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RESEARCH ARTICLE

Synergy degree measurement of traditional manufacturing and green industry driven by digital economy in Yangtze River Delta region

Yi Liu[a], Yuanyuan Wang[a], Zhendong Ming[b*]

a. Management School, Hangzhou Dianzi University, Hangzhou 310018, PR China

b. Hangzhou Automation Technology Institute Co., Ltd, Hangzhou 310012, PR China

ABSTRACT

Measuring the collaborative development of the manufacturing industry with green industry can sort out the green development context of the traditional manufacturing industry in digital economy era and provide the reference for realizing the green transformation of traditional manufacturing industry. This paper proposes the coordinated development evaluation model from the perspective of industrial, social and environmental subsystems based on the theory of the social shaping of technology. Furthermore, this paper applies the entropy method and order parameter method to measure the synergy degree of composite system of traditional manufacturing industry, digital economy and green industry in Yangtze River Delta region based on the panel data of China Statistical Yearbook from 2013 to 2021. The research shows that the order degree of traditional manufacturing industry, digital economy and green industry subsystem has been effectively increased year by year, while the synergy degree is still low in different provinces. The traditional manufacturing industries should build the digital innovation ecosystem and utilize digital technology to improve the high energy consumption production process and achieve the dual goals of "low-carbon development and digital transformation".

KEYWORDS

Traditional manufacturing industry; Digital economy; Green industry; Synergy degree; Order parameters; Order degree

1 Introduction

China's manufacturing industry still faces significant obstacles, such as low technological levels, high consumption with heavy emissions, and being at the middle and lower ends of the global value chain, which have long hindered the advancement of China's traditional manufacturing industry. The report of the 20th National Congress of the Communist Party of China advocates

Corresponding author: zgshuzi@163.com

focusing on the real economy, accelerating the development of the digital economy, promoting its deep integration with the real economy, and fostering the development of high-end, intelligent, and environmentally friendly manufacturing industries. The collaborative development of manufacturing industry with green industry is an effective way to enhance the green transformation efficiency of traditional manufacturing industry in digital economy era. The digital economy plays a vital role in promoting green development of the traditional manufacturing industry with the rapid development of digital technologies such as big data, cloud computing, and the Internet of Things, and the emergence of new business models like e-commerce and mobile payments (Wamba et al., 2015). The digital economy provides services for the manufacturing industry to make the research & development (R&D), production, management and marketing through Internet technology, which aids enterprises to enhance technological innovation, improve industrial structures and achieve value-added outcomes (Kurfess et al., 2020). The digital economy influences the transformation of manufacturing enterprises by optimizing the allocation of production assets and advocating green consumption (Pei et al., 2023).

The Yangtze River Delta is one of the most economically vibrant region with a complete manufacturing system in China, and it's of great significance to explore the coordination mechanism between green development and digital economy, which constructs the regional green transformation pattern and realizes the high-quality development of the traditional manufacturing industry. The order parameter provides important direction for the internal study of the mechanism, and not only represents the degree of coordination of the sub-mechanisms but also the outcome of any kind of cooperation between the sub-mechanisms (Berasategi et al., 2011). Therefore, this paper investigates the industrial green transformation mechanism and explores the digital economy's influence on traditional manufacturing industry and green industry from its essence, characteristics, functions, and values to development. This paper adapts the order parameter method to analyze the order degree of the composited system of traditional manufacturing industry, digital economy and green industry subsystems based on the social shaping of technology theory. The synergy degree of the green transformation of the traditional manufacturing industry is measured based on the synergetic theory and the entropy method according to the statistical data of the Yangtze River Delta from 2014 to 2021, so as to promote the digitalization, green transformation and upgrading of traditional manufacturing industry in China.

The multi-agent regional industrial cooperative innovation alliance can effectively improve regional industrial innovation performance, and the stable and effective condition of the alliance is a good income distribution mechanism.

