearity problem (Table 6).

Table 7 shows the regression results. Column (1) is a nationwide test, and column (2) replaces economic development with the logarithm of gross regional product as a robustness test. In addition, the theoretical model (Figure 1) finds that the coupled and coordinated development of *DE* and *IM* will promote resource sharing and enhance the ability to create economic value. Therefore, it is inferred that the level of economic development (*gdp*) and high-level talent input (*hhc*) may be endogenous variables. In view of this, instrumental variables are constructed with the level of economic development (*gdp*) and high-level talent input (*hhc*) lagging one stage, respectively. The regression results of the second stage of instrumental variables are shown in column (3). Columns (4)–(6) are regional tests.

Table 5. Descriptive statistics.

Variable	Mean	p50	sd	max	min	N
cd_DEMI	0.3178642	0.2886253	0.1661832	0.9391482	0.053634	210
op	0.2630429	0.1375129	0.2686985	1.257114	0.0127789	210
eco	10.89546	10.79819	0.4491707	13.56274	10.04979	210
hhc	0.3324753	0.248674	0.2588408	1	0.0237893	210
is	1.253848	1.081782	0.68291	5.169242	0.5722364	210
ixf	0.0168461	0.0141423	0.0112827	0.0631469	0.0045827	210

Table 6. Correlation coefficient matrix of explanatory variables and variance inflation factor.

Variable	*op*	*eco*	*hhc*	*is*	*ixf*
op	1.000				
eco	0.692 *	1.000			
hhc	0.146	0.162	1.000		
is	0.490 *	0.390 *	0.119	1.000	
ixf	0.793 *	0.705 *	0.274 *	0.635 *	1.000
VIF	3.020	2.220	1.100	1.710	4.220
1/VIF	0.332	0.451	0.905	0.586	0.237

(* $p < 0.1$, ** $p < 0.05$ and *** $p < 0.01$).

Table 7. Fixed effect regression results.

	Nationwide	Robustness Test	Endogenous Processing	East	Middle	West
op	−0.0306	−0.0253	0.0286	0.0120	−0.0256	0.197 ***
	(0.0265)	(0.0234)	(0.0371)	(0.0546)	(0.0952)	(0.0655)
eco	0.0656 **	0.0963 ***	0.159 **	0.0420	0.126 ***	0.106 ***
	(0.0282)	(0.0171)	(0.0651)	(0.0292)	(0.0282)	(0.0237)
hhc	0.106 ***	0.0908 ***	0.0985 ***	0.167 ***	−0.0102	0.111 ***
	(0.0237)	(0.0214)	(0.0373)	(0.0459)	(0.0730)	(0.0200)
is	−0.0149	−0.00487	0.0191	−0.0487 *	0.00587	0.0389 **
	(0.0125)	(0.0112)	(0.0225)	(0.0253)	(0.0135)	(0.0177)
ixf	5.149 ***	5.403 ***	5.499 ***	2.790 *	9.733 ***	4.981 ***
	(1.089)	(1.060)	(1.358)	(1.566)	(1.414)	(1.538)
_cons	−0.492 ***	−0.743 ***	−1.818 **	−0.0816	−1.200 ***	−1.091 ***
	(0.314)	(0.169)	(0.875)	(0.363)	(0.290)	(0.261)
Year	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes
N	210	210	180	77	56	77
R^2	0.991	0.992	0.989	0.993	0.991	0.991

(Standard errors in parentheses, * $p < 0.1$, ** $p < 0.05$ and *** $p < 0.01$).

Nationwide, the degree of opening to the outside world and the industrial structure have no significant effects on the coordination degree of *DE* and *IM*, while regional economic development, high-level talent input and innovation importance have a significant effect on the coordination degree of *DE* and *IM*. The robustness test results remain unchanged, proving the reliability of this conclusion. The regression coefficient of instrumental variables in the results of the first stage of the instrumental variable test passed the significance test, and the F statistic of the first stage was greater than 10 suggested by the rule of thumb, indicating that the instrumental variables in this paper do not have the problem of weak instrumental variables. Both the Cragg–Donald Wald F statistic and the Kleibergen–Paap rk LM statistic have passed the test, indicating the rationality of the selection of instrumental variables in this paper. The results of the second-stage regression (column 3) have no significant changes from the results of the benchmark regression. The results of this paper are still valid after considering the endogeneity problem.

By region, high-level talent investment and innovation emphasis in the east will improve the coordination degree of *DE* and *IM*, and economic development has no significant effect, but the industrial structure is inhibited. This is because the east is more developed, the tertiary industry accounts for a relatively high proportion and promoting the tertiary industry and weakening the secondary industry is not conducive to the coupling and coordination of *DE* and *IM*. The degree of emphasis on economic development and innovation in middle China significantly promotes the coordination degree between *DE* and *IM*, while other variables have no significant impact. The reason may be that the infrastructure and other conditions in the middle region cannot reach the status of the advanced region in the east, but compared with the western region, the talent is more sufficient, and the relative regional development has been saturated. Only increasing talent can not play a good role, but also cooperate with infrastructure and capital investment. For the west, improving the degree of opening, economic development, high-level talent input, industrial structure and innovation emphasis all promote the coordination degree of *DE* and *IM*. The reason is that the western region is an underdeveloped region with relatively backward talent, capital, infrastructure and industrial structure. Improving regional openness, economic level, talent and capital investment and optimizing industrial structure are conducive to improving the coordination degree of *DE* and *IM*. Overall, the degree of innovation attention has an absolutely positive impact on the coordination degree of *DE* and *IM* coupling in each region, and the degree of opening to the outside world, regional economic development, high-level talent investment and optimization of industrial structure need to formulate policies in line with local development conditions according to the development situation of each region. Chen et al. (2023) pointed out that the level of economic development, government support and industrial structure affect the development of *DE* [78], and the coupling coordination level of *DE* and *IM* is closely related to the development of *DE*. Therefore, their conclusions are consistent with our conclusions to a certain extent.

