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The Development Status of the Manufacturing Industry and the Impact of Digital Characteristics from the Perspective of Innovation

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Abstract: From the perspective of innovation of manufacturing links, this paper conducted research on the current situation of manufacturing development and the relationship between regional economy development and digital transformation, aiming to offer suggestions and reference for relevant policy making. Firstly, taking the INCOPAT patent database as the data source, a quantitative analysis was conducted on the patent data of five key links in the manufacturing industry, which obtained the current situation and digital characteristics of the manufacturing industry development from the perspective of link innovation. Then, based on the relevant economic panel data of regions in China, coupling coordination analysis was conducted to investigate the current characteristics of digital transformation of the five links and the coordinated development of the regional economy from 2017 to 2021. The development level and characteristic relations of 31 provinces or cities in these two systems were analyzed. On the whole, the coordinated development level of the two systems in China is steadily rising but varies among different regions, that is, economically developed regions tend to have better digital transformation development. In general, manufacturing digital transformation in China highly relates to regional economy development. Moreover, the development speed of the two systems tends to be stable from 2017 to 2021. The regions with different coordinated development types should formulate corresponding policies to accelerate manufacturing digital transformation and regional economy development.

Keywords: manufacturing; digitization; regional economies; coupled co scheduling

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1. Introduction

In recent years, under the influence of factors such as trade war, epidemic, and military conflicts, the development of manufacturing industry in China is in the face of dual pressure from developing countries with lower labor costs and developed countries with better preferential policies. In 2021, the 14th five-year plan for the national, economic, and social development of the People's Republic of China and the outline of long-term goals for 2035 proposed to further implement the strategy of building a strong manufacturing country, promoting industrial base upgrading, industrial chain modernization, and promoting the high-quality development of the manufacturing industry. Digitalization and intelligence are significant for the upgrading of the manufacturing industry. However, compared with the leading developed countries, China still has a chasing space in the aspects of digitalization and intelligence in manufacturing industry. Accelerating the digitalization transformation in manufacturing industry is a prominent starting point for China to maintain innovation and sustainable development. Grasping the status quo of manufacturing industry development in China, discussing the coordination between digital transformation and regional economy development, space-time differences, and other issues, will help to explore the new path and mode of manufacturing digital transformation in China, provide reference to

China's policy-making, and have great practical significance for realizing the strategic goal of China's manufacturing power.

1.1. Research on Manufacturing Digital Transformation

This kind of research mainly focuses on the measurement, the digital economy and the path for transformation, and the influencing factors of transformation.

In the aspect of the measurement of manufacturing digital transformation, the use of index data and weight calculation are the research hotspots. Song et al. [1] investigated the impact and mechanism of industrial digitization on enterprises and applied the input–output analysis to calculate the level of manufacturing digital transformation in China. Fan and Wu [2] analyzed the level of provincial-level digitalization in China and evaluated the development level of various indicators based on principal component analysis. Martell et al. [3] investigated automation and digitalization of a Mexican manufacturing company in the view of digital technology. Tolstykh et al. [4] used fuzzy methods to analyze a series of indicators for measuring the potential of digitalization in a regional economy. Their analysis was conducted based on the case of a district in Russia. Building an evaluation system from a different perspective is an innovation of many studies. Wan et al. [5] built a perfect and rich index system to evaluate the manufacturing digital transformation from the perspective of architecture, which provides a basic basis for the government to guide and help digital transformation in enterprises. In the context of intelligent manufacturing, Jing et al. [6] evaluated the traditional manufacturing industry and provided a decision-making reference for the digital transformation in enterprises, based on an evaluation system according to the perspective of scientific evaluation. Keles and Alptekin [7] constructed an evaluation system for countries' digital efficiency. This system covers various areas including infrastructure, job, technology, business and so on, involving the data of quite a few countries including France, Italy and so on. Kuntsman and Arenkov [8] constructed an indicator system for evaluating Russia's regional digital maturity. This system was related to digital technology. Thordsen et al. [9] also discussed digital maturity evaluation.

In terms of digital economy, digital technology, and digital transformation path, it is a research hotspot to explore the research path from the perspective of industry differentiation. Chen and Cai [10] used digital technology patents as the core variable to evaluate the situation of digital promoting and the growth of manufacturing industry, obtained its industry heterogeneity characteristics, and put forward corresponding suggestions. Zhang and Wang [11] used digital input as the main evaluation index to calculate and evaluate the relationship between digital input and the output of various industries and GDP changes, and summarized the path and function characteristics of digital transformation. Some researchers focus on policy suggestions for manufacturing digital transformation. Feng W [12] discussed the problems, paths, and methods of manufacturing digital transformation and put forward corresponding policies from the background of digital economy. Song et al. [13] comprehensively analyzed the digital development and digital background of manufacturing industry in Hebei Province and put forward the development path. Kong and Ding [14] developed a new transformation path based on the discussion on the logical core characteristics of manufacturing digital transformation. Fang and Zhang [15] discussed the new business value of digital transformation through existing cases, providing reference of digital transformation for manufacturing enterprises. Arlinghaus and Rosca [16] proposed a method of risk assessment and strategies of risk mitigation for the development of digital manufacturing, based on the analysis on industry 4.0 applications in Germany and interviews with experts. Kumar et al. [17] developed a framework to analyze the social acceptability of technologies of industry 4.0 by conducting research on Indian manufacturing industry. Some researchers focus on the digital twin for manufacturing industry, including digital twin ecosystem [18], digital twin framework [19], and framework or architecture for developing digital twin [20,21]. Some researchers pay attention to other technologies for developing digital manufacturing, such as digital platforms for learning manufacturing processes planning [22], education programs for the engineers of digital manufacturing systems [23], and digital thread tools for the extension of product life [24].

In terms of the influencing factors, using enterprise data and panel statistical data as the research data basis is a popular choice. Yang and Ye [25] analyzed the impact factors and effects of digital transformation in enterprises, and put forward countermeasures and suggestions. Sun and Zhang [26] analyzed the impact factors of manufacturing digital transformation according to China's provincial panel data, and mined the differences between regions and industries. Hu et al. [27] explored the impact on enterprise digital development on inefficient investment decisions by analyzing the real economic data of China's listed enterprises. Tong [28] adopted the TOE framework (T for "technology", O for "organization" and E for "Environment") to conduct an empirical study on the factors which influenced manufacturing digital transformation, based on the enterprise level. Vogelsang et al. [29] conducted interviews with experts to identify the barriers of digital transformation in manufacturing industry. He and Liu [30] found that industrial Internet showed positive promotion for the digital transformation of manufacturing enterprises. Arumugam et al. [31] analyzed the influencing factors of adopting digital technologies, based on the data of Malaysian manufacturing industry. Tasnim et al. [32] conducted their research from a more specific perspective in manufacturing industry, that is, impact factors of digital technology adoption in supply chain management. The used data were collected from Bangladeshi manufacturing enterprises. Tumbajoy and Munoz-anasco [33] focused on the perspective of enterprise. They investigated influencing factors of the digital manufacturing adoption in small and medium-sized enterprises. Gardas et al. [34] paid attention to the perspective of technology. They analyzed the impact factors of the adoption of digital twins for smart manufacturing.

1.2. Research on Coupling Coordination Degree

In terms of this research topic, the relationship between manufacturing digitalization and regional economy is not yet covered in current studies. The existing research mainly evaluates and analyzes the panel data of the real economy, focusing on mining the characteristics of spatial–temporal differences, involving many fields. Fu and Liu [35] designed indexes for high-quality development and further analyzed the coupling coordination level, space–time change characteristics and obstacles of industrial digitalization and manufacturing industry, by analyzing the case of the Yangtze River Delta. Zhang and Meng [36] conducted coupling coordination analysis on the relationship between digital economy and intelligent manufacturing and achieved several empirical findings. Wang et al. [37] analyzed the coupling coordination between digitalization and the upgrading of traditional industry. Li [38] used statistical yearbook data to analyze the coupling level of electronic manufacturing and communication manufacturing in high-tech manufacturing. Chen et al. [39] constructed a coordinated evaluation model to analyze the coordinated development of strategic emerging industries and regional economy in Jiangxi Province. Jiang et al. [40] discussed the coupling coordination relationship between logistics industry and regional economy. Ma et al. [41] applied two models and a method to investigate the coupling coordination between digital finance and advanced manufacturing industry. Xu et al. [42] conducted coupling analysis on the relationship between high-tech industry and regional economy in four economic regions in China and gave policy recommendations. Zhang et al. [43] constructed a system for evaluating the coupling coordination between green innovation and digital economy. They also investigated the impact factors of the coupling coordination degree. Wang and Tan [44] built a coupled and coordinated evaluation system for manufacturing and regional economy in prefecture level cities in Guangdong Province, analyzed the characteristics of the corresponding coordinated development level, and put forward suggestions accordingly. Duan and Xu [45] analyzed and studied the relationship between digitalization and high-quality development of manufacturing industry through several models such as coupling coordination degree, obtained corresponding development characteristics, and put forward corresponding suggestions accordingly.

1.3. Innovation and Research Path of This Paper

To sum up, the existing literature has provided a relatively solid theoretical basis for follow-up research, but there are still some deficiencies: (1) Previous research has not yet focused on the development and digital characteristics of manufacturing industry from the perspective of patents. (2) The indicators used to measure digitalization are of high homogeneity. At present, much of the literature on digitalization measurement mainly uses statistical panel data indicators, and the evaluation indicators of various articles are of high homogeneity. (3) There is a lack of more objective data indicators which more closely relate to the actual development of digitalization. Currently, a unified standard of the measurement of manufacturing digital transformation is not yet established, which fails to reflect the development level of digitalization directly. (4) Research on manufacturing digital transformation and the coordinated development of regional economy is not yet investigated. The coupling and coordination degree has been widely used to evaluate the coordinated development between the two systems, but it is still relatively lacking in the evaluation of the relationship between manufacturing digital transformation and regional economy relations.