2 Literature review and theoretical analysis

Ren (2023) believes that the coordinated development of industrial digitization and digital industrialization has promoted the construction of a modern industrial system and the new development of new industrialization. Wang (2023) discusses that the multi-agent regional industrial cooperative innovation alliance can effectively improve the regional industrial innovation performance, and the stable and effective condition of the alliance is a good income distribution mechanism. Wu & Meng (2022) proposes that digital transformation can enhance the production quality and optimize the energy consumption structure of the manufacturing industry in the Yangtze River Economic Belt. Jones et al. (2021) suggests that digital transformation requires not only digital iteration of technology, but also digital innovation to optimize traditional business processes. Luo & Qiu (2022) believes that digital economy can change the external environment and redesign business processes, such as production processes, marketing processes and supply chain processes, and the green development of the manufacturing industry can be achieved through the spatial spillover effect of digital technology. Qi & Tao (2018) proposes that digital twin can make intelligent manufacturing more responsive and predictive through the accurate analysis by big data technology, which connects the physical world of the manufacturing industry with the network world. Shi (2021) points out that the deep integration of digital economy and manufacturing industry lies in the digital transformation of the manufacturing industrial chain by integrating digital technology. Hong & Ren (2023) believes that the deep integration of digital economy and real economy can enhance the modernization level of the real economy by digital technology and data elements. Yang et al. (2023) finds that the integration level of digital economy and manufacturing industry has reached an imbalanced condition by the coupling coordination model, and the digital economy is experiencing more rapid development than the manufacturing industry in China. Li (2023) utilizes the coupling coordination degree model to measure the integration level of the manufacturing industry and digital economy, which has a notable positive impact on the innovation efficiency of manufacturing industry. Li & Cheng (2023) applies the demand and supply-driven model of input-output method to analyze the backward and forward association fusion effects of manufacturing industry and digital economy industries in China. Su et al. (2023) studies the coupling degrees and value-added abilities of the digital economy and manufacturing industry by constructing the coupling model and calculating the average contribution rate of the digital economy and manufacturing industry. China's domestic scholars have extensively investigated the influence of digital economy on the manufacturing industry. However, it lacked a comprehensive quantitative analysis on the synergy development of digital economy, traditional manufacturing industry and green industry from the multi-level perspective of socio-technical transition background.

Synergistic sustainable development is rooted in differentiated advantages among industries (Hao & Guo, 2021). Industries collaborate to create mutually beneficial results and even establish multi-win situations for shared growth through interactive and integrative techniques across upstream and downstream sectors. Haken (2004) applies the synergy theory to study the self-organization of an unstable open system by its coordination mechanism under external energy and material exchange. The social shaping of technology (SST) underscores the dynamic synergistic evolution observed across multiple layers of interdependence and interaction within a socio-technical system, which can effectively promote the sustainable transformation and development of large-scale social-technical systems (Li, 2019). Sheng (2007) analyzes the relations between technology and society in the view of SST from the animadverting on the technological determinism by the social shaping of technology, technological choice, technological innovation, *etc*. This paper analyzes the synergy development effects of composited system among traditional manufacturing industry, digital economy and green industry in the Yangtze River Delta region based on the SST theory, as shown in Figure 1.

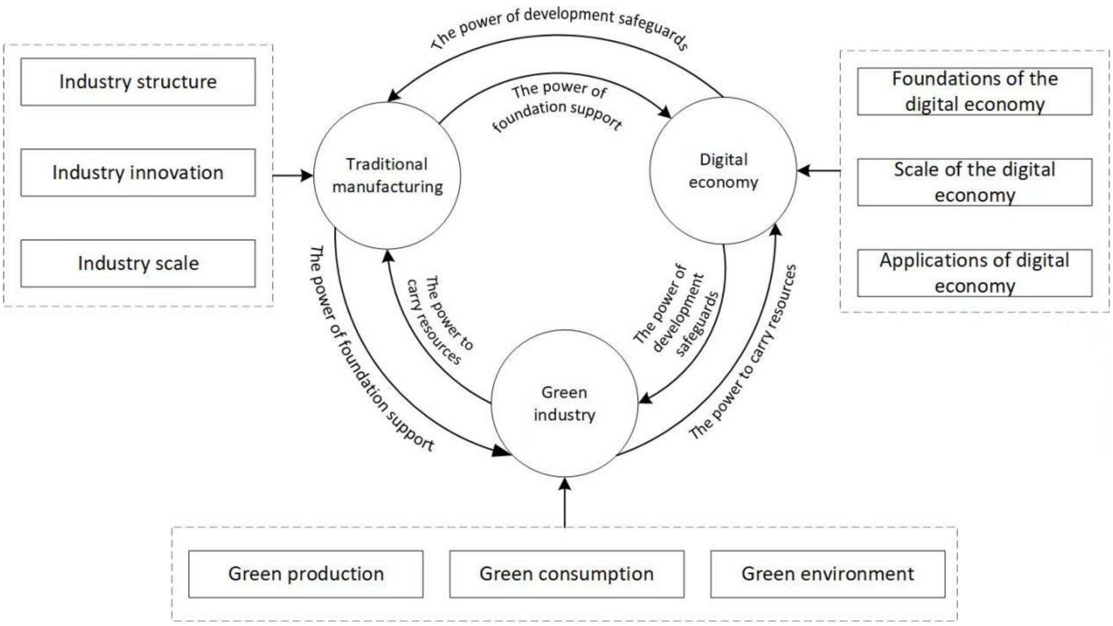

Figure 1 The synergy development of traditional manufacturing industry, digital economy and green industry