4.5. Spatial Effect Analysis

Formula (11) calculates the global Moran index of the degree of coordination between the *DE* and *IM* for 2013–2019 (Table 8). From a nationwide perspective, the Moreland index of coordination degree is significantly positive; in other words, the coordination degree of *DE* and *IM* in each provincial administrative region shows a spatially positive correlation. This also confirms the views of Ma and Zhu (2022) [18], Zhang et al. (2022) [23] and Ying et al. (2021) [79], which showed that research related to *DE* and *IM* should also consider spatial effects. From the local perspective, the spatial effect of coordination degree is different. The Moreland index in the east is negative but not significant, indicating that the coordination degree in this region is in discrete distribution. At the same time, the degree of coupling coordination between *DE* and *IM* in provincial administrative requirements in the east region is significantly different. The reason may be that although the eastern region as a whole has a better development environment for *DE* and *IM*, with more complete policy guidance, the national *DE* and *IM* development ceiling areas are also included in them. Taking Beijing, Shanghai and other super-first-tier cities as an example, the comparison to Hebei, Hainan and other provinces with their economic and policy gap is still large. In the central region, except 2013, the Moreland index of coordination degree is positive, and the Moreland index of 2015–2019 is at least significant at the level of 10%, indicating that the coupling coordination degree of *DE* and *IM* in the central region presents a certain agglomeration phenomenon and a positive autocorrelation agglomeration in space. The Moreland index in Western China is significantly positive, indicating that the coupling coordination degree of *DE* and *IM* in Western China also presents a positive autocorrelation cluster in space. This also shows that for the central and western regions, their own policy systems and innovation environments are not as good as those of the eastern region, and it is more important to use inter-provincial cooperation to realize complementary advantages and promote the coupled and coordinated development of *DE* and *IM*.

Table 8. Global Moran index.

Index \ Year	2013	2014	2015	2016	2017	2018	2019
Nationwide: Moran's I	0.061	0.066	0.071	0.071	0.064	0.065	0.062
p-value	0.003	0.002	0.001	0.001	0.002	0.002	0.003
East: Moran's I	−0.062	−0.056	−0.041	−0.026	−0.011	−0.046	−0.049
p-value	0.399	0.382	0.34	0.307	0.271	0.354	0.362
Middle: Moran's I	−0.008	0.029	0.093	0.115	0.140	0.236	0.197
p-value	0.210	0.151	0.078	0.059	0.042	0.009	0.017
West: Moran's I	0.036	0.044	0.058	0.060	0.055	0.063	0.076
p-value	0.024	0.018	0.011	0.010	0.013	0.009	0.006

Formula (12) was used to calculate the local Moreland index of coordination degree of each provincial administrative region from 2013 to 2019 and draw its scatter plot. Due to space limitations, only 2013 and 2019 are shown, as shown in Figures 4 and 5. Analysis found that most of the provincial-level administrative region in the first three quadrants, provincial administrative region level *DE* and *IM* coordination degree of the spatial distribution of the performance for the "high-high (H-H)" and "low-low (L-L)" agglomeration modes. Zhejiang, Shanghai, Shandong, Jiangsu, Fujian, Anhui, Hubei, Hunan and other places have relatively developed economies and abundant innovation resources and are always in the "high-high (L-L)" cluster. Gansu, Qinghai, Ningxia, Xinjiang, Yunnan, Heilongjiang, Shaanxi and other regions, although there is a small spatial difference, due to their own infrastructure, capital and talent are relatively short all year round in the "low-low (L-L)" cluster. The provincial administrative regions represented by Guangdong and Sichuan, although their own coupling coordination degree is high, the surrounding provincial administrative regions are low, and they are always in the "high-low (H-L)" cluster. Although the coordination degree of *DE* and *IM* is high in the neighbouring areas of Hainan, Jiangxi, Hebei and Shanxi, due to other reasons such as traffic, it is not conducive to the radiation welfare of neighbouring areas, and it is always in the "low-high (L-H)" cluster. For Hainan, although it is located in the eastern region, it is still in the "low-high (L-H)" agglomeration area, which also confirms the conclusion of the previous analysis, and there is a big difference in the coupling coordination degree of *DE* and *IM* among provincial administrative regions in the eastern region.

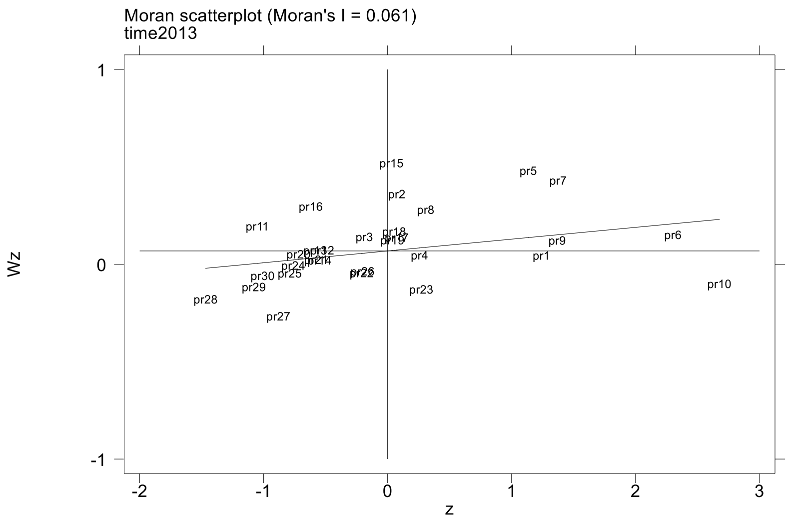

Figure 4. Local Moran index scatter distribution in 2013.