Therefore, this study focuses on the innovation perspective, through the patent measurement of the five key links of manufacturing industry in China, including product design, product manufacturing, warehouse and transportation, raw material procurement, order processing and wholesale and retail, to obtain the innovation and development status and digital characteristics of each link of the manufacturing industry. Then, the coupling coordination analysis is conducted to investigate the characteristics and change trends of manufacturing digital transformation in China and coordinated development of regional economy. This paper discusses the positive synergy and space–time differences between the two systems and provides a reference basis of China's policy formulation and implementation, aiming to promote the rapid development of manufacturing digitalization, the realization of the strategic goal of China's manufacturing power, and the continuous growth of regional economy.

Moreover, current studies have empirically validated the contribution of manufacturing digital transformation on sustainability. Wang et al. [46] found that the digital development of enterprises significantly promoted the green transformation of manufacturing industry based on data of Chinese A-share listed manufacturing enterprises. Chen et al. [47] achieved a similar conclusion. Zhang et al. [48] indicated the effect of digital technology development on reducing domestic embodied carbon intensity by analyzing the panel data of regions in China. Similarly, Lyu et al. [49] pointed out that digital transformation had significant promotion on the development of low-carbon technology. Our paper aims to provide insights for formulating appropriate policies to accelerate the manufacturing digital transformation and regional economy development, which also contributes to sustainable development of manufacturing industry.

The research procedure of this paper is illustrated in Figure 1.

(1) The patent data and panel data of the regional economy are collected from reliable online databases and then preprocessed for further studies (Section 2).
(2) A series of analyses are conducted to investigate the development status and digital characteristics of manufacturing industry, including time trend analysis, regional difference analysis and practice subject analysis (Section 3).
(3) According to the discussion on the coupling and coordination mechanism, the proposed index system and the constructed models, empirical analysis is conducted to investigate the coupling and coordinated development of manufacturing digital transformation and regional economy (Section 4).
(4) A conclusion is achieved based on analysis (Section 5).

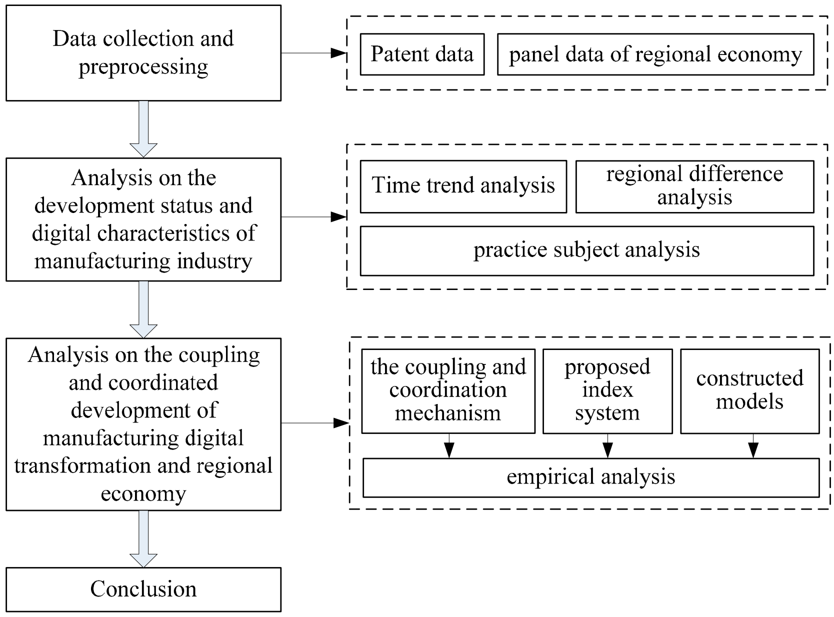

Figure 1. The research procedure.

2. Data Description and Preprocessing

2.1. Data Description

(1) The manufacturing patent data comes from the INCOPAT patent database. According to the texts related to each link to the manufacturing industry, the patents are collected and classified, and the manufacturing sector innovation data for 34 provincial administrative regions in China are obtained. The keywords used in the search of each link are shown in Table 1. By matching the keywords between each link of the manufacturing industry with the patent description text, the search sorted out more than 440,000 pieces of patent data authorized by Chinese applicants for the manufacturing industry from 2017 to 2021.

Table 1. Patent data search.

Manufacturing Links	Search Keywords
Product design	Product design, overall design, shape design, shape design, function design, auxiliary design, computer-aided process design
Raw material procurement	Procurement, supplier management, material management
Product manufacturing	Product manufacturing, main production scheduling, workshop operation management, manufacturing resource planning, total quality management, timely production, capacity demand planning, workshop operation management, manufacturing resource planning, total quality management, timely production, capacity demand planning, product life cycle management, digital manufacturing, computer integrated manufacturing system, computer-aided manufacturing, advanced planning and scheduling system, manufacturing process, product data management
Warehousing and transportation	Warehousing and transportation, warehousing system, logistics system, intelligent warehousing, warehousing management, intelligent transportation, cargo loading and unloading, location management, warehousing system, picking system, three-dimensional shelf, warehousing management, sorting system, intelligent logistics, logistics management, logistics warehouse, transportation tools, loading and unloading tools, transportation planning, transfer system, road transportation, short haul transportation, distribution center
Order processing and wholesale and retail	Order processing, wholesale, retail, order management, commodity information management, distribution management, sales management, inventory data, customer information management, settlement management, commodity prices, commodity labels, commodity information collection, commodity information query, traceability information server, inventory inventory inventory inventory, barcode management, sales records, commodity number, regional dealers, goods query, warehousing query, outbound query, circulation nodes, transfer management

(2) The panel data for regional economy comes from the National Bureau of statistics (http://www.stats.gov.cn/, accessed on 1 January 2023). Based on the annual data of 31 provincial administrative regions in Chinese Mainland, the economic data related to the indicator system are obtained. If the indicator data of some years are missing, the average value of the corresponding indicators in other years will be used instead.

(3) The statistical description for the patent data and panel data of regional economy are shown in Tables 2 and 3, respectively.

Table 2. Statistical description of patent data.

Attribute	Min	Max	Mean	Median	First Quartile	Second Quartile
(a) Year 2017						
Number of digital patents for product design	0.00	437.00	62.42	25.00	5.50	61.00
Digital patent ratio of product design (%)	0.00	23.51	6.09	4.90	2.94	8.85
Number of digital patents for raw material procurement	0.00	196.00	27.87	11.00	1.00	25.50
Raw material procurement digital patent ratio (%)	0.00	22.86	7.46	6.75	2.58	10.21
Number of digital patents for product manufacturing	0.00	356.00	47.39	16.00	1.00	43.50
Digital patent ratio of product manufacturing (%)	0.00	13.10	5.11	5.30	1.59	7.03
Number of warehousing and transportation digital patents	0.00	129.00	20.29	9.00	2.50	19.00
Warehousing and transportation digital patent ratio (%)	0.00	14.14	5.80	5.71	3.57	7.37
Number of digital patents for order processing and wholesale and retail	0.00	122.00	19.74	6.00	3.00	19.00
Order processing and wholesale and retail digital patent ratio (%)	0.00	44.17	22.32	24.15	14.17	28.04
(b) Year 2018						
Number of digital patents for product design	0.00	461.00	58.94	18.00	3.50	51.00
Digital patent ratio of product design (%)	0.00	17.01	4.98	3.81	2.49	6.87
Number of digital patents for raw material procurement	0.00	206.00	25.87	8.00	2.50	20.50
Raw material procurement digital patent ratio (%)	0.00	17.08	5.92	5.87	3.40	7.30
Number of digital patents for product manufacturing	0.00	380.00	45.16	10.00	1.00	51.50
Digital patent ratio of product manufacturing (%)	0.00	22.22	4.89	2.79	1.29	5.56
Number of warehousing and transportation digital patents	0.00	117.00	20.07	9.50	3.25	19.50
Warehousing and transportation digital patent ratio (%)	0.00	30.00	5.51	4.56	2.33	8.11
Number of digital patents for order processing and wholesale and retail	0.00	225.00	27.19	7.00	3.00	19.50
Order processing and wholesale and retail digital patent ratio (%)	0.00	48.43	16.53	14.29	9.68	22.90
(c) Year 2019						
Number of digital patents for product design	0.00	638.00	75.65	19.00	6.00	91.50
Digital patent ratio of product design (%)	0.00	17.83	6.20	5.88	2.32	9.86
Number of digital patents for raw material procurement	1.00	303.00	37.10	14.00	2.50	36.50
Raw material procurement digital patent ratio (%)	1.28	50.00	8.83	6.54	4.44	8.57
Number of digital patents for product manufacturing	0.00	513.00	62.74	16.00	3.00	59.00
Digital patent ratio of product manufacturing (%)	0.00	15.38	5.76	5.90	3.07	7.50
Number of warehousing and transportation digital patents	0.00	120.00	19.94	8.00	3.00	24.00
Warehousing and transportation digital patent ratio (%)	0.00	12.00	4.69	4.02	2.41	6.11
Number of digital patents for order processing and wholesale and retail	0.00	240.00	27.29	6.00	2.00	22.50
Order processing and wholesale and retail digital patent ratio (%)	0.00	33.00	13.05	11.11	6.50	20.77

Table 2. *Cont.*

Attribute	Min	Max	Mean	Median	First Quartile	Second Quartile
(d) Year 2020						
Number of digital patents for product design	0.00	634.00	72.00	25.00	5.00	83.00
Digital patent ratio of product design (%)	0.00	25.00	7.31	6.67	4.24	9.42
Number of digital patents for raw material procurement	0.00	296.00	40.84	14.00	6.00	41.00
Raw material procurement digital patent ratio (%)	0.00	20.00	5.61	4.26	3.06	7.12
Number of digital patents for product manufacturing	0.00	488.00	56.29	14.00	3.00	58.00
Digital patent ratio of product manufacturing (%)	0.00	25.00	5.57	4.26	2.94	7.06
Number of warehousing and transportation digital patents	0.00	152.00	25.77	13.00	3.50	24.00
Warehousing and transportation digital patent ratio (%)	0.00	16.28	4.72	4.47	2.17	6.02
Number of digital patents for order processing and wholesale and retail	0.00	383.00	38.90	10.00	3.00	30.00
Order processing and wholesale and retail digital patent ratio (%)	0.00	60.00	16.77	15.79	8.77	20.82
(e) Year 2021						
Number of digital patents for product design	1.00	1064.00	119.87	55.00	6.00	130.00
Digital patent ratio of product design (%)	1.59	50.00	11.30	8.97	6.48	12.80
Number of digital patents for raw material procurement	1.00	623.00	82.61	33.00	8.00	93.50
Raw material procurement digital patent ratio (%)	2.04	26.83	6.89	5.35	3.37	8.56
Number of digital patents for product manufacturing	0.00	829.00	91.35	33.00	4.50	88.00
Digital patent ratio of product manufacturing (%)	0.00	20.02	5.74	5.82	3.90	6.93
Number of warehousing and transportation digital patents	0.00	329.00	50.45	21.00	5.50	50.00
Warehousing and transportation digital patent ratio (%)	0.00	18.26	6.27	5.28	3.77	9.51
Number of digital patents for order processing and wholesale and retail	0.00	622.00	77.71	16.00	6.00	59.00
Order processing and wholesale and retail digital patent ratio (%)	0.00	60.55	20.29	19.51	12.18	27.83

Table 3. Statistical description of panel data of regional economy.