3 Research methodology

3.1 The order parameter system of traditional manufacturing, digital economy and green industry

This paper divides the composite system into three independent subsystems with different attributes— traditional manufacturing industry, digital economy and green industry based on the SST theory. Considering the principles of scientific, systematic, representative and feasible selection of indicators, the order parameters of the three subsystems are determined after analyzing the synergistic development of traditional manufacturing industry and green industry driven by digital economy in the Yangtze River Delta of China. The traditional manufacturing industry subsystem consists of 11 order parameters reflecting industry structure, industry innovation and industry scale; digital economy subsystem consists of 10 order parameters presenting foundations of digital economy, scale of digital economy and applications of digital economy, while the green industry subsystem consists of 11 order parameters indicating green production, green consumption and environmental regulation. Table 1 shows the order parameters of each subsystem in detail.

Table 1 Evaluation index system of traditional manufacturing, digital economy and green industry

Subsystems	Primary indexes	Secondary indexes	Unit	Type
Traditional manufacturing	Industry structure	X1: Selling expenses of enterprises above considerable scale	Billions of yuan	+
		X2: Industrial rationalization level	/	+
		X3: Industrial advanced level	/	+
	Industry innovation	X4: Manufacturing innovation capacity	/	+
		X5: Number of R&D personnel	People	+
		X6: R&D funding	million	+

		X7: Number of R&D projects	item	+
		X8: Number of new product projects	item	+
	Industry scale	X9: Employees in manufacturing industry	million	+
		X10: Wages of manufacturing personnel	billion	+
		X11: Number of enterprises above scale	individuals	+
Digital economy	Foundations of digital economy	Y1: Number of mobile phone subscribers	ten thousand households	+
		Y2: Internet broadband access ports	million	+
		Y3: Digital equipment investment	million	+
		Y4: Mobile phone exchange capacity	million households	+
		Y5: Optical fiber cable construction level	/	+
	Scale of the digital economy	Y6: Consumption scale of digital products	billion	+
		Y7:IT talent reserve and scale	/	+
		Y8: Wages of information service industry personnel	billion	+
		Y9: Technology market turnover	billion	+
	Applications of digital economy	Y10: Internal expenditure on research and experimental development	billion	+
		Y11: Patents granted	Item	+
Green industry	Green production	Z1: Harmless treatment rate of domestic waste	%	+
		Z2: Comprehensive utilization rate of industrial waste	%	+
		Z3: GDP per unit of land	billion yuan/square kilometer	+
		Z4: Energy consumption	million tones	−
		Z5: Electricity consumption	billion kWh	−
	Green consumption	Z6: Investment in industrial pollution control	million tones	+
		Z7: Total natural gas supply	billion cubic meters	+
		Z8: Pesticide use per unit area of agricultural land	tones/ha	−
	Environmental regulation	Z9: Local financial expenditure on environmental protection	billion yuan	+
		Z10: Park area per capita	Square meters/person	+
		Z11: Per capita civilian car ownership	Vehicle/person	−

Note:"＋" is the positive index, "－"is the negative index

The specific measurement indicators in Table1 are described as follows:

(1) Industrial rationalization level (X2) is assessed based on the Thiel index redefined by Gan & Zheng (2011). It incorporates the total output value of the secondary industry and the total output

value of the tertiary industry. The calculation formula is as follows:

$$TL = \sum_{i=1}^{n} (\frac{Y_i}{Y}) \ln (\frac{Y_i}{L_i} \Big/ \frac{Y}{L}) \qquad (1)$$

where Y denotes the gross output, L is total employment, i represents the industry, n is the number of industrial sectors, Y_i/Y indicates the output structure, L_i/L represents the employment structure, and Y/L denotes productivity. A non-zero Thiel index signifies a deviation from the equilibrium state in the industrial structure. The smaller the Thiel index is, the higher the degree of rationalization of the industrial structure.

(2) Manufacturing innovation capacity (X4) is measured by the number of invention patent applications submitted by industrial enterprises above a certain scale, divided by the number of domestic invention patent applications received.

(3) Digital equipment investment (Y3) is calculated as the amount of fixed asset investment in the information transmission, software, and information technology service industry. The level of fiber optic cable construction is determined by the length of long-distance fiber optic cables divided by the country's area. The level of the IT talent pool is measured by the number of employees in the information service industry divided by the number of employees in the manufacturing industry.