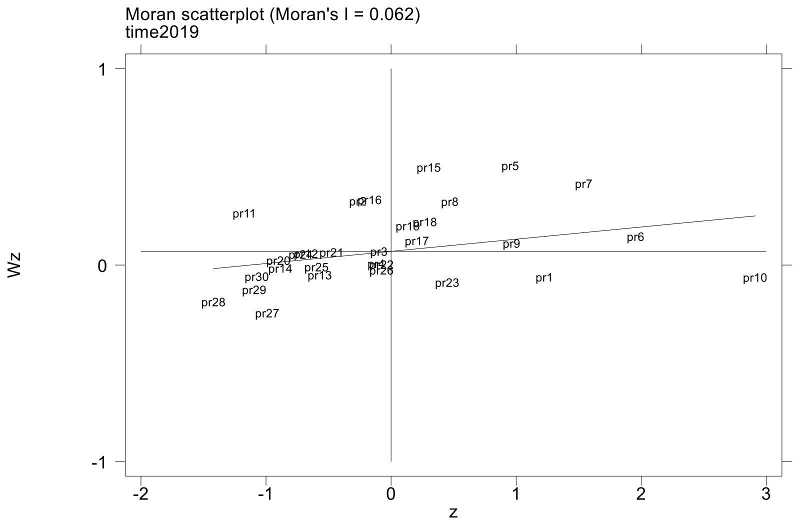

Figure 5. Local Moran index scatter distribution in 2019.

4.6. Discussion

Through theoretical model construction and empirical testing, this paper determines the coupling coordination relationship between *DE* and *IM* at the provincial level in China. Clarify the development status and trend of the subsystem and coupling system of *DE* and *IM*, analyze the obstacle factors, influencing factors and spatial correlation of the coordinated development of *DE* and *IM*, point out the coordinated development path of *DE* and *IM*, and provide theoretical reference for sustainable economic development from the perspective of the coupled coordination of *DE* and *IM*.

Through theoretical analysis and empirical testing, we find that *DE* and *IM* complement each other in infrastructure, technological innovation, product optimization, organizational change and other levels of interdependence. There is a coupling and coordination relationship; the current *DE* and *IM* coupling degree is high, but their coordination needs to be improved. Barbosa et al. (2022) used statistical analysis of the literature to draw the conclusion that *IM* is closely related to digital infrastructure [40]. Our study fully supports this view through statistical data. In addition, the development speed of the *DE* subsystem greatly exceeds that of intelligent manufacturing, which also warns us that when developing *DE*, we should not sacrifice the real economy and avoid being distracted from the intended purpose.

When exploring the path of promoting the coupling and coordinated development of *DE* and *IM*, it is found that we should not only improve the digital supporting facilities of enterprises, strengthen the intelligent application of the manufacturing industry, and improve the innovation and application level of digital intelligent technology. It should also be based on the actual development of the region, based on improving regional opening, economic development, high-level talent investment, innovation attention and promoting the rationalization of industrial structure as well as the *DE* and *IM* to achieve high-quality coupling. In addition, we also find that the coupling coordination of *DE* and *IM* is not only affected by internal factors at the system level but also has spatial correlation. This is also consistent with the spatial effects pointed out by Ma and Zhu (2022) [18], Zhang et al. (2022) [23] and Ying et al. (2021) [79] when exploring the impact of digital economy and intelligent manufacturing on sustainable economic development. Our research results show that the coordination degree of the digital economy and intelligent manufacturing presents a spatial positive correlation, and its spatial distribution is manifested as "high-high (H-H)" and "low-low (L-L)" agglomeration patterns. It can be seen that to promote the coupled and coordinated development of digital economy and intelligent manufacturing, not only should improve the internal development environment of the region but also effectively play the spatial linkage effect.

This research mainly shows three contributions at the level of theoretical research and practical application. First, it innovatively places *DE* and *IM* in the same framework, explores the coupling and coordination relationship between *DE* and *IM*, and promotes the cross-integration of digital economy theory and intelligent manufacturing theory. The importance of *DE* and *IM* for sustainable economic development has been agreed upon [3,13]. In addition, some scholars have noted that the *DE* and *IM* have a complex relationship of mutual influence, mutual promotion and interdependence [15–17]. But at present, it is only a simple explanation of the relationship between the two, without further discussion. By analyzing the theory of digital economy and intelligent manufacturing, our research constructs the coupling coordination theory model of *DE* and *IM*, conducts empirical tests to clarify the coupling coordination relationship between *DE* and *IM* and promotes the cross-integration of digital economy and intelligent manufacturing theory.

Second, the theoretical application of coupling coordination theory is extended. Coupling coordination theory is a kind of system theory that is often used to explore how the interacting elements affect each other, aiming to reveal the interrelationship between different parts of the system. It is a multidisciplinary, interdisciplinary theory that integrates economic, social and natural sciences. It has been proven to be reasonable for research on the ecological environment [63] and has also been used by scholars to study the relationship between the digital industry and the physical industry [54]. However, as an important development direction of the real economy, *IM* has not yet been studied in relation to the coupling and coordination relationship with the *DE*. Our research is based on the coupled coordination theory, putting the *DE* and *IM* in the same research framework and extending the theoretical application of the coupled coordination theory.