Attribute	Min	Max	Mean	Median	First Quartile	Second Quartile
(a) Year 2017						
Regional GDP	1349.00	91,648.70	26,841.82	20,210.80	12,381.80	33,835.25
Total assets of industrial enterprises beyond designated size	1393.75	116,706.58	36,190.63	30,608.01	18,410.38	42,804.53
General budget revenue of local finance	185.83	11,320.35	2950.63	2252.38	1540.18	3327.77
Total imports and exports of the place where the business unit is located	655,751.00	1,006,678,374.00	132,489,170.06	46,337,190.00	17,864,923.00	106,257,124.50
Full time equivalent of R&D personnel in industrial enterprises beyond designated size	202.00	457,342.00	88,265.90	49,463.00	19,921.00	94,234.50
R&D funds for industrial enterprises beyond designated size	3186.00	18,650,313.00	3,875,148.10	2,411,418.00	787,906.00	4,552,825.00
Fixed asset investment (excluding farmers) increased over the previous year	−36.80	18.50	5.44	6.60	2.40	9.70
Value added index of secondary industry (last year = 100)	99.20	110.80	105.90	106.70	103.85	107.15
Value added index of tertiary industry (last year = 100)	105.00	111.40	108.85	109.50	107.95	110.00
Industrial output	110.10	35,344.00	9079.97	6202.40	3543.75	11,226.75

Table 3. *Cont.*

Attribute	Min	Max	Mean	Median	First Quartile	Second Quartile
(b) Year 2018						
Regional GDP	1548.40	99,945.20	29,487.66	22,716.50	13,104.70	37,508.75
Total assets of industrial enterprises beyond designated size	1570.00	124,284.20	36,592.97	30,626.90	17,563.40	43,368.85
General budget revenue of local finance	230.35	12,105.26	3158.17	2292.70	1606.43	3639.94
Total imports and exports of the place where the business unit is located	723,178.00	1,084,464,573.00	149,110,174.03	53,304,882.00	20,339,455.50	118,579,213.50
Full time equivalent of R&D personnel in industrial enterprises beyond designated size	326.00	621,950.00	96,168.81	53,133.00	14,443.50	103,920.50
R&D funds for industrial enterprises beyond designated size	8625.00	21,072,031.00	4,178,976.23	2,677,714.00	683,980.00	5,208,317.00
Fixed asset investment (excluding farmers) increased over the previous year	−28.30	15.80	2.97	7.00	−1.15	10.55
Value added index of secondary industry (last year = 100)	100.20	116.80	106.15	105.90	104.00	107.50
Value added index of tertiary industry (last year = 100)	104.80	110.00	107.96	108.20	107.35	109.00
Industrial output	127.00	37,651.10	9676.92	6268.10	3949.20	11,645.20
(c) Year 2019						
Regional GDP	1697.80	107,986.90	31,687.76	24,667.30	13,826.30	41,110.35
Total assets of industrial enterprises beyond designated size	1726.29	137,738.29	38,899.00	32,747.28	17,411.10	46,388.64
General budget revenue of local finance	221.99	12,654.53	3260.67	2410.41	1672.55	3890.44
Total imports and exports of the place where the business unit is located	544,815.00	1,036,626,724.00	147,673,905.55	58,043,282.00	19,942,874.00	105,982,854.50
Full time equivalent of R&D personnel in industrial enterprises beyond designated size	264.00	642,490.00	101,671.87	45,685.00	15,027.50	111,344.50
R&D funds for industrial enterprises beyond designated size	5574.00	23,148,566.00	4,506,806.16	2,851,859.00	812,534.00	5,885,823.50
Fixed asset investment (excluding farmers) increased over the previous year	−16.30	13.90	4.15	6.10	1.75	9.20
Value added index of secondary industry (last year = 100)	100.50	108.80	105.43	105.60	104.00	106.70
Value added index of tertiary industry (last year = 100)	103.30	110.40	107.41	107.80	106.45	108.35
Industrial output	131.70	39,141.80	10,078.06	6582.70	4037.15	12,580.85
(d) Year 2020						
Regional GDP	1902.70	111,151.60	32,578.63	25,041.40	13,904.35	42,273.55
Total assets of industrial enterprises beyond designated size	2044.00	150,717.82	42,048.36	34,255.77	19,000.98	50,436.43
General budget revenue of local finance	220.99	12,923.85	3230.43	2296.57	1597.08	3997.65
Total imports and exports of the place where the business unit is located	310,532.00	1,024,024,456.00	150,190,747.13	64,470,226.00	19,950,068.00	111,609,993.50
Full time equivalent of R&D personnel in industrial enterprises beyond designated size	190.00	700,017.00	111,626.13	48,809.00	16,332.50	123,268.00
R&D funds for industrial enterprises beyond designated size	8944.00	24,999,527.00	4,926,222.77	2,974,157.00	915,011.00	6,372,149.00

Table 3. *Cont.*

Attribute	Min	Max	Mean	Median	First Quartile	Second Quartile
Fixed asset investment (excluding farmers) increased over the previous year	−18.80	16.20	3.87	4.10	2.90	7.65
Value added index of secondary industry (last year = 100)	91.60	116.10	103.24	103.20	101.75	104.40
Value added index of tertiary industry (last year = 100)	96.40	105.60	102.17	102.60	101.05	103.70
Industrial output	158.60	39,353.90	10,057.48	6990.80	3969.05	12,788.05
(e) Year 2021						
Regional GDP	2080.20	124,369.70	36,701.41	27,894.00	15,839.40	47,436.75
Total assets of industrial enterprises beyond designated size	2139.10	169,766.70	45,576.77	37,260.60	20,824.20	54,933.10
General budget revenue of local finance	215.59	14,103.43	3583.13	2775.27	1709.36	4257.48
Total imports and exports of the place where the business unit is located	484,532.00	1,279,548,187.00	195,209,317.19	83,814,594.00	23,768,064.50	139,943,423.50
Full time equivalent of R&D personnel in industrial enterprises beyond designated size	245.50	605,449.75	99,433.18	50,518.25	17,362.00	108,191.88
R&D funds for industrial enterprises beyond designated size	6582.25	21,967,609.25	4,371,788.31	2,814,242.50	786,958.25	5,535,125.75
Fixed asset investment (excluding farmers) increased over the previous year	−14.20	20.40	6.00	6.10	4.25	9.60
Value added index of secondary industry (last year = 100)	99.10	123.20	107.50	106.70	106.05	108.45
Value added index of tertiary industry (last year = 100)	105.40	115.30	108.14	107.70	107.05	108.75
Industrial output	189.90	45,143.00	11,889.35	9339.80	4958.10	14,795.25

2.2. Calculation Methods of Digital Patent

After collecting and sorting out the corresponding patents, the digital proportion of patents is calculated based on the study of Chen and Cai [10], and the World Intellectual Property Organization (WIPO) 35 technical fields and the IPC comparison table (2019.07 version). The IPC classification numbers of patents belonging to digital technologies are shown in Table 4. Based on the IPC number in Table 4, the authorized patents of each link collected are sorted out and identified, the digital technology patents applied to each link between the manufacturing industry are selected, and the corresponding number and proportion is calculated to realize the calculation of the level of manufacturing digital transformation.

Table 4. IPC main classification number of digital patents.

Technical Field	IPC Main Classification Number
Audiovisual technologies	G09F+; G09G+; G11B+; H04N3+; H04N5+; H04N7+; H04N9+; H04N11+; H04N13+; H04N15+; H04N17+; H04N19+; H04N 101+; H04R+; mH04S+; H05K+
Telecom	G08C+; H01P+; H01Q+; H04B+; H04H+; H04J+; H04K+; H04M+; H04N1+; H04Q+
Digital communication	H04L+; H04N21+; H04W+
Basic communication processing	H03B+; H03C+; H03D+; H03F+; H03G+; H03H+; H03J+; H03K+; H03L+; H03M+
Computer technology	G06C+; G06D+; G06E+; G06F+; G06G+; G06J+; G06K+; G06M+; G06N+; G06T+; G10L+; G11C+; G16B+; G16C+; G16Z+
Information technology management methods	G06Q+

3. Analysis of the Development Status and Digital Characteristics of Manufacturing Industry

3.1. Time Trend Analysis

(1) Annual changes from the number of authorized patents in each link

After sorting and analyzing the patent data related to manufacturing industry in the INCOPAT patent database, we can obtain the year change of new patents (Figure 2) related to product design, product manufacturing, warehouse and transportation, raw material procurement, order processing and wholesale and retail of Chinese applicants in the manufacturing field from 2017 to 2021. It is indicated in Figure 2 that the number of newly added authorized patents in the manufacturing industry on the whole is growing. In addition to product design, the growth rates of the other four links are further increased from 2019 to 2021. It indicates that the manufacturing industry has a very good development in the four links to raw material purchasing, product manufacturing, warehouse and transportation, order processing and wholesale and retail, and the level of technological innovation has been improved further. In terms of product design, there is an obvious downward trend in the number of newly authorized patents from 2019 to 2020, which may be related to the China–U.S. trade war.