3.2 Subsystem order degree model

According to the synergy theory, this paper abstracts the composite system as $S = \{S_1, S_2, S_3\}$, where S_1 is the traditional manufacturing subsystem, S_2 is the digital economy subsystem, and S_3 is the green industry subsystem. It is assumed that the order parameter of each subsystem is $X_{ij} = (X_{i1}, X_{i2}, ..., X_{in})$, where $n \geq 1$, $X_{min} \leq X_{ij} \leq X_{max}$, $j \in [1, n]$. Let X_{max} and X_{min} be the maximum and minimum values of the order parameter X_{ij} in each system. It is assumed that $X_{i1}, X_{i2}, ..., X_{il}$ are positive indicators, and each value is positively correlated with the degree of order. On the contrary, $X_{il+1}, X_{il+2}, ... X_{in}$ are negative indexes, and each value is negatively correlated with the order degree. So the order degree model of the order parameter component of the subsystem can be calculated as follows:

$$U_i(X_{ij}) = \begin{cases} \dfrac{X_{ij} - X_{min}}{X_{max} - X_{min}}, j = 1,2, ..., m \\ \dfrac{X_{max} - X_{ij}}{X_{max} - X_{min}}, j = m+1, m+2, ..., n \end{cases} \qquad (2)$$

In this study, the linear weighting method is employed to quantify the order degree of three subsystems (Zhang et al., 2018), and the order degree of the subsystem U_i (X_i) is calculated as follows:

$$U_i(X_i) = \sum_{j=1}^{n} \lambda_j U_i(X_{ij}) \qquad (3)$$

Where λ_j is the weight of each order parameter, which is determined by the entropy method (Li et al.,2012).

3.3 Construct synergy model

In this paper, the synergy degree between traditional manufacturing industry, digital economy and green industry is measured by the composite system synergy model with the initial time point of the time series as the benchmark, which can observe the evolution trajectory of the composite system from disorder to the synergy status (Shi et al., 2022). The formula of composite system synergy degree, denoted as *C*, is calculated by Equation (7) and (8):

$$C = \theta \times \sqrt[m]{\prod_{i=1}^{m} \left| U_i^{\mathrm{t}}(X_i) - U_i^{\mathrm{t}-1}(X_i) \right|} \qquad (7)$$

Where,

$$\theta = \begin{cases} 1, & U_i^{\mathrm{t}}(X_i) - U_i^{\mathrm{t}-1}(X_i) > 0 \\ -1, & others \end{cases} \qquad (8)$$

Where $U_i^{\mathrm{t}}(X_i)$ and $U_i^{\mathrm{t}-1}(X_i)$ denote the order degree of each subsystem at time *t,* and $C \in [-1,1]$. The bigger the *C* is, the better the synergistic development of the composite system. It can be seen that only when the order degree of green industry, traditional manufacturing industry or digital economy subsystem is improved, the order degree of the composite system can rapidly increase as a whole.

4 Empirical analysis

4.1 Data source

This paper studies the impact of digital economy on the green development of traditional manufacturing industry by measuring the synergistic level of traditional manufacturing industry, digital economy industry and green industry. The data used by this study is sourced from the *China Science and Technology Statistical Yearbook*, the *China Industrial Statistical Yearbook*, statistical yearbooks of relevant provinces in the Yangtze River Delta, and information materials posted on the website of the National Bureau of Statistics, including the annual information disclosure report and environmental protection status bulletin. Furthermore, the research period of this paper starts from 2013 to 2021, and any missing data are filled by linear interpolation. Considering the diverse units of panel data, the data was processed by the standard deviation of Z-Score method to achieve dimensionless representation. Table 2 shows the standardized data of the traditional manufacturing, digital economy, and green industry in Zhejiang province.

Table 2 The standardized data of each subsystem in Zhejiang province during 2013 and 2021