Third, it provides reference for various regions in China to improve and promote the coupling and coordinated development policies of *DE* and *IM*, and it also provides theoretical reference for other countries to formulate future development strategies of *DE* and *IM*. China and the rest of the world are faced with the need for economic sustainability, and although it has been found that the *DE* and *IM* may help achieve this goal [2,3,11–13], most studies focus on their single impact on economic sustainability [10,20,22,34]. We connect the two, attempting to use their mutual promotion relationship to help the rapid and healthy development of *DE* and *IM* and provide new ideas for the realization of sustainable economic development.

5. Conclusions

5.1. Main Conclusions

The theory of digital economy, intelligent manufacturing and coupling coordination is analyzed, the theoretical framework of coupled coordination between *DE* and *IM* is constructed and estimates the development index of *DE* and *IM* in each provincial administrative region of China from 2013 to 2019. The development, evolution trend, obstacle factors, influencing factors and spatial correlation of the two are analyzed from the perspectives of internal systems, regional development and spatial interaction, which is of great significance to realize the coupling and coordination of *DE* and *IM*. Relevant conclusions are drawn.

First, the two coupling subjects of *DE* and *IM* are mainly cross-coupled from infrastructure, technological innovation, product optimization and organizational change. The coupling degree is high, but the coordination degree is low, and the development and progress speed of the former is better than the latter. From a regional point of view, the *DE* and *IM* are more developed in the eastern region, and the degree of coupling and coordination is also the same. This paper does not stick to the single development perspective of *DE* and *IM* but puts them in the same framework and clarifies their interactive relationship, which is conducive to promoting the cross integration of digital economy and intelligent manufacturing theories and provides new ideas for accelerating the development of both.

Second, the coupled evolution trend of *DE* and *IM* shows that the former is growing faster than the latter, and the gap between the two is gradually expanding in the evolution process. The study of the two obstacle factors found that the main obstacle to the development of *DE* is the imperfect supporting facilities of enterprises, the shortcomings of technological innovation and the lack of technical application ability, and the main obstacle to the development of *IM* is the insufficient level of intelligent application and technological innovation. The key development direction of China's *DE* and *IM* in the future is defined from the inside of the coupled system.

Third, nationwide, the investment of high-level talents and the importance of innovation on the coupling coordination degree of *DE* and *IM* are positive, but the industrial structure has an inhibitory effect. The eastern region and nationwide are similar; however, they did not play a significant role in promoting economic development. For the central region, only economic development and an emphasis on innovation can significantly boost it. For the western region, the above factors will play an optimistic role. This also shows that the formulation of policies for the coordinated development of *DE* and *IM* coupling in various regions should be adapted to local conditions, combined with their own development, and should not be directly copied.

Fourth, the coupling coordination degree of *DE* and *IM* presents a spatially positive correlation, and there are significant regional differences. In addition, its spatial distribution in each provincial administrative region shows the pattern of "high-high (H-H)" and "low-low (L-L)". These research results not only expand the theoretical application of coupled coordination theory but also provide references for China and other countries to formulate development policies for *DE* and *IM*.

5.2. Policy Recommendations

The following opinions are put forward for the coupling and coordinated development of China's *DE* and *IM*.

First, from the internal perspective of the coupled system of *DE* and *IM*, the research finds that the development speed of *DE* is significantly higher than that of *IM*. Therefore, in the future, intelligent manufacturing policy support and guidance should be increased to improve the development speed of *IM*. From the research results of obstacle factors, the next stage should improve the construction of supporting facilities for the development of enterprise *DE* through policy guidance, tackle the key core technologies of *DE* and *IM*, and improve the level of technological innovation. In addition, accelerate the construction of a high-level technology trading market, focus on examining the efficiency of the transformation of results, improve the reward system, and promote the efficiency of the transformation and application of *DE* and *IM* technology achievements.

Second, from the perspective of internal development in each region, opening, economic development, high-level talent investment, industrial structure and innovation emphasis in each region will have an impact on the coupling and coordination of *DE* and *IM*. However, due to different regional development conditions, the impact is also different, which also shows that different regions should scientifically analyze their own policy priorities according to their own development conditions and should not copy but rather follow the principle of adapting to local conditions. Among them, the east should make good use of its own economic development advantages, absorb more high-level talents and guide diversified investment in *DE* and *IM*. Meanwhile, the blind pursuit of a high-order, industrial structure to industrial structure rationalization should be avoided. The middle should further improve its economic development level, increase investment in innovation funds, lower the entry threshold for innovation investors and improve the financial support system for innovation, so as to absorb more human resources. Due to the lack of resources and economy, the western region should promote the coupling and coordination of digital economy and intelligent manufacturing from multiple perspectives such as opening up, economic development, talent absorption, optimization of industrial structure and financial support.

Third, from the perspective of spatial correlation in each region, the study found that the coupling and coordination degree of *DE* and *IM* are not only related to the system level of the region but also to the spatial level. Therefore, it is particularly important to exert the spatial linkage effect of various regions to narrow the coupling coordination gap between *DE* and *IM*. First of all, the national level should increase the attention to the development of *IM* through policy guidance, capital investment, support for vulnerable areas, etc., strengthen regional mutual recognition, promote the flow of resources, improve the development speed of *IM*, narrow the regional development gap and guide the implementation of the "east number west count" project, in order to strengthen its pulling role in *IM*. Secondly, the provincial administrative regions of "high-low (H-L)" agglomeration areas, represented by Guangdong and Sichuan, take advantage of their own advantages to play a radiating role in the surrounding areas and promote the surrounding provinces to achieve a good coupling and coordination state of *DE* and *IM*. Thirdly, the provincial administrative regions of "low-high (L-H)" agglomeration areas represented by Hainan, Jiangxi, Hebei and Shanxi should strengthen business communication and technical exchanges with the neighbouring provincial administrative regions, improve their own *DE* and *IM* development environments, and improve their coupling and coordinated development levels.