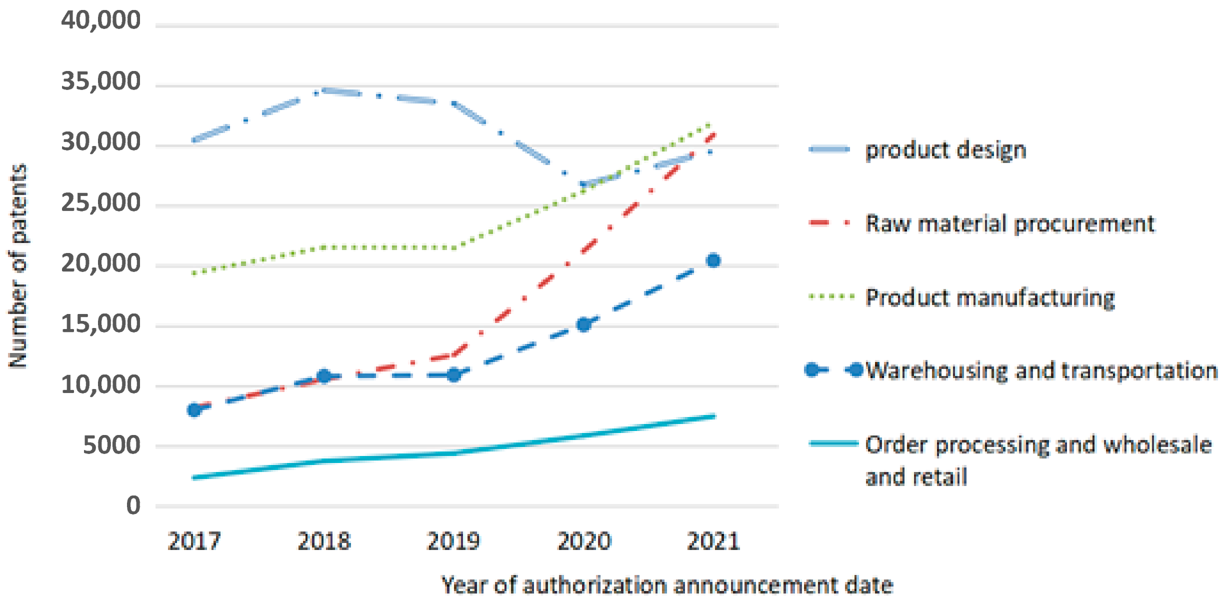

Figure 2. Number of newly authorized patents in each link to the manufacturing industry from 2017 to 2021.

(2) Changes in the number of digital patents in each link

Using the above-mentioned identification method of digital patents, we can analyze the new authorized patents in each manufacturing link and get the distribution of digital patents in each link to the manufacturing industry (Figure 3). It is indicated in Figure 3 that on the whole, the digital development of manufacturing industry shows an upward trend, and the number of new digital patents in all links has increased significantly. The upward trend is the most obvious in 2020–2021, which shows good development momentum of China's manufacturing digital transformation, with better results in the last two years, and the core technology innovation ability has been significantly improved.

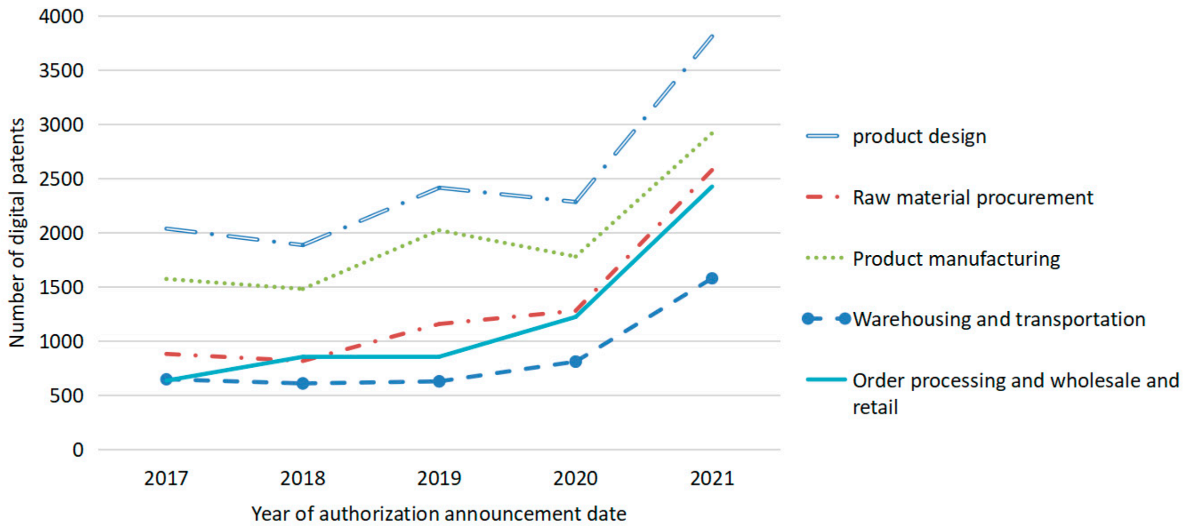

Figure 3. Number of new digital patents in each link to the manufacturing industry from 2017 to 2021.

(3) Analysis on the overall change trend of manufacturing industry

The data from the five key links are calculated and summed as the data representation of the manufacturing industry development. The trend change chart of newly authorized patents in manufacturing industry in China from 2017 to 2021 is presented in Figure 4. It is indicated in Figure 4 that the development and digitalization of manufacturing industry in China was on the rise from 2020 to 2021.

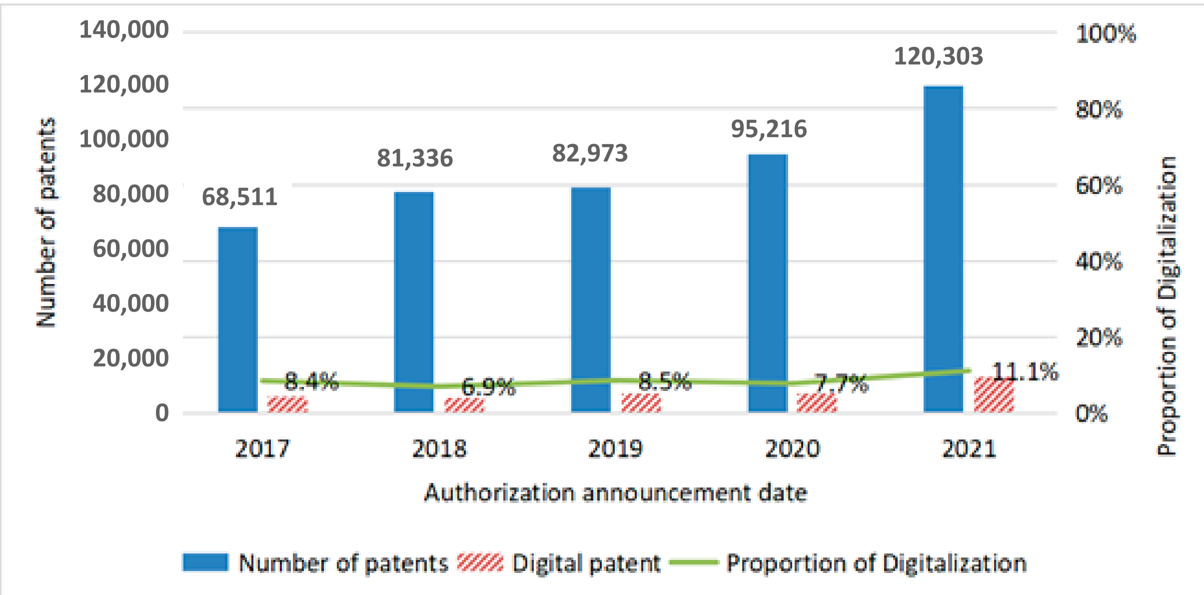

Figure 4. Number of newly authorized patents and digital characteristics in the manufacturing industry from 2017 to 2021.

3.2. Regional Difference Analysis

Taking the data from five links to manufacturing industry as the characterization data for the overall manufacturing industry development, analysis can be conducted to investigate the development status and digital characteristics of regional manufacturing industry, and get the regional distribution of manufacturing industry development (Figure 5). Based on the observation in Figure 5, Guangdong is the most dynamic region from 2017 to 2021, owning the biggest number of new authorized patents. Moreover, developed regions including Jiangsu, Zhejiang, Beijing, and Shanghai also rank in the forefront. In terms of digitalization of manufacturing industry, Beijing has the highest proportion of digitalization. While maintaining a large number of patents, the proportion of digitalization ranks first, indicating that Beijing is in a leading position in digitalization, and the corresponding technology and policy measures may be relatively perfect and mature. In addition, Taiwan, Hong Kong, Sichuan, Tibet, Shaanxi, Guangdong, and other regions also indicate a high proportion of digitalization. As regions with a relatively developed economy and technology, Taiwan and Hong Kong have a high degree of digitalization and are in the lead in some digital technologies; Sichuan, Guangdong and Shaanxi still have a high proportion of digitalization when they have a large number of patents, indicating that these three provinces are at the forefront of digitalization transformation and may take the lead in future industrial optimization and upgrading. Due to the small number of patents and digitalization in Tibet, digitalization accounts are high proportionally.