Year	Traditional manufacturing										
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11
2013	-0.468	-0.274	-0.778	0.403	0.005	-0.47	-0.109	-0.115	0.444	-0.422	0.57
2014	-0.344	-0.376	-0.786	0.178	0.158	-0.341	-0.010	-0.019	0.399	-0.297	0.645
2015	-0.283	-0.489	-0.672	-0.306	0.308	-0.208	0.168	0.076	0.276	-0.260	0.664
2016	-0.132	-0.607	-0.544	-0.657	0.337	-0.081	0.370	0.284	0.186	-0.211	0.603
2017	-0.060	-0.685	-0.432	-0.557	0.405	0.065	0.656	0.517	0.181	-0.102	0.593
2018	0.145	-0.805	-0.362	-0.738	0.750	0.246	0.904	0.916	0.023	-0.015	0.630
2019	0.333	-0.906	-0.227	-0.168	1.078	0.443	1.487	1.504	0.007	0.146	0.929
2020	0.351	-1.024	-0.101	-0.178	1.242	0.631	2.039	2.109	0.146	0.375	1.062
2021	0.623	-1.015	-0.213	5.179	1.252	0.934	2.233	2.906	0.225	0.819	1.400

Year	Digital economy										
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11
2013	0.297	-0.671	-1.111	0.018	-0.721	-0.809	-0.719	-0.747	-1.089	-0.753	0.072
2014	0.426	-0.580	-0.949	0.082	-0.725	-0.736	-0.674	-0.685	-1.080	-0.630	-0.026
2015	0.388	0.464	-0.182	0.136	-0.699	-0.607	-0.613	-0.592	-1.065	-0.490	0.302
2016	0.363	0.440	-0.006	0.188	-0.699	-0.407	-0.526	-0.445	-0.920	-0.329	0.207
2017	0.521	0.799	0.068	0.864	-0.637	-0.410	-0.354	-0.133	-0.737	-0.145	0.153
2018	0.830	1.051	0.106	1.048	-0.677	-0.092	-0.326	-0.007	-0.353	0.097	0.653
2019	1.014	1.205	0.265	0.898	-0.686	0.325	-0.207	0.376	0.076	0.400	0.658
2020	0.949	1.081	0.429	0.898	-0.668	0.426	-0.129	0.739	0.820	0.657	1.408
2021	1.067	1.182	0.537	0.898	-0.624	0.866	-0.004	1.242	1.473	0.914	1.929
Year	Green industry										
	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11
2013	0.973	0.227	-1.117	-0.079	0.034	-0.065	2.589	-1.287	-1.288	-0.175	-0.202
2014	1.448	0.127	-1.121	-0.057	0.063	0.303	2.492	-1.020	-1.010	0.012	0.067
2015	1.018	0.086	-1.078	0.039	0.089	-0.188	2.337	-1.044	-0.425	0.130	0.328
2016	1.094	-0.573	-0.964	0.120	0.263	0.303	1.842	-0.861	-0.506	0.122	0.664
2017	-0.020	-0.468	-0.931	0.211	0.437	0.303	1.516	-0.595	-0.15	0.183	0.989
2018	-0.096	-0.005	-0.893	0.290	0.623	0.303	1.313	-0.209	-0.093	0.349	1.296
2019	-0.156	0.342	-0.776	0.377	0.718	0.303	0.873	-0.124	0.832	0.471	1.571
2020	0.631	1.308	-0.691	0.653	0.785	0.303	0.451	0.201	0.227	0.292	1.801
2021	-0.945	1.481	-0.643	0.891	1.159	0.303	0.050	0.789	0.016	0.000	2.139

4.2 The order degree of order parameters

To measure the synergy degree of each subsystem, the information entropy method is applied to calculate the order parameter weight of each indicator. The order degree of order parameters in each subsystem of Zhejiang province is calculated based on the normalized data from 2013-2021, and the results are shown in Table 3.

Table 3 The order degree of order parameters of each subsystem in Zhejiang province during 2013 and 2021

Year	Traditional manufacturing										
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11
2013	0.22	0.23	0.08	0.21	0.34	0.18	0.27	0.22	0.48	0.27	0.65
2014	0.26	0.20	0.08	0.17	0.39	0.21	0.31	0.25	0.47	0.30	0.68
2015	0.28	0.16	0.11	0.09	0.44	0.25	0.36	0.27	0.43	0.31	0.69
2016	0.33	0.13	0.15	0.03	0.45	0.28	0.42	0.33	0.40	0.33	0.67
2017	0.35	0.10	0.18	0.05	0.48	0.32	0.51	0.39	0.40	0.36	0.66
2018	0.42	0.07	0.20	0.02	0.59	0.36	0.59	0.49	0.34	0.38	0.67
2019	0.48	0.04	0.24	0.11	0.70	0.42	0.77	0.64	0.34	0.43	0.78
2020	0.49	0.00	0.28	0.11	0.75	0.47	0.94	0.80	0.39	0.49	0.83
2021	0.58	0.00	0.25	1.00	0.76	0.54	1.00	1.00	0.41	0.62	0.95
Weights	0.08	0.10	0.08	0.09	0.11	0.08	0.11	0.11	0.11	0.06	0.08