These policy recommendations are based on China's actual national conditions, but it is worth learning from them for the rest of the world. It is worth emphasizing that other countries should apply it on the basis of a full analysis of their own developments.

5.3. Limitations and Future Research

Although our research has achieved important theoretical contributions and practical effects, it still has the following shortcomings.

First, for the research objects and data, the research objects are located in provincial administrative units in China. However, compared with the city- or county-level data, it is difficult to describe the coupling coordination and influencing factors of *DE* and *IM* in detail. In addition, the sample data interval has a certain lag.

Second, as for the research content, when we explored the evolution trend and evolution speed of the subsystems of *DE* and *IM*, we only demonstrated the correctness of the evolution trend of the subsystems through regression fitting and failed to achieve effective prediction of the future stage. Moreover, when studying the coupling and coordination factors of *DE* and *IM*, although regional innovation support, economic development, human capital, industrial structure, etc., are comprehensively considered, there are still incomplete considerations.

Third, this study is based on the actual situation in China, and the experimental data are only from China. Nevertheless, in the context of the rapid development of today's *DE* and *IM*, other countries are also facing the coupling and coordination needs of *DE* and *IM*. The research methods and conclusions of this paper can also provide theoretical references for other countries. However, it must be noted that due to the differences in the development policies and innovation environment of *DE* and *IM* in other countries and regions, it is not appropriate to directly apply the conclusions of this paper to the development guidance of *DE* and *IM* in other countries and regions, and it is necessary to further adjust the strategic planning according to the development level and policy environment of local *DE* and *IM*.

In view of the shortcomings, future studies can further refine the research objects, such as major cities or county-level administrative regions in China, while further updating the data. In addition, other influencing factors such as policies and regional innovation bases can be considered in the coupled coordination of *DE* and *IM*. The coupling model is combined with the BP neural network and other predictive models to predict the future of coupling coordination development in *DE* and *IM*. Meanwhile, future studies can validate and extend the findings of this paper by introducing data from other countries.

Author Contributions: Conceptualization, W.Z.; investigation, W.Z.; resources, F.M.; writing—review and editing, F.M.; supervision, W.Z. and F.M.; project administration, F.M.; funding acquisition, F.M.; writing—original draft, W.Z.; software, W.Z.; methodology, W.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Social Science Fund of China (20FJYB022) and the Heilongjiang Provincial Natural Science Foundation Project (LH2020G004).

Data Availability Statement: Not applicable.

Acknowledgments: We are extremely grateful to the editors and anonymous reviewers for reviewing this study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pan, W.R.; Xie, T.; Wang, Z.W.; Ma, L.S. Digital economy: An innovation driver for total factor productivity. *J. Bus. Res.* **2022**, *139*, 303–311. [CrossRef]
2. Hosan, S.; Karmaker, S.C.; Rahman, M.M.; Chapman, A.J.; Saha, B.B. Dynamic links among the demographic dividend, digitalization, energy intensity and sustainable economic growth: Empirical evidence from emerging economies. *J. Clean. Prod.* **2022**, *330*, 129858. [CrossRef]
3. Balcerzak, A.P.; Pietrzak, M.B. Digital economy in Visegrad Countries. Multiple-criteria Decision Analysis at Regional Level in The Years 2012 and 2015. *J. Compet.* **2017**, *9*, 5–18. [CrossRef]