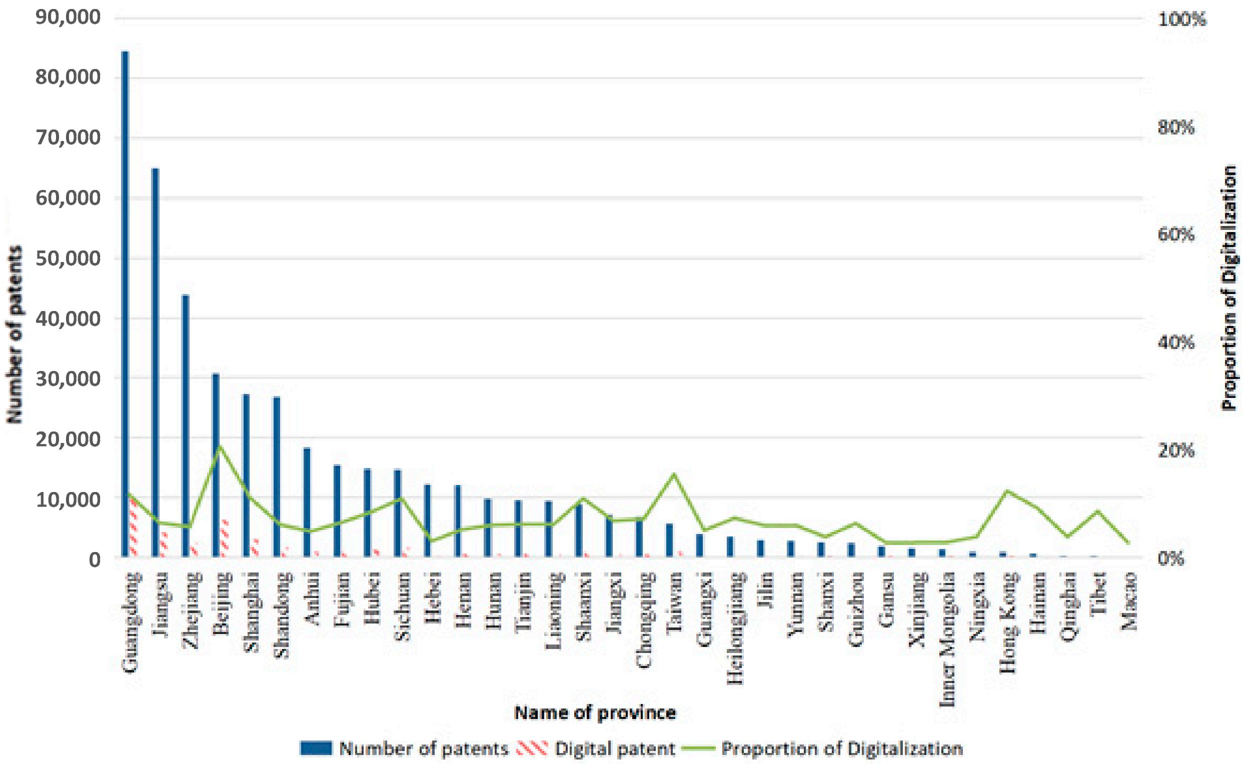

Figure 5. Regional distribution of new authorized patents and digital features in China's manufacturing industry from 2017 to 2021.

On the whole, the development of innovation and digitalization in manufacturing industry closely relates to the economic level. The development level in the developed areas of the southeast coast is significantly higher than that in the economically underdeveloped areas such as Southwest and Northwest China. For the realization of digital transformation and upgrading in manufacturing industry, it may be necessary for the region to reach a certain economic level. Therefore, supporting the less digitalized areas may have a better effect of the direction of promoting economic development.

3.3. Practice Subject Analysis

By analyzing the types of patent applicants, we can obtain the main characteristics of the practice of manufacturing innovation and digital development. Through analysis and sorting, we can obtain the characteristics of patent applicants (Figure 6). Based on Figure 6, several conclusions can be drawn: (1) enterprises are the most important practice subjects in the innovative development and digitalization in manufacturing industry. The amount of patents and the amount of digitalized patents are significantly more than other types of patent applicants, and their contributions are far more than other types of practice subjects; (2) Colleges and universities have the highest proportion of patent digitalization among applicants, and scientific research institutions also have a high proportion of digitalization, indicating that they have a good role in the promotion on the innovation and digital transformation development in manufacturing industry; (3) The number of individual applications for manufacturing patents is also relatively large, which has made important contributions to the innovation and development in manufacturing industry, but the digital level is relatively low; (4) The composite type are the symbol of the cooperation of multiple practice subjects, and its patents have a high proportion of digitalization, which shows that the cooperation of multiple practice subjects can promote the digitalization transformation of manufacturing industry.

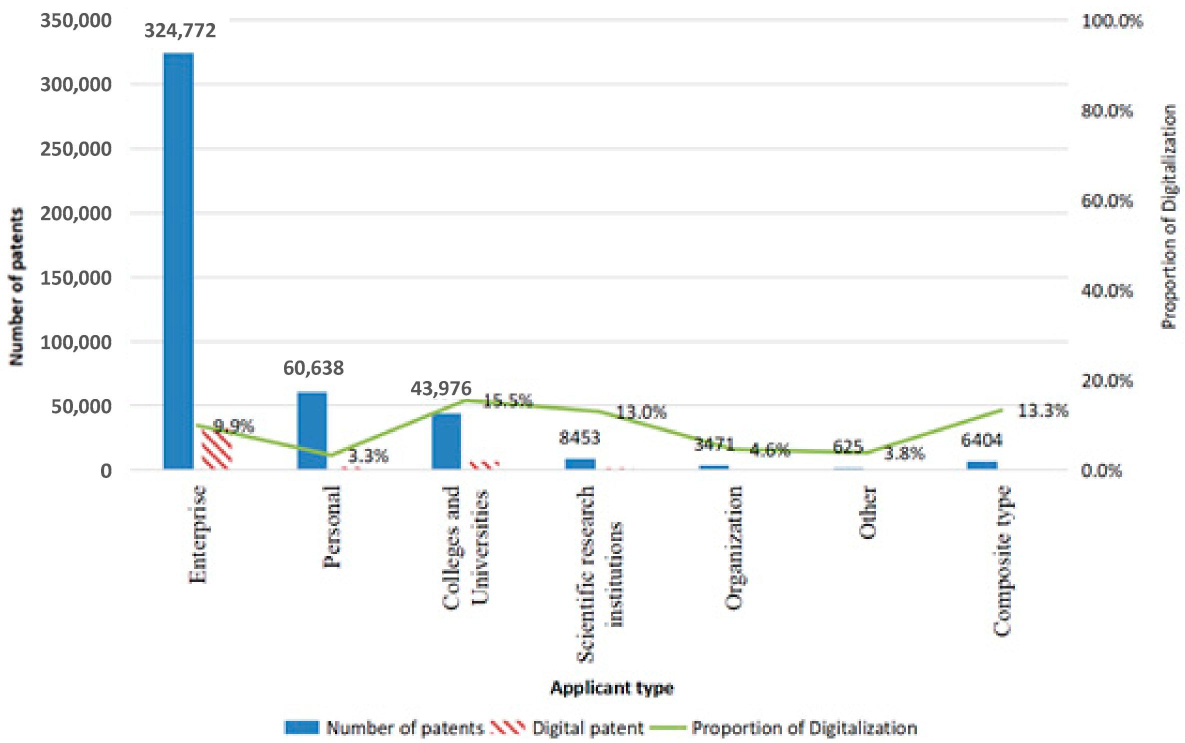

Figure 6. Distribution of newly authorized patent applicants for the manufacturing industry from 2017 to 2021. Note: (1) Because some data items are blank, the total data calculated in this figure will be different from the above; (2) "Composite type" in the figure refers to two or more types of applicants including enterprises, individuals, colleges and universities, scientific research institutions, institutions and groups; (3) "Other" refers to the basic types of non-enterprises, individuals, colleges and universities, scientific research institutions, institutions and groups.

4. Research on the Coupling and Coordinated Development of Manufacturing Digital Transformation and Regional Economy

According to previous studies [39,42,44] and the above research and analysis, it can be found that there is a close relationship between manufacturing digital transformation and regional economy. Therefore, the coupling coordination analysis on the interaction between manufacturing digital transformation and regional economy development is conducted in this section.

4.1. Analysis on the Coupling and Coordination Mechanism of Manufacturing Digital Transformation and Regional Economy

Manufacturing digitalization mainly refers to the upgrading and optimization in traditional manufacturing industry under the support and guidance of digital technology, and the further promotion on the comprehensive optimization and upgrading in manufacturing production mode, operation mode and business mode. “Coupling” is used to describe the phenomenon of synergy between two systems due to interaction. The coupling model is built to measure the interaction between two systems on each other. In recent years, the principle of coupling and coordination has been applied to the areas of social science. For investigating the coupling and coordinated development of manufacturing digital transformation and regional economy, we first need to analyze the corresponding coordination mechanism.

(1) Manufacturing digital transformation promotes regional economy development

Manufacturing digital transformation is beneficial for promoting economic growth. After the digital upgrading of manufacturing industry, it helps to increase the efficiency of design, production, operation, and other aspects, effectively reduce costs, improve output, and then realize the improvement of economic benefits. The investment in manufacturing digital transformation will expand the development of digital technology industry, breed new economic growth points, and achieve economic growth. The digital transformation of manufacturing is conducive to innovative development. While developing and exploring new technologies, it often generates new economic added value, enhances product heterogeneity, broadens industrial development space, and realizes the improvement in economic benefits. On the whole, the manufacturing digital transformation can promote the coordination of various production factors, the utilization efficiency of all factors, and economy growth.

Manufacturing digital transformation promotes innovative development. The application and scientific research of digital technologies are beneficial for the cost reduction of searching and using various knowledge resources, improvement of the circulation efficiency of innovative elements, realization of the optimization and upgrading in structures of regional industries, optimization of resource allocation, shortening of the product research and development cycle, and the creation of new economic value.