Year	Digital economy										
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11
2013	0.56	0.21	0.01	0.36	0.06	0.11	0.00	0.09	0.00	0.16	0.26
2014	0.60	0.24	0.05	0.38	0.06	0.12	0.01	0.10	0.00	0.19	0.24
2015	0.59	0.58	0.23	0.40	0.07	0.15	0.03	0.13	0.01	0.23	0.32
2016	0.58	0.57	0.27	0.41	0.07	0.20	0.05	0.16	0.05	0.27	0.29
2017	0.63	0.68	0.29	0.60	0.09	0.20	0.09	0.23	0.10	0.32	0.28
2018	0.74	0.76	0.30	0.65	0.08	0.27	0.10	0.26	0.20	0.38	0.40
2019	0.80	0.81	0.33	0.61	0.07	0.37	0.13	0.35	0.32	0.46	0.40
2020	0.77	0.77	0.37	0.61	0.08	0.39	0.14	0.43	0.52	0.52	0.58
2021	0.81	0.81	0.40	0.61	0.09	0.49	0.18	0.55	0.70	0.59	0.70
Weights	0.07	0.07	0.08	0.07	0.12	0.07	0.16	0.09	0.10	0.06	0.11
Year	Green industry										
	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11
2013	0.69	0.71	0.00	0.94	0.02	0.13	0.61	0.64	0.64	0.00	0.59
2014	0.82	0.68	0.00	1.00	0.09	0.20	0.66	0.63	0.63	0.03	0.52
2015	0.70	0.67	0.01	0.92	0.09	0.35	0.70	0.59	0.62	0.07	0.46
2016	0.72	0.52	0.05	1.00	0.14	0.33	0.70	0.56	0.56	0.21	0.37
2017	0.42	0.54	0.06	1.00	0.21	0.42	0.72	0.53	0.51	0.30	0.29
2018	0.40	0.65	0.07	1.00	0.31	0.44	0.77	0.50	0.45	0.36	0.21
2019	0.38	0.73	0.11	1.00	0.33	0.67	0.80	0.47	0.42	0.48	0.14
2020	0.60	0.96	0.13	1.00	0.42	0.52	0.75	0.37	0.40	0.60	0.09
2021	0.16	1.00	0.15	1.00	0.57	0.47	0.66	0.28	0.28	0.71	0.00
Weights	0.12	0.04	0.21	0.02	0.14	0.08	0.08	0.12	0.07	0.05	0.06

4.3 Analysis of order degree and synergy degree

The synergy degree of each subsystem is calculated by inputting the weight and order degree of order parameters. The order degree of composed subsystems in Yangtze River Delta region is shown in Table 4.

Table 4 The order degree of subsystems in Yangtze River Delta region during 2013 and 2021

Province	Year	Traditional manufacturing	Digital economy	Green industry
Shanghai	2013	0.114	0.152	0.538
	2014	0.126	0.232	0.584
	2015	0.121	0.248	0.522
	2016	0.130	0.297	0.558
	2017	0.132	0.318	0.565
	2018	0.131	0.350	0.515
	2019	0.142	0.423	0.538
	2020	0.152	0.513	0.503
	2021	0.180	0.608	0.508
Anhui	2013	0.134	0.034	0.434
	2014	0.138	0.050	0.410

	2015	0.134	0.082	0.427
	2016	0.141	0.096	0.463
	2017	0.154	0.118	0.476
	2018	0.165	0.131	0.466
	2019	0.188	0.150	0.496
	2020	0.180	0.173	0.479
	2021	0.209	0.249	0.479
Jiangsu	2013	0.467	0.248	0.565
	2014	0.518	0.267	0.565
	2015	0.526	0.311	0.636
	2016	0.547	0.329	0.635
	2017	0.552	0.366	0.599
	2018	0.561	0.449	0.667
	2019	0.603	0.498	0.665
	2020	0.641	0.593	0.673
	2021	0.707	0.675	0.626
Zhejiang	2013	0.291	0.143	0.348
	2014	0.304	0.156	0.379
	2015	0.311	0.214	0.374
	2016	0.322	0.231	0.378
	2017	0.348	0.278	0.356
	2018	0.381	0.33	0.371
	2019	0.457	0.373	0.402
	2020	0.514	0.427	0.426
	2021	0.651	0.493	0.372