4. Ma, X.J.; Wang, C.X.; Dong, B.Y.; Gu, G.C.; Chen, R.M.; Li, Y.F.; Zou, H.F.; Zhang, W.F.; Li, Q.N. Carbon emissions from energy consumption in China: Its measurement and driving factors. *Sci. Total Environ.* **2019**, *648*, 1411–1420. [CrossRef] [PubMed]
5. Heubaum, H.; Biermann, F. Integrating global energy and climate governance: The changing role of the International Energy Agency. *Energy Policy* **2015**, *87*, 229–239. [CrossRef]
6. Zhang, G.X.; Deng, N.N.; Mou, H.Z.; Zhang, Z.G.; Chen, X.F. The impact of the policy and behavior of public participation on environmental governance performance: Empirical analysis based on provincial panel data in China. *Energy Policy* **2019**, *129*, 1347–1354. [CrossRef]
7. Zhou, X.; Yu, Y.; Yang, F.; Shi, Q.F. Spatial-temporal heterogeneity of green innovation in China. *J. Clean. Prod.* **2021**, *282*, 124464. [CrossRef]
8. Yin, S.; Yu, Y.Y. An adoption-implementation framework of digital green knowledge to improve the performance of digital green innovation practices for industry 5.0. *J. Clean. Prod.* **2022**, *363*, 132608. [CrossRef]
9. Yin, S.; Zhang, N.; Ullah, K.; Gao, S. Enhancing Digital Innovation for the Sustainable Transformation of Manufacturing Industry: A Pressure-State-Response System Framework to Perceptions of Digital Green Innovation and Its Performance for Green and Intelligent Manufacturing. *Systems* **2022**, *10*, 72. [CrossRef]
10. Zhou, J.; Li, P.G.; Zhou, Y.H.; Wang, B.C.; Zang, J.Y.; Meng, L. Toward New-Generation Intelligent Manufacturing. *Engineering* **2018**, *4*, 11–20. [CrossRef]
11. He, B.; Bai, K.J. Digital twin-based sustainable Intelligent manufacturing: A review. *Adv. Manuf.* **2021**, *9*, 1–21. [CrossRef]
12. Chen, J.H.; Zhang, W.Y.; Wang, H. Intelligent bearing structure and temperature field analysis based on finite element simulation for sustainable and green manufacturing. *J. Intell. Manuf.* **2021**, *32*, 745–756. [CrossRef]
13. Fisher, O.J.; Watson, N.J.; Escrig, J.E.; Gomes, R.L. Intelligent Resource Use to Deliver Waste Valorisation and Process Resilience in Manufacturing Environments Moving towards sustainable process manufacturing. *Johns. Matthey Technol. Rev.* **2020**, *64*, 93–99. [CrossRef]
14. Li, K.; Kim, D.J.; Lang, K.R.; Kauffman, R.J.; Naldi, M. How should we understand the digital economy in Asia? Critical assessment and research agenda. *Electron. Commer. Res. Appl.* **2020**, *44*, 101004. [CrossRef] [PubMed]
15. Kovacs, O. The dark corners of industry 4.0-Grounding economic governance 2.0. *Technol. Soc.* **2018**, *55*, 140–145. [CrossRef]
16. Rajput, S.; Singh, S.P. Industry 4.0 Model for circular economy and cleaner production. *J. Clean. Prod.* **2020**, *277*, 123853. [CrossRef]
17. Fang, X.D.; Chen, H.C. Using vendor management inventory system for goods inventory management in IoT manufacturing. *Enterp. Inf. Syst.* **2022**, *16*, 1–27. [CrossRef]
18. Ma, D.; Zhu, Q. Innovation in emerging economies: Research on the digital economy driving high-quality green development. *J. Bus. Res.* **2022**, *145*, 801–813. [CrossRef]
19. Ma, Q.; Tariq, M.; Mahmood, H.; Khan, Z. The nexus between digital economy and carbon dioxide emissions in China: The moderating role of investments in research and development. *Technol. Soc.* **2022**, *68*, 101910. [CrossRef]
20. Zhang, J.N.; Lyu, Y.W.; Li, Y.T.; Geng, Y. Digital economy: An innovation driving factor for low-carbon development. *Environ. Impact Assess. Rev.* **2022**, *96*, 106821. [CrossRef]
21. Wang, J.; Dong, K.; Dong, X.; Taghizadeh-Hesary, F. Assessing the digital economy and its carbon-mitigation effects: The case of China. *Energy Econ.* **2022**, *113*, 106198. [CrossRef]
22. Yi, M.; Liu, Y.F.; Sheng, M.S.; Wen, L. Effects of digital economy on carbon emission reduction: New evidence from China. *Energy Policy* **2022**, *171*, 113271. [CrossRef]