The manufacturing digital transformation is beneficial for the accumulation of regional human capital. The manufacturing digital transformation requires the participation of talents with high-tech knowledge. Moreover, human capital acts as the engine of regional economic growth. Supporting digital transformation through capital projects can attract a large amount of excellent talents, realize the accumulation of regional human capital, and promote regional economic development.

(2) Regional economy plays a supporting role in manufacturing digital transformation

The manufacturing digital transformation needs financial support. Digital transformation requires investment and application of high-tech digital technology. In addition, a large amount of funds is required at each stage of development. Effective digital transformation requires strong economic strength. Economically developed regions are easier to receive financial support for accelerating manufacturing digitalization development.

The manufacturing digital transformation is inseparable from a good platform and perfect infrastructure. Only regions with better economies can have enough capital to provide the basis of digital development.

The manufacturing digital transformation also needs the support from a large amount of excellent talents. Economically developed regions often have better educational resources, can attract numerous high-quality talents, and provide intellectual support for the digital transformation.

Based on the above discussion, there is a coupling relationship between manufacturing digital transformation and the development of regional economy. Manufacturing digital transformation has improved the production efficiency through technological innovation, changed the production and operation mode, accelerated the optimization and upgrading of industrial structure, optimized the mode of resource allocation, and improved industrial competitiveness. In summary, manufacturing digital transformation directly or indirectly promotes regional economic development. Regional economy provides financial guarantee, intellectual support, standard guidance and a good external environment for digital transformation and development of manufacturing industry. It can be concluded that manufacturing digital transformation promotes regional economy development, and the achievements of regional economy development support manufacturing digital transformation. According to the relationship between the two, we can build a corresponding index system to evaluate manufacturing digital transformation and regional economy development.

4.2. Evaluation System Construction

According to existing relevant studies [2,5,6,35,38,42,44,45], this paper starts from the innovation perspective of five key links to manufacturing product design, product manufacturing, warehouse and transportation, raw material procurement, order processing and wholesale and retail, and takes the innovation digital level of five links as the evaluation dimension to build the evaluation system of manufacturing digital transformation. The evaluation system of regional economic development is developed from the three dimensions of economic benefit, sustainable development, and economy growth.

The complete evaluation index system is presented in Table 5. The weights presented in Table 3 were determined by Formula (1) to Formula (6) in Section 4.3. The indicator type was determined by the values of indicators. If values of indicators are positive (negative), its indicator type is "positive (+)" ("negative (−)"). Indicators of manufacturing digital transformation are achieved by statistical classification and counting on the patent data (Section 2.2). Indicators of the evaluation system of regional economy development is directly achieved from the attributes in the panel data for regional economy.

Table 5. Evaluation indexes system of the coupling system between digitalization of manufacturing sector innovation and regional economy development.

Target Layer	Primary Index	Secondary Indicators	Unit	Indicator Type	Weight
Digital transformation of manufacturing industry	Product design innovation Digitalization	Number of digital patents for product design	/	+	0.147
		Digital patent ratio of product design	%	+	0.045
	Innovative digitalization of raw material procurement	Number of digital patents for raw material procurement	/	+	0.147
		Raw material procurement digital patent ratio	%	+	0.053
	Product manufacturing innovation Digitalization	Number of digital patents for product manufacturing	/	+	0.16
		Digital patent ratio of product manufacturing	%	+	0.062
	Innovative digitalization of warehousing and transportation	Number of warehousing and transportation digital patents	/	+	0.122
		Warehousing and transportation digital patent ratio	%	+	0.049
	Order processing and wholesale and retail innovation Digitalization	Number of digital patents for order processing and wholesale and retail	/	+	0.17
		Order processing and wholesale and retail digital patent ratio	%	+	0.044

Table 5. *Cont.*

Target Layer	Primary Index	Secondary Indicators	Unit	Indicator Type	Weight
Regional economic development	Economic performance	Regional GDP	100 million yuan	+	0.087
		Total assets of Industrial Enterprises beyond designated size	100 million yuan	+	0.084
		General budget revenue of local finance	100 million yuan	+	0.092
		Total imports and exports of the place where the business unit is located	Thousand dollars	+	0.22
	Innovation-driven development	Full time equivalent of R&D personnel in industrial enterprises beyond designated size	Person per year	+	0.189
		R&D funds for industrial enterprises beyond designated size	Ten thousand yuan	+	0.159
	Economic growth	Fixed asset investment (excluding farmers) increased over the previous year	%	+	0.017
		Value added index of secondary industry (last year = 100)	/	+	0.026
		Value added index of tertiary industry (last year = 100)	/	+	0.026
		Industrial output	100 million yuan	+	0.102

4.3. Model Construction

(1) Construction and standardization of efficacy function

Let U_{ij} be the efficacy function of the coupling system of "new digital transformation of manufacturing—regional economy" (i denotes the order parameter, and j denotes the index). The corresponding value of U_{ij} is denoted by X_{ij}. U_{ij} (i = 1, 2) is the comprehensive system value of manufacturing digital transformation and the regional economy system. u_{ij} denotes the efficiency coefficient which indicates contribution of each index to the system efficiency. Because of the fact that the units of evaluation indexes vary (Table 5), the range standardization method is adopted to normalized indexes for determining the efficacy function U_{ij}.

When U_{ij} is a positive indicator:

$$u_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \tag{1}$$

When U_{ij} is a negative indicator:

$$u_{ij} = \frac{\min(X_{ij}) - X_{ij}}{\max(X_{ij}) - \min(X_{ij})} \tag{2}$$

(2) Calculation of the comprehensive contribution value of order parameter.

The comprehensive contribution value of order parameter is calculated by linear weighting method. Set U_1 as the total order parameter of the *i*th system, the calculation formula is as follows:

$$U_i = \sum_{j=i}^{m} \omega_{ij} u_{ij}, \quad \sum_{j=\mathrm{i}}^{m} \omega_{ij} = 1 \tag{3}$$

In Formula (3), ω_{ij} is the weight of each index, and it is calculated by using the entropy method, which evaluates the importance of the index by the variation degree of the value of each index. The smaller the information entropy of an index in the evaluation system, the more information the index provides and it is more valuable, that is, the index plays a more important role with greater weight. The objective weighting can avoid the deviation caused by human factors of the subjective weighting method. The calculation formula of objective weighting is as follows:

The *i*-th index of the *j*-th order parameter:

$$P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}} \tag{4}$$

The total contribution of each sample to attribute X_j is:

$$E_j = -\sum_{i=1}^{m} p_{ij} \ln(P_{ij}) / \ln m \tag{5}$$

Then the weight of each attribute is W_i, where: $d_i = 1 - E_i$; $\sum_{j=1}^{n} W_j = 1$

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{6}$$

(3) Coupling model

This study uses coupling degree (CD) as well as coupling coordination degree (CCD) to describe and measure the system coordination relationship. When two subsystems of manufacturing digital transformation and regional economy are coupled, the coupling degree model is:

$$C = 2[U_1 \times U_2/(U1 + U2)(U1 + U2)]^{1/2} = \frac{2(U_1 \times U_2)^{1/2}}{U1 + U2} \tag{7}$$

C denotes the CD value of manufacturing digital transformation and regional economy system, reflecting the degree of mutual coordination between the two, and $C \in [0,1]$. Larger value of C indicates greater synergy and higher correlation between the two systems. Referring to the classification principle of CD grades in [50], the CDs can be grouped into five grades (Table 6).

(4) Coupling coordination degree model

The CD reflects the synchronization degree between subsystems. However, in some cases, it fails to reflect the overall efficiency and synergy.

It cannot show the state of the development level between systems. For example, when both systems are in the preliminary development stage, the value of the integrated system is not high, which will also lead to the situation of too high CD. This defect can be solved by CCD. When calculating coordination degree between the systems, the comprehensive development level of the subsystems is also considered, which can better reflect the level of coupling and coordinated development between manufacturing digital transformation and regional economy. Based on previous research, the coupling and coordination model for manufacturing digital transformation and regional economy system is expressed as:

$$D = \sqrt{C \times T};\ T = \alpha_1 U_1 + \alpha_2 U_2 \tag{8}$$

In formula (8): D refers to coupling co scheduling; T denotes the comprehensive evaluation index of the overall synergy or contribution to the manufacturing digital transformation and regional economy; α_1, α_2 is the undetermined coefficient. Referring to the existing literature and relevant research, it is considered that the two systems are equally important, giving α_1 = 0.5, α_2 = 0.5. In order to determine the degree of coordinated development between the two systems, the coordination degree of the composite system is classified according to the research of Tian and Wang [50] (Table 7).

Table 6. Value range and corresponding grade of CD.

Range of C Value	Coupling Level	Coupling Stage	Characteristic
[0.0~0.5]	1	Low coupling period	The interaction between manufacturing digital transformation and regional economy development is weak. When C = 0, there is no interaction between the two systems and they develop disorderly
(0.5~0.7]	2	Lower coupling stage	The interaction between the manufacturing digital transformation and regional economy development has gradually strengthened, the digital process has begun to accelerate, and the demand for capital and other production factors has increased, which requires strong support from the government
(0.7~0.9]	3	Benign coupling period	The manufacturing digital transformation and regional economy development gradually cooperate with each other, and the positive impact between them is significantly enhanced, developing in the direction of benign coupling
(0.9~1.0]	4	High level coupling period	The manufacturing digital transformation and the orderly development of regional economy, the government has also taken a variety of environmental regulation measures and incentive policies to encourage innovation subjects to carry out digital transformation. When C = 1.0, the two systems basically achieve coordination and coupling and develop towards high quality

Table 7. Value range and corresponding level to coupling coordination dispatching.