Figure 2-4 show the orderliness within the range of (0, 1) of the traditional manufacturing industry and digital economy sub-systems in Yangtze River Delta region, which form a dynamic evolution force to promote the system upgrading from disorder to order. On the other hand, the development trend of green industry subsystem shows the comparative upward trajectory in different provinces of the Yangtze River Delta region. As for the traditional manufacturing subsystem, the order degree of Shanghai is the lowest with a range from 0.114 to 0.180, whereas Jiangsu shows the highest order degree ranging from 0.467 to 0.707. While the digital economy subsystem denotes an increasing development trend from 2013 to 2021. Notably, Shanghai's digital economy subsystem shows more significant progress, while the order degree of digital economy in Anhui province gradually increases from 0.034 to 0.249. The developments of the green industry subsystem in the four provinces show the fluctuation from 2013 to 2021, while Jiangsu province exhibits relatively better development in the green industry with an overall gradual upward trend.

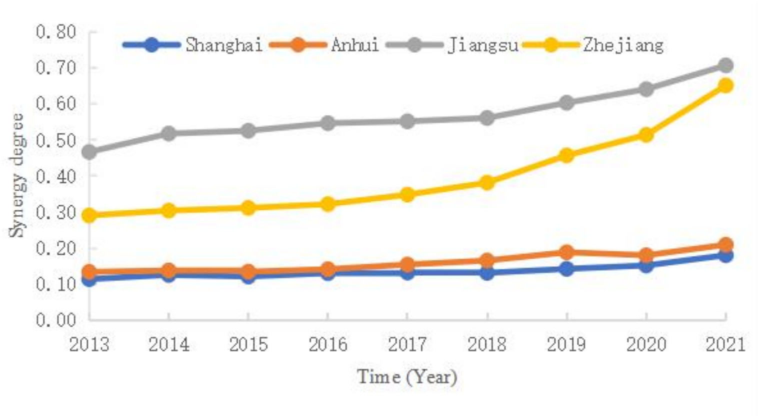

Figure 2 The order degree of traditional manufacturing subsystem

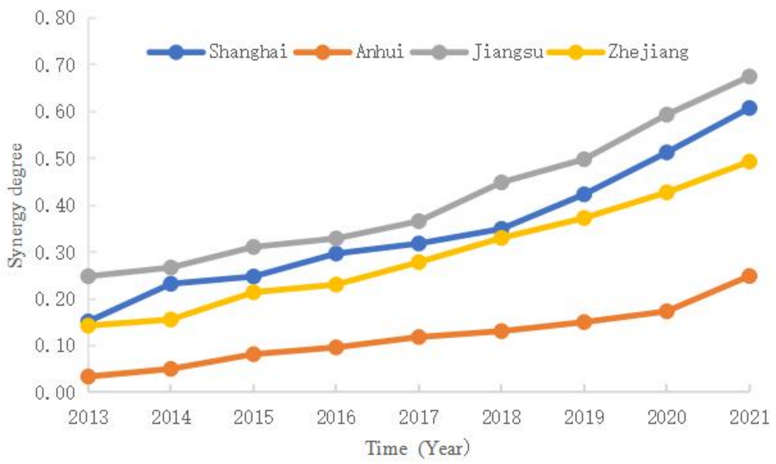

Figure 3 The order degree of the digital economy subsystem

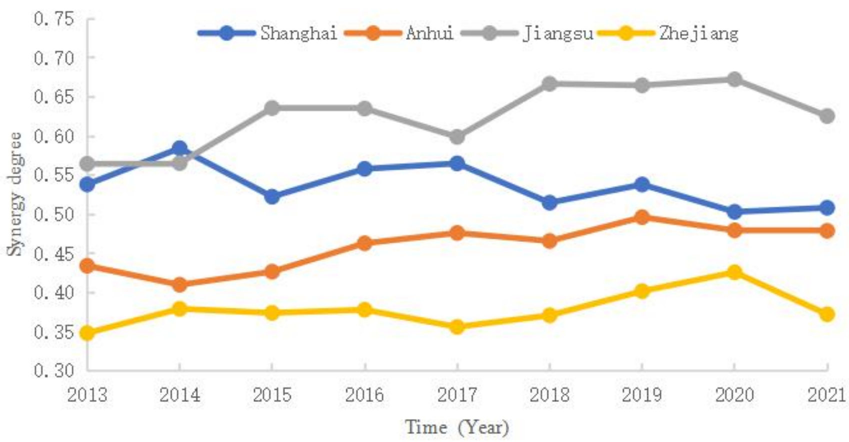

Figure 4 The order degree of the green industry subsystem

Considering the statistical data from 2014 to 2021, we build a collaborative analysis system to estimate the relationship between digital economy development with regional industrial green transformation in the Yangtze River Delta region of China. The synergy degree of traditional manufacturing industry, digital economy and green industry can be calculated through the panel data, and the results are shown in Table 5, which is in the development stage from low coupling coordination to moderate coupling coordination.