23. Zhang, W.; Liu, X.M.; Wang, D.; Zhou, J.P. Digital economy and carbon emission performance: Evidence at China's city level. *Energy Policy* **2022**, *165*, 112927. [CrossRef]
24. Shahbaz, M.; Wang, J.D.; Dong, K.Y.; Zhao, J. The impact of digital economy on energy transition across the globe: The mediating role of government governance. *Renew. Sustain. Energy Rev.* **2022**, *166*, 112620. [CrossRef]
25. Luo, S.Y.; Yimamu, N.; Li, Y.R.; Wu, H.T.; Irfan, M.; Hao, Y. Digitalization and sustainable development: How could digital economy development improve green innovation in China? *Bus. Strategy Environ.* **2023**, *32*, 1847–1871. [CrossRef]
26. Wu, J.; Lin, K.X.; Sun, J.S. Improving urban energy efficiency: What role does the digital economy play? *J. Clean. Prod.* **2023**, *842*, 138104. [CrossRef]
27. Ren, Z.; Zhang, J. Digital Economy, Clean Energy Consumption, and High-Quality Economic Development: The Case of China. *Sustainability* **2023**, *15*, 13588. [CrossRef]
28. Barenji, A.V.; Liu, X.L.; Guo, H.Y.; Li, Z. A digital twin-driven approach towards smart manufacturing: Reduced energy consumption for a robotic cellular. *Int. J. Comput. Integr. Manuf.* **2020**, *34*, 844–859. [CrossRef]
29. Zhong, R.Y.; Xu, X.; Klotz, E.; Newman, S.T. Intelligent Manufacturing in the Context of Industry 4.0: A Review. *Engineering* **2017**, *3*, 616–630. [CrossRef]
30. Wan, N.; Li, L.; Ye, C.M.; Wang, B. Risk Assessment in Intelligent Manufacturing Process: A Case Study of an Optical Cable Automatic Arranging Robot. *IEEE Access* **2019**, *7*, 105892–105901. [CrossRef]
31. Kim, J.; Seo, D.; Moon, J.; Kim, J.; Kim, H.; Jeong, J. Design and Implementation of an HCPS-Based PCB Smart Factory System for Next-Generation Intelligent Manufacturing. *Appl. Sci.* **2022**, *12*, 7645. [CrossRef]
32. Lan, X.Y.; Chen, H. Simulation analysis of production scheduling algorithm for intelligent manufacturing cell based on artificial intelligence technology. *Soft Comput.* **2023**, *27*, 6007–6017. [CrossRef]
33. Sun, F.L.; Diao, Z.F. Federated Learning and Blockchain-Enabled Intelligent Manufacturing for Sustainable Energy Production in Industry 4.0. *Processes* **2023**, *11*, 1482. [CrossRef]
34. Yang, Z.H.; Shen, Y. The impact of intelligent manufacturing on industrial green total factor productivity and its multiple mechanisms. *Front. Environ. Sci.* **2023**, *10*, 1058664. [CrossRef]
35. Zhang, L.; Li, J. Analysis of the influence of entrepreneurial psychology on the index system of digital development of the equipment manufacturing industry. *Front. Psychol.* **2022**, *13*, 1026603. [CrossRef]
36. Jiao, R.G.; Commuri, S.; Panchal, J.; Milisavljevic-Syed, J.; Allen, J.K.; Mistree, F.; Schaefer, D. Design Engineering in the Age of Industry 4.0. *J. Mech. Des.* **2021**, *143*, 070801. [CrossRef]
37. Martin-Gomez, A.; Avila-Gutierrez, M.J.; Aguayo-Gonzalez, F. Holonic Reengineering to Foster Sustainable Cyber-Physical Systems Design in Cognitive Manufacturing. *Appl. Sci.* **2021**, *11*, 2941. [CrossRef]
38. Garcia, A.; Bregon, A.; Martinez-Prieto, M.A. A non-intrusive Industry 4.0 retrofitting approach for collaborative maintenance in traditional manufacturing. *Comput. Ind. Eng.* **2022**, *164*, 107896. [CrossRef]
39. Turner, C.; Oyekan, J.; Garn, W.; Duggan, C.; Abdou, K. Industry 5.0 and the Circular Economy: Utilizing LCA with Intelligent Products. *Sustainability* **2022**, *14*, 14847. [CrossRef]
40. Barbosa, C.R.H.; Sousa, M.C.; Almeida, M.F.L.; Calili, R.F. Smart Manufacturing and Digitalization of Metrology: A Systematic Literature Review and a Research Agenda. *Sensors* **2022**, *22*, 6114. [CrossRef]
41. Liu, L.L.; Wan, X.; Gao, Z.G.; Zhang, X.Y. An improved MPGA-ACO-BP algorithm and comprehensive evaluation system for intelligence workshop multi-modal data fusion. *Adv. Eng. Inform.* **2023**, *56*, 101980. [CrossRef]
42. Li, Y.; Yang, X.D.; Ran, Q.Y.; Wu, H.T.; Irfan, M.; Ahmad, M. Energy structure, digital economy, and carbon emissions: Evidence from China. *Environ. Sci. Pollut. Res.* **2021**, *28*, 64606–64629. [CrossRef]
43. Ma, S.Y.; Zhang, Y.F.; Liu, Y.; Yang, H.D.; Lv, J.X.; Ren, S. Data-driven sustainable intelligent manufacturing based on demand response for energy-intensive industries. *J. Clean. Prod.* **2020**, *274*, 123155. [CrossRef]
44. Tian, H.N.; Li, Y.F.; Zhang, Y. Digital and intelligent empowerment: Can big data capability drive green process innovation of manufacturing enterprises? *J. Clean. Prod.* **2022**, *377*, 134261. [CrossRef]
45. Jiang, S.X.; Li, Y.F.; You, N. Corporate digitalization, application modes, and green growth: Evidence from the innovation of Chinese listed companies. *Front. Environ. Sci.* **2023**, *10*, 1103540. [CrossRef]
46. Zhou, G.H.; Zhang, C.; Li, Z.; Ding, K.; Wang, C. Knowledge-driven digital twin manufacturing cell towards intelligent manufacturing. *Int. J. Prod. Res.* **2020**, *58*, 1034–1051. [CrossRef]
47. Sufian, A.T.; Abdullah, B.M.; Ateeq, M.; Wah, R.; Clements, D. Six-Gear Roadmap towards the Smart Factory. *Appl. Sci.* **2021**, *11*, 3568. [CrossRef]
48. Liu, Y.; Zhao, X.; Mao, F. The synergy degree measurement and transformation path of China's traditional manufacturing industry enabled by digital economy. *Math. Biosci. Eng.* **2022**, *19*, 5738–5753.
49. Zhou, Y.; Zang, J.Y.; Miao, Z.Z.; Minshall, T. Upgrading Pathways of Intelligent Manufacturing in China: Transitioning across Technological Paradigms. *Engineering* **2019**, *5*, 691–701. [CrossRef]
50. Chakroun, A.; Hani, Y.; Elmhamedi, A.; Masmoudi, F. A proposed integrated manufacturing system of a workshop producing brass accessories in the context of industry 4.0. *Int. J. Adv. Manuf. Technol.* **2023**, *127*, 2017–2033. [CrossRef]
51. Liu, Q.; Leng, J.W.; Yan, D.X.; Zhang, D.; Wei, L.J.; Yu, A.L.; Zhao, R.L.; Zhang, H.; Chen, X. Digital twin-based designing of the configuration, motion, control, and optimization model of a flow-type smart manufacturing system. *J. Manuf. Syst.* **2021**, *58*, 52–64. [CrossRef]