D-Value Interval of CCD	Coordination Level	CCD	D-Value Interval of CCD	Coordination Level	CCD
(0.0~0.1)	1	Extreme disorder	[0.5~0.6)	6	Reluctantly coordinate
[0.1~0.2)	2	Serious disorder	[0.6~0.7)	7	Primary coordination
[0.2~0.3)	3	Moderate disorder	[0.7~0.8)	8	Intermediate coordination
[0.3~0.4)	4	Mild disorder	[0.8~0.9)	9	Good coordination
[0.4~0.5)	5	Verge of disorder	[0.9~1.0)	10	High quality coordination

4.4. Empirical Analysis

4.4.1. Comprehensive Index (U_1) Analyses of Manufacturing Digital Transformation

By sorting out and analyzing the patent digitalization of the five links between manufacturing industry in each province, the comprehensive development index of manufacturing digitalization transformation in China's provinces (cities) from the perspective of innovation can be calculated by the entropy method, as shown in Figure 7. From a regional perspective, it is indicated that Guangdong has the highest comprehensive index value of manufacturing digital transformation, and its score is obviously in the leading position, followed by Beijing, Jiangsu, Zhejiang and Sichuan. The comprehensive index of manufacturing digital transformation of the above provinces and cities has exceeded 0.4, significantly higher than other provinces. On the whole, the economic development of these regions is also relatively good. The index of manufacturing digital transformation in all provinces and cities in 2017 was higher than that in the other four years, and the index change in 2018 to 2021 was relatively small and tended to be stable.

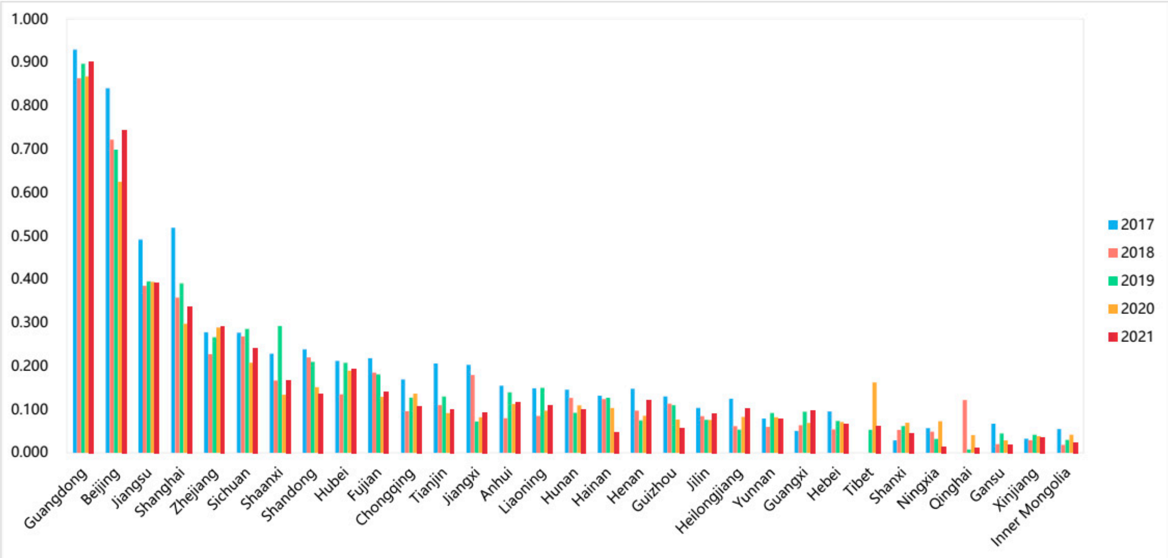

Figure 7. Bar chart of manufacturing digital transformation comprehensive index.

4.4.2. Analysis of Regional Economic Development Indexes (U_2)

Figure 8 is the bar chart of the regional economic development index, which shows the regional distribution and year of the regional economic development index. For regional distribution, the economic development index values of Guangdong, Jiangsu, Zhejiang, Shandong, Shanghai, and other eastern coastal provinces and cities are in leading positions. In terms of time, the economic development index in 2017 is slightly higher than that in the next four years. The index has little change in 2018 to 2021, and the overall trend is similar to the comprehensive index of manufacturing digital transformation. There is an increasing downward pressure on the economy. Moreover, the growth tends to be stable, which requires new economic growth points and stimulus points.

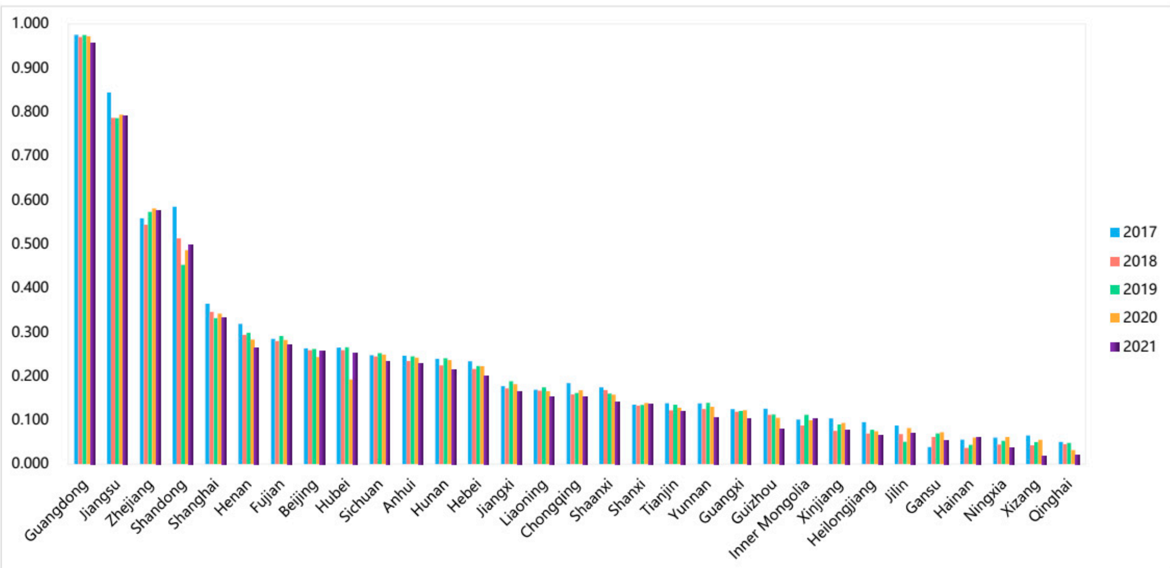

Figure 8. Bar chart of regional economic development index.

4.4.3. Analysis on the Characteristics of the Coupling and Coordinated Development of Manufacturing Digital Transformation and Regional Economy

Formulas (1)–(8) were used to calculate CD and CCD of the manufacturing digital transformation and regional economy development system in various provinces and cities. The results are given in Tables 8 and 9.

Table 8. Measurement results of the coupling degree (C) of manufacturing digital transformation and regional economy in 31 provinces and cities from 2017 to 2021 (For the Attribute "Coupling phase (2021)", HC for "High-level Coupling", BC for "Benign Coupling").

Province	2017	2018	2019	2020	2021	Coupling Phase (2021)
Shanghai	0.984	0.999	0.996	0.997	0.999	HC
Yunnan	0.962	0.935	0.979	0.973	0.99	HC
Inner Mongolia	0.954	0.751	0.817	0.912	0.766	BC
Beijing	0.851	0.881	0.89	0.897	0.875	BC
Jilin	0.996	0.993	0.979	0.999	0.991	HC
Sichuan	0.998	0.998	0.998	0.995	0.999	HC
Tianjin	0.98	0.998	0.999	0.986	0.995	HC
Ningxia	0.999	0.998	0.97	0.996	0.887	BC
Anhui	0.973	0.871	0.961	0.931	0.945	HC
Shandong	0.907	0.916	0.93	0.851	0.82	BC
Shanxi	0.759	0.902	0.929	0.943	0.865	BC
Guangdong	0.999	0.998	0.999	0.998	0.999	HC
Guangxi	0.906	0.953	0.993	0.959	0.999	HC
Xinjiang	0.853	0.896	0.929	0.908	0.919	HC
Jiangsu	0.964	0.939	0.943	0.941	0.941	HC
Jiangxi	0.997	0.999	0.896	0.925	0.958	HC
Hebei	0.907	0.801	0.864	0.856	0.863	BC
Henan	0.931	0.864	0.801	0.844	0.93	HC
Zhejiang	0.942	0.911	0.931	0.942	0.945	HC
Hainan	0.913	0.839	0.873	0.964	0.993	HC
Hubei	0.993	0.949	0.992	0.999	0.991	HC
Hunan	0.97	0.96	0.896	0.93	0.93	HC
Gansu	0.962	0.861	0.975	0.901	0.883	BC
Fujian	0.991	0.978	0.972	0.928	0.946	HC
Tibet	0	0	0.999	0.87	0.829	BC
Guizhou	0.999	0.999	0.999	0.987	0.987	HC
Liaoning	0.998	0.945	0.997	0.965	0.985	HC
Chongqing	0.999	0.969	0.993	0.994	0.984	HC
Shaanxi	0.991	0.999	0.956	0.996	0.996	HC
Qinghai	0	0.889	0.69	0.992	0.945	HC
Heilongjiang	0.99	0.998	0.982	0.998	0.976	HC

Table 9. Calculation results of collaborative scheduling (d) for manufacturing digital transformation and regional economy coupling in 31 provinces and cities from 2017 to 2021. (For the Attribute "Coordination level (average)", HC for "High quality coordination", IC for "Intermediate coordination", PC for "Primary coordination", RC for "Reluctantly coordinate", VD for "Verge of disorder", MID for "Mild disorder", MOD for "Moderate disorder", ED for "Extreme disorder").