Table 5 The synergy of subsystems in the Yangtze River Delta region

Province	Year	C_{123}	C_{12}	C_{23}	C_{13}
Shanghai	2014	0.035	0.031	0.061	0.023
	2015	-0.016	-0.008	-0.031	-0.017
	2016	0.025	0.021	0.042	0.018
	2017	0.006	0.006	0.012	0.003
	2018	-0.011	-0.005	-0.040	-0.007
	2019	0.027	0.029	0.041	0.016
	2020	-0.031	0.029	-0.056	-0.018
	2021	0.024	0.052	0.022	0.012
Anhui	2014	-0.012	0.008	-0.020	-0.010
	2015	-0.012	-0.010	0.023	-0.008
	2016	0.015	0.010	0.023	0.016
	2017	0.016	0.017	0.017	0.013
	2018	-0.011	0.012	-0.011	-0.011
	2019	0.024	0.021	0.024	0.026
	2020	-0.015	-0.014	-0.020	-0.012
	2021	-0.011	0.047	-0.007	-0.004
Jiangsu	2014	0.009	0.031	0.004	0.007
	2015	0.029	0.019	0.056	0.024
	2016	-0.006	0.019	-0.004	-0.004
	2017	-0.019	0.014	-0.037	-0.014
	2018	0.037	0.028	0.075	0.025
	2019	-0.016	0.046	-0.010	-0.009
	2020	0.030	0.060	0.027	0.017
	2021	-0.063	0.073	-0.062	-0.056
Zhejiang	2014	0.018	0.013	0.020	0.021
	2015	-0.013	0.021	-0.017	-0.006
	2016	0.009	0.013	0.008	0.007
	2017	-0.030	0.036	-0.032	-0.024
	2018	0.029	0.041	0.028	0.022
	2019	0.046	0.057	0.036	0.048
	2020	0.042	0.056	0.036	0.037
	2021	-0.079	0.095	-0.059	-0.086

Note: C_{123} is the synergy degree of the composite system of traditional manufacturing, digital economy and green industry; C_{12} is the synergy degree of the composite system of traditional manufacturing and digital economy; C_{23} is the synergy degree of the composite system of digital economy and green industry; C_{13} is the synergy degree of the composite system of traditional manufacturing and green industry.

Table 5 shows that the three subsystems exhibit favorable development as independent systems, while the synergy of the composite system comprising three industries is not optimal.

The synergy degree of the traditional manufacturing industry, digital economy, and green industry in the Yangtze River Delta region fluctuates within the range of (-0.08, 0.06). The synergy degree of traditional manufacturing and digital economy has a relative high level within the range of (-0.02, 0.1), indicating that the synergy development of traditional manufacturing with digital economy has an upward growth trend in the Yangtze River Delta region. With the development of digital economy in the different provinces, the production efficiency and business performance of traditional manufacturing industries have improved significantly. On the other hand, the synergy degree of the composite system involving green industry is relatively low. The synergy degree of digital economy and green industry exhibits the lowest level with a range of (-0.07, 0.080). The synergy degree of traditional manufacturing industry and green industry shows significant fluctuations within the range of (-0.09, 0.050), which the synergistic development mechanism of traditional manufacturing industry, digital economy and green industry hasn't been fully established in the Yangtze River Delta region. Therefore, traditional manufacturing industry should motivate the green technology innovation and embrace digital technology to achieve the green transformation.

5 Conclusion

This paper constructs the complex system synergy model to measure the synergistic degree of the composite system of traditional manufacturing industry, digital economy, and green industry based on the SST theory. A comparative analysis is conducted for the provinces in the Yangtze River Delta region regarding the subsystem order degree and an overall analysis of the composite system synergy degree. Due to the rapid development of digital economy in the Yangtze River Delta region in recent years, the results of the analysis show that the traditional manufacturing industry subsystem and the digital economy subsystem exhibit an upward development trend, whereas the green industry subsystem displays a comparatively stable trend. Therefore, the government should establish appropriate policies to regulate and guide the green transformation of traditional manufacturing industry. At the same time, the traditional manufacturing industry should build a green digital ecosystem and strengthen the construction of digital infrastructure to accelerate the green technology innovation and embrace digital technology to enhance production efficiency and refine management practices, to achieve the digital transformation and low-carbon development of the traditional manufacturing industry.

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Conflict of interests

The authors declare no conflict of interest.

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