52. Laudien, S.M.; Daxböck, B. Business model innovation processes of average market players: A qualitative-empirical analysis. *RD Manag.* **2017**, *47*, 420–430. [CrossRef]
53. Guo, F.; Wang, J.Y.; Wang, F.; Kong, T.; Zhang, X.; Cheng, Z.Y. Measuring China's digital financial inclusion: Index compilation and spatial characteristics. *China Econ. Q.* **2020**, *19*, 1401–1418. (In Chinese) [CrossRef]
54. Zhou, S.J.; Wang, J.H.; Xu, B. Innovative coupling and coordination: Automobile and digital industries. *Technol. Forecast. Soc. Chang.* **2022**, *176*, 121497. [CrossRef]
55. Wang, L.H.; Shao, J. Digital economy, entrepreneurship and energy efficiency. *Energy* **2023**, *269*, 126801. [CrossRef]
56. Zhang, M.L.; Yin, S. Can China's Digital Economy and Green Economy Achieve Coordinated Development? *Sustainability* **2023**, *15*, 5666. [CrossRef]
57. Chen, W.; Wu, Y. Does intellectual property protection stimulate digital economy development? *J. Appl. Econ.* **2022**, *25*, 723–730. [CrossRef]
58. Li, Z.G.; Wang, J. The Dynamic Impact of digital economy on Carbon Emission Reduction: Evidence City-level Empirical Data in China. *J. Clean. Prod.* **2022**, *351*, 131570. [CrossRef]
59. Shen, W.M.; Hao, Q.; Yoon, H.J.; Norrie, D.H. Applications of agent-based systems in intelligent manufacturing: An updated review. *Adv. Eng. Inform.* **2006**, *20*, 415–431. [CrossRef]
60. Wang, Q.; Geng, C.X.; E, H.T.; Song, J.R. Research on capital allocation efficiencies with four-dimensional factor capitals from China's intelligent manufacturing enterprises. *PLoS ONE* **2022**, *17*, e0270588. [CrossRef]
61. Hsu, L.C. Investment Decision Making Using a Combined Factor Analysis and Entropy-Base Topsis Model. *J. Bus. Econ. Manag.* **2013**, *14*, 448–466. [CrossRef]
62. Kaynak, S.; Altuntas, S.; Dereli, T. Comparing the innovation performance of EU candidate countries: An entropy-based TOPSIS approach. *Econ. Res.-Ekon. Istraz.* **2017**, *30*, 31–54. [CrossRef]
63. Chen, J.D.; Li, Z.W.; Dong, Y.Z.; Song, M.L.; Shahbaz, M.; Xie, Q.J. Coupling coordination between carbon emissions and the eco-environment in China. *J. Clean. Prod.* **2020**, *276*, 123848. [CrossRef]
64. Cheng, K.; He, K.X.; Fu, Q.; Tagawa, K.; Guo, X.X. Assessing the coordination of regional water and soil resources and ecological-environment system based on speed characteristics. *J. Clean. Prod.* **2022**, *339*, 130718. [CrossRef]
65. Wang, D.; Shen, Y.; Zhao, Y.Y.; He, W.; Liu, X.; Qian, X.Y.; Lv, T. Integrated assessment and obstacle factor diagnosis of China's scientific coal production capacity based on the PSR sustainability framework. *Resour. Policy* **2020**, *68*, 101794. [CrossRef]
66. He, Y.; Liu, G.L. Coupling coordination analysis of low-carbon development, technology innovation, and new urbanization: Data from 30 provinces and cities in China. *Front. Public Health* **2022**, *10*, 1047691. [CrossRef]
67. Zhu, Y.; Yang, F.; Gong, B.G.; Zeng, W. Assessing the efficiency of innovation entities in China: Evidence from a nonhomogeneous data envelopment analysis and Tobit. *Electron. Commer. Res.* **2022**, *23*, 175–205. [CrossRef]
68. Hausken, K.; Moxnes, J.F. Innovation, Development and National Indices. *Soc. Indic. Res.* **2019**, *141*, 1165–1188. [CrossRef]
69. Lenihan, H.; McGuirk, H.; Murphy, K.R. Driving innovation: Public policy and human capital. *Res. Policy* **2019**, *48*, 103791. [CrossRef]
70. Jirakraisiri, J.; Badir, Y.F.; Frank, B. Translating green strategic intent into green process innovation performance: The role of green intellectual capital. *J. Intellect. Cap.* **2021**, *22*, 43–67. [CrossRef]
71. Costantini, V.; Monni, S. Environment, human development and economic growth. *Ecol. Econ.* **2008**, *64*, 867–880. [CrossRef]
72. Zhu, X.W. Have carbon emissions been reduced due to the upgrading of industrial structure? Analysis of the mediating effect based on technological innovation. *Environ. Sci. Pollut. Res.* **2022**, *29*, 54890–54901. [CrossRef] [PubMed]
73. Chung, S. Building a national innovation system through regional innovation systems. *Technovation* **2022**, *22*, 485–491. [CrossRef]
74. Wen, H.M.; Yue, J.L.; Li, J.; Xiu, X.D.; Zhong, S. Can digital finance reduce industrial pollution? New evidence from 260 cities in China. *PLoS ONE* **2022**, *17*, e0266564. [CrossRef] [PubMed]
75. Jin, W.; Zhang, H.Q.; Liu, S.S.; Zhang, H.B. Technological innovation, environmental regulation, and green total factor efficiency of industrial water resources. *J. Clean. Prod.* **2019**, *211*, 61–69. [CrossRef]
76. Wang, J.Q.; Shahbaz, M.; Song, M.L. Evaluating energy economic security and its influencing factors in China. *Energy* **2021**, *229*, 120638. [CrossRef]
77. Li, C.Y. China's multi-dimensional ecological well-being performance evaluation: A new method based on coupling coordination model. *Ecol. Indic.* **2022**, *143*, 109321. [CrossRef]
78. Chen, Y.; Xu, S.R.; Lyulyov, O.; Pimonenko, T. China's digital economy development: Incentives and challenges. *Technol. Econ. Dev. Econ.* **2023**, *29*, 518–538. [CrossRef]
79. Ying, L.M.; Li, M.H.; Yang, J. Agglomeration and driving factors of regional innovation space based on intelligent manufacturing and green economy. *Environ. Technol. Innov.* **2021**, *22*, 101398. [CrossRef]