Province	2017	2018	2019	2020	2021	Average Value	Coordination Level (Average)
Guangdong	0.976	0.957	0.967	0.958	0.964	0.964	HC
Jiangsu	0.803	0.742	0.747	0.748	0.747	0.757	IC
Beijing	0.686	0.657	0.654	0.624	0.661	0.657	PC
Zhejiang	0.628	0.593	0.625	0.64	0.64	0.625	PC
Shanghai	0.659	0.593	0.6	0.565	0.578	0.599	RC
Shandong	0.611	0.579	0.555	0.521	0.51	0.555	RC
Sichuan	0.512	0.506	0.518	0.477	0.487	0.5	RC

Table 9. *Cont.*

Province	2017	2018	2019	2020	2021	Average Value	Coordination Level (Average)
Fujian	0.499	0.477	0.479	0.437	0.441	0.466	VD
Hubei	0.487	0.432	0.484	0.437	0.469	0.462	VD
Shaanxi	0.447	0.409	0.465	0.381	0.392	0.419	VD
Henan	0.466	0.411	0.387	0.394	0.423	0.416	VD
Anhui	0.442	0.37	0.43	0.406	0.403	0.41	VD
Hunan	0.432	0.411	0.386	0.401	0.381	0.402	VD
Chongqing	0.42	0.351	0.379	0.389	0.357	0.379	MID
Jiangxi	0.435	0.419	0.342	0.349	0.351	0.379	MID
Liaoning	0.398	0.345	0.402	0.356	0.359	0.372	MID
Tianjin	0.411	0.34	0.364	0.329	0.33	0.355	MID
Hebei	0.386	0.329	0.358	0.355	0.339	0.353	MID
Guizhou	0.358	0.336	0.334	0.3	0.259	0.317	MID
Yunnan	0.323	0.294	0.337	0.321	0.301	0.315	MID
Guangxi	0.282	0.295	0.327	0.303	0.316	0.305	MID
Shanxi	0.249	0.29	0.302	0.313	0.281	0.287	MOD
Heilongjiang	0.33	0.256	0.254	0.28	0.287	0.281	MOD
Jilin	0.309	0.275	0.249	0.281	0.28	0.279	MOD
Hainan	0.292	0.26	0.273	0.281	0.232	0.268	MOD
Inner Mongolia	0.273	0.199	0.241	0.254	0.218	0.237	MOD
Xinjiang	0.241	0.216	0.248	0.245	0.226	0.235	MOD
Ningxia	0.242	0.216	0.203	0.259	0.151	0.214	MOD
Gansu	0.226	0.187	0.237	0.214	0.179	0.208	MOD
Qinghai	0	0.273	0.139	0.19	0.12	0.144	ED
Tibet	0	0	0.227	0.308	0.179	0.143	ED

(1) Analysis of the coupling degree (C) between manufacturing digital transformation and regional economy

The coupling foundation of manufacturing digital transformation and regional economy development is solid, and the CD is high. As shown in Table 8, the overall observation from 2017 to 2021 has exceeded 0.900. Most regions belong to a "High-level Coupling" period, and some are in a "Benign Coupling" period. Manufacturing digital transformation and regional economy development gradually cooperate with each other, and the positive impact on them is significantly enhanced, and its value also shows an upward trend in the time series. Among them, Tibet and Qinghai, which have a relatively low degree of coupling, have also shown distinct benign evolution. For example, Tibet has developed from 0 in 2017 and 2018 to 0.829 in 2021, gradually completing the leap of "low level—high levels", and most regions within the scope of the study have reached a high degree of coupling, which once again confirms the internal relationship between the two systems.

(2) Analysis of manufacturing digital transformation and regional economic coupling co scheduling (D)

In terms of time, the CCD of multiple regions and two systems showed a stable trend from 2017 to 2021, and the positive synergy effect of digitalization and economy development changed little. As for spatial distribution, compared with CD, the CCD level of each region has significant differences. As shown in Table 9, from 2017 to 2021, only Guangdong reached the high-quality coordination level, and the average value of coupling coordination in five years was 0.964, significantly higher than other provinces and cities, indicating that Guangdong has achieved excellent results and becomes a pioneer in leading the manufacturing digital transformation and economy development in China. On the other hand, among the 31 provinces within the scope of the study, only 7 provinces and cities including Guangdong, Jiangsu, Beijing, Zhejiang, Shanghai, Shandong and Sichuan have achieved "barely coordinated". In these regions, the digitalization of manufacturing industry and economic development can promote and support each other to a higher level.

They are the provinces and cities that are most likely to complete industrial optimization and upgrading and move towards a higher stage of development in China in the future. However, the coupling synergy of the two systems in Shanxi, Heilongjiang, Jilin, Hainan, Inner Mongolia, Xinjiang, Ningxia, Gansu, Qinghai and Tibet has been in moderate or extreme imbalance for a long time, and the positive synergy between digital transformation and economy development is poor. It is essential to further investigate existing problems and improve the reference basis of the formulation and implementation of relevant policies.

4.4.4. Analysis on the Types of Coordinated Development of Manufacturing Digital Transformation and Regional Economy

Combined with the reality of manufacturing digitalization and economy development, this paper further analyzes the coordinated development degree of manufacturing digitalization transformation and regional economy, and uses the relative difference between U_1 and U_2 to determine the basic type of its evolution [50,51]. According to the evaluation standard, the absolute value of the difference between U_1 and U_2 is less than 0.1, which is regarded as the type of synchronous development between the manufacturing digital transformation and regional economy. However, if the coupling coordination degree D at this time is less than 0.3, it is regarded as the type of double-sided lag; When the difference between U_1 and U_2 is greater than 0.1, it is regarded as the regional digital dominant type; On the contrary, when the difference between U_1 and U_2 is less than -0.1, it is an economic advantage type. According to this rule, we can get the type of coordinated development of provinces and cities in 2017–2021 as shown in Table 10. Table 10 shows the changing trend of coordinated development types of various provinces and cities from 2017 to 2021. For example, Shanghai was in the digital advantage type of 2017, the comprehensive index of manufacturing digital transformation was higher than that of regional economy, which indicates that at this stage, the level of digital transformation development in Shanghai was higher than that in the economic field. From 2018 to 2021, the coordinated development type of Shanghai has changed into a more healthy and reasonable synchronous development type, which shows that the synergy of the two systems in Shanghai has been improved, and the interaction between the two systems is stronger. From 2017 to 2021, Beijing was in the development state of digital advantage, which shows that the development level of manufacturing digital transformation in Beijing is higher than its economic development level, and the advantages of digital development need to be transformed into economic development by corresponding policies.

Table 10. Types of coordinated development of provinces and cities in 2017–2021.

Coordination Type	2017	2018	2019	2020	2021
Synchronous development type	Yunnan, Jilin, Sichuan, Tianjin, Anhui, Guangdong, Jiangxi, Hubei, Hunan, Fujian, Guizhou, Liaoning, Chongqing, Shaanxi, Heilongjiang	Shanghai, Sichuan, Tianjin, Jiangxi, Hunan, Fujian, Guizhou, Liaoning, Chongqing, Shaanxi	Shanghai, Yunnan, Sichuan, Tianjin, Shanxi, Guangdong, Guangxi, Hubei, Guizhou, Liaoning, Chongqing	Shanghai, Yunnan, Sichuan, Tianjin, Shanxi, Guangxi, Jiangxi, Hubei, Guizhou, Liaoning, Chongqing, Shaanxi	Shanghai, Yunnan, Sichuan, Tianjin, Guangdong, Guangxi, Jiangxi, Hubei, Liaoning, Chongqing, Shaanxi
Economic advantage type	Shandong, Shanxi, Jiangsu, Hebei, Henan, Zhejiang	Anhui, Shandong, Guangdong, Jiangsu, Hebei, Henan, Zhejiang, Hubei	Anhui, Shandong, Jiangsu, Jiangxi, Hebei, Henan, Zhejiang, Hunan, Fujian	Anhui, Shandong, Guangdong, Jiangsu, Hebei, Henan, Zhejiang, Hunan, Fujian	Anhui, Shandong, Jiangsu, Hebei, Henan, Zhejiang, Hunan, Fujian
Digital dominant	Shanghai, Beijing	Beijing	Beijing, Shaanxi	Beijing	Beijing
Double sided hysteresis type	Inner Mongolia, Ningxia, Guangxi, Xinjiang, Hainan, Gansu, Tibet, Qinghai	Yunnan, Inner Mongolia, Jilin, Ningxia, Shanxi, Guangxi, Xinjiang, Hainan, Gansu, Tibet, Qinghai, Heilongjiang	Inner Mongolia, Jilin, Ningxia, Xinjiang, Hainan, Gansu, Tibet, Qinghai, Heilongjiang	Tibet, Inner Mongolia, Jilin, Ningxia, Xinjiang, Hainan, Gansu, Qinghai, Heilongjiang	Inner Mongolia, Jilin, Ningxia, Shanxi, Xinjiang, Hainan, Gansu, Tibet, Guizhou, Qinghai, Heilongjiang

5. Conclusions

In this study, the innovation, development, and digitalization characteristics of five key links of manufacturing industry are obtained through patent metrology analysis, and the data of these five links are taken as the overall representation of manufacturing data for analysis. Then, the comprehensive evaluation index system of manufacturing digital transformation and regional economy is constructed. The comprehensive indexes of manufacturing digital transformation and the regional economy development of 31 provinces and cities in China are analyzed respectively by using entropy method and physical coupling coordination degree model. The temporal and spatial characteristics of CD and CCD in each province are analyzed.

Our research provides insights for understanding different coordination types of provinces and cities, from the perspective of innovation. After comprehensive research and analysis, the main conclusion is given as follows. According to the development level, coupling degree and coupling coordination degree types of the two systems in the provinces and cities, the coordination types of the provinces and cities can be divided into four coordinated development types: "synchronous development", "digital advantage", "economic advantage" and "double-sided lag". There should be different support countermeasures according to different coordinated development types of different regions:

For the synchronous development type, we should give more relaxed financing policies and more preferential talent policies, and give the two systems broad growth space and nutrients. For the digital advantage type, we should consider increasing projects such as industry university research cooperation to enable the achievements and advantages of the manufacturing digital development to regional economy development. For the economic advantage type, the government can appropriately increase scientific research projects or other economic means to reduce the burden of enterprises undergoing manufacturing digital transformation, so as to provide guarantee of enterprises to realize digital transformation. For the double-sided lagging type, we should consider the difficulties encountered in development according to local conditions, and further promote manufacturing digital development while solving the problems of economic development.